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SAIIE34

ILLUMINATE THE PATH AHEAD

Proceedings

14 - 16 October 2024

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SAIIE34

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Preface

The 34th Southern African Institute for Industrial Engineering (SAIIE) conference brings together academics, practitioners, and students to engage with some of the most pressing challenges facing humanity today. In a world grappling with climate change, dwindling resources, poverty, illiteracy, and technological disruption, industrial engineers play a critical role in illuminating problems and crafting innovative solutions. Our collective expertise in systems analysis, process improvement, and data-driven decision-making is more essential than ever.

This year's conference theme, "ILLUMINATE THE PATH AHEAD", highlights the unique ability of industrial engineers to shine a light on these complex issues, guiding enterprises, communities, and industries towards a sustainable and prosperous future. The contributions in this year's proceedings demonstrate the power of knowledge to tackle these challenges, inspired by the timeless words of Louis Pasteur: "Because knowledge belongs to humanity, and it is the torch that illuminates the world."

We are pleased to see a diverse range of submissions this year, with papers exploring emerging topics such as *Using machine learning and agent-based simulation to predict learner progression for high school education system*, alongside traditional focus areas like *Optimisation of Quality in the Automotive Sector*. The conference continues to attract participants from various sectors, showcasing the breadth and depth of industrial engineering in South Africa and beyond.

The submission and review process

For this conference, prospective speakers could submit full papers or abstracts only. Abstracts for the full-paper track were screened based on suitability, and successful authors were invited to submit a full-length paper. These submissions were screened using Turnitin plagiarism software to uphold academic integrity. Submissions that passed this screening process were then reviewed using a double-blind, peer-review process. The review process was managed through an online conference system that allows reviewers to provide online feedback and records all reviewer feedback and editorial decisions taken during the process. Papers were allocated at least two reviewers, often teaming up academics and industry experts to facilitate a true peer-review process. Only papers that passed the peer-review process are published in the conference proceedings. The conference proceedings include submissions from 10 academic institutions in South Africa and authors with affiliations in industry and international academic institutions. No institution contributes more than 30% towards the papers published in the proceedings.

A total of 135 submissions were received, with 114 peer-reviewed papers making it through the process. As with previous years, the top twenty best-reviewed papers were selected for the South African Journal of Industrial Engineering (SAJIE) special edition, consequently, these papers were withdrawn from the proceedings.

This conference has three key outputs:

- The Conference Event: featuring live presentations, panel discussions, and interactive poster sessions, fostering engagement and collaboration among delegates.
- The Conference Proceedings (this document): providing full access to peer-reviewed papers, available electronically and archived for future reference.
- The Special Edition of SAJIE: highlighting the best submissions, which will be published later this year.

This year's editorial process was supported by an exceptional team, with Menzi Mncwango, Mia Mangaroo-Pillay, Anthea Venter, Chantelle Du Plessis, Joke Bührmann, Teresa Hattingh and Dr Zee, playing pivotal roles in ensuring a smooth review process.

A heartfelt thank you to all our authors, reviewers, and organising committee members for their tireless dedication and contributions. Your efforts continue to push the boundaries of industrial engineering, illuminating the path forward for our profession.

We trust that this year's conference will inspire and challenge you, sparking new ideas and collaborations that will shape the future of industrial engineering.

Prof Teresa Hattingh & Dr Philani Zincume
Editors
October 2024

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About the University of South Africa

Unisa is the largest open distance learning institution in Africa and the longest-standing dedicated distance education university in the world. UNISA enrolls nearly one-third of all South African students. Given our rootedness in South Africa and the African continent, Unisa today can truly claim to be the African university in the service of humanity. UNISA offers an unparalleled range of study choices, ranging from short courses and certificate programmes, to three-and four-year diplomas, advanced diplomas and degrees. It further offers post graduate diplomas, masters and doctoral degrees, with close to 400 000 current students. The Department of Industrial Engineering located within the School of Engineering in the College of Science, Engineering and Technology (CSET) offers a range of undergraduate industrial engineering programmes which are accredited by the Engineering Council of South Africa. The Department of Industrial Engineering also offers post graduate qualifications. The globally respected and widely referenced Times Higher Education (THE) World University Rankings 2023 (www.timeshighereducation.com), which rates over 1700 universities across 104 countries and regions has placed UNISA's Engineering disciplines across the board in joint first place in South Africa. UNISA joins North-West University and Stellenbosch University in the top spot.

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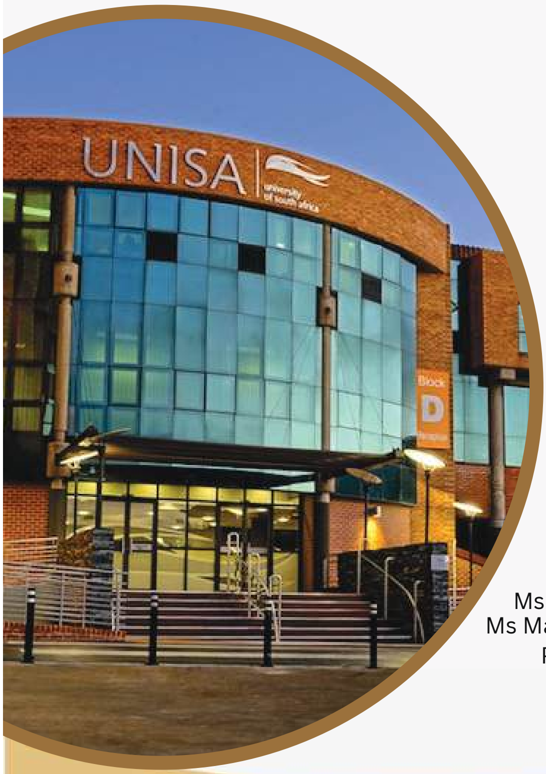
- Bachelor of Engineering Technology Honours (NQF 8)
- Master of Engineering (MEng) (NQF 9) by research
- Doctor of Philosophy in Engineering (NQF10)

About the Industrial Engineering Profession

The domain of industrial engineering is concerned with the design, installation, and continuous improvement of integrated systems of people, materials, information, equipment, and energy. The discipline draws knowledge and skills in mathematical, physical, and social sciences together with principles and methods of engineering and analysis and design to specify, predict, and assess the outcomes to be attained from such systems.



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The research interests in the Department of Industrial Engineering include amongst others:

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- Quality Engineering
- Digital Transformation
- Productivity and Optimization
- Safety Engineering
- Supply Chain Engineering
- Advanced Manufacturing
- Technology Adoption

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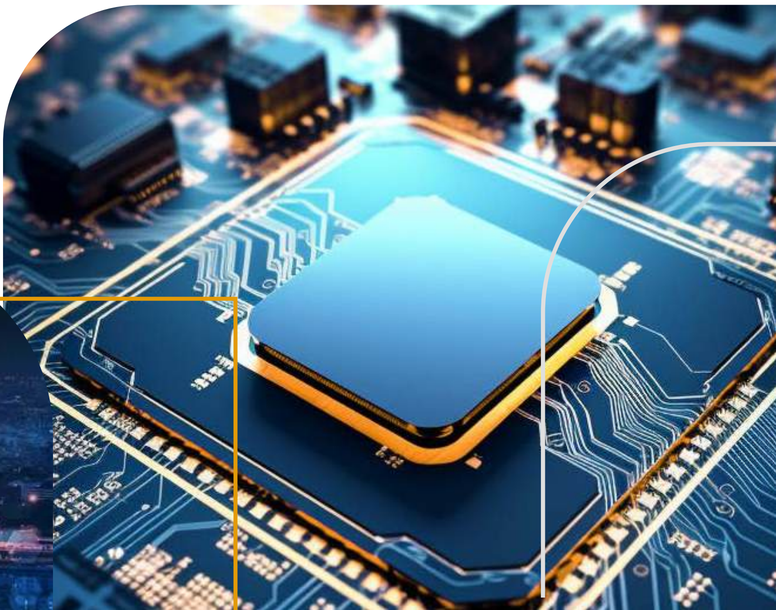

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S. Pretorius and M.P.M. Mohlapiso

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T. Tsoku, L. Van Dyk and W. Maisiri

PREDICTION OF WATER HYACINTH COVERAGE ON THE HARTBEESPOORT DAM
C.D. Camacho de Gouveia and J.H. Bührmann

HOLISTIC HUMAN CAPITAL DEVELOPMENT: DRIVER TO SUSTAINABLE SUPPLY CHAIN MANAGEMENT IN AFRICA IN THE 4IR ERA
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USING MACHINE LEARNING AND AGENT-BASED SIMULATION TO PREDICT LEARNER PROGRESS FOR THE SOUTH AFRICAN HIGH SCHOOL EDUCATION SYSTEM
M. Van den Heever, E. Becker, L. Venter and J.F. Bekker

THE IMPLICATION OF INTEGRATING ARTIFICIAL INTELLIGENCE INTO DATA-DRIVEN DECISION-MAKING
J. Sutherns and G.B. Fanta

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Content

Ref[1]	Paper Title & Authors	Page
7	**LEAN 4.0 IN SOUTH AFRICA: ILLUMINATING THE PATH AHEAD** M. Mangaroo-Pillay	44
8	**COMPARISON OF ARCHIMEDES AND MICROSCOPIC IMAGING METHODS FOR THE MEASUREMENT OF RELATIVE DENSITY OF 304SS ADDITIVELY MANUFACTURED PARTS** T. Mashayamombe and S. Matope	66
9	**A SIMULATION-BASED APPROACH TO ILLUMINATE INVENTORY CONTROL DECISIONS: POLICY IDENTIFICATION AND OPTIMISATION FOR STAKEHOLDER INFORMED STRATEGIES** R. Wagener, C. Bisset and C. Du Plessis	82
10	**OPTIMISING UNDERGROUND MINE TRAIN SCHEDULING: A MIXED-INTEGER LINEAR PROGRAMMING APPROACH** H.J. Snyman, C. Bisset and R. Luies	99
14	**ASSESSING MAINTENANCE 4.0 MATURITY: A CASE STUDY OF A SOUTH AFRICAN MINING COMPANY** K. Mabe, S. Grobbelaar and R.H. Peach	115
15	**DEVELOPING AN ENTERPRISE RISK MANAGEMENT (ERM) MODEL TO INCLUDE PROJECT RISK MANAGEMENT, CASE STUDY: CONSULTING ENGINEERING, WINDHOEK NAMIBIA** T.J. Duvenhage and S. Grobbelaar	130
16	**THE SUITABILITY OF INCREMENTAL INNOVATION FOR COMPETITIVE DIFFERENTIATION: A REVIEW OF THE SMARTPHONE INDUSTRY** S. Toro, M. Zitha, P. Mokgoro, S. Semuli and S. Grobbelaar	147
22	**THE SOCIO-ECONOMIC EFFECTS OF AIRBNB AS A DISRUPTIVE INNOVATION ON BUSINESS AND SOCIETY** K.K. Bareki, I. Cuyler, T. Mahlalela, M. Nkosi, T. Nkuna and S. Grobbelaar	165
23	**ENHANCING DECISION-MAKING IN SOUTH AFRICAN SMMES THROUGH BUSINESS INTELLIGENCE** D. Dau and H. Steenkamp	181
24	**TOPIC MODELLING OF ACADEMIC PUBLICATIONS IN TIMBER CONSTRUCTION AND ENGINEERED WOOD** N. Mnguni, S. Grobbelaar and R. Oosthuizen	194
25	**THE APPLICATION OF OPTIMISATION TECHNIQUES IN CRICKET: A SYSTEMATIC LITERATURE REVIEW** M.F. Alberts, C. Bisset and R. Coetzer	209
26	**DEVELOPING MACHINE LEARNING-BASED MODELS FOR OPTIMAL MAINTENANCE SCHEDULING WITHIN THE FOOD INDUSTRY** R. Oosthuizen, C. Bisset and C. Du Plessis	231

---

[1] *The Reference Number is a unique paper reference that is used throughout the conference to identify the paper. This is also used as a page number prefix in the proceedings, and papers are sorted according to this number in the proceedings.*

Ref[1]	Paper Title & Authors	Page
27	UTILISING DATABASE MANAGEMENT SYSTEMS AND STATISTICAL PROCESS CONTROL TO ELEVATE QUALITY ASSURANCE FOR AGRICULTURAL PERISHABLES J. Van Der Merwe, C. Du Plessis and C. Bisset	248
30	AN INDUSTRIAL ENGINEERING LIGHTHOUSE MODEL FOR TRANSDISCIPLINARY PROBLEM SOLVING AND SUSTAINABLE DEVELOPMENT IN SOUTH AFRICA M. Roopa	272
32	INCORPORATING BUSINESS INTELLIGENCE MANAGEMENT INTO THE ENGINEERING STEEL INDUSTRY TO ENHANCE ITS ECONOMIC RESILIENCE C. Du Toit and S. Grobbelaar	287
33	EVALUATION OF THE SOUTH AFRICAN SAWMILL INDUSTRY’S NATIONAL COMPETITIVE ADVANTAGE USING PORTER’S DIAMOND MODEL V. Tshavhungwe and S. Grobbelaar	306
34	THE DEVELOPMENT OF A DDDM IMPLEMENTATION FRAMEWORK FOR THE SOUTH AFRICAN MINING INDUSTRY R.A.D.P. Bisschoff and S. Grobbelaar	325
35	INDUSTRIAL POLICY IS A KEY DRIVER OF LOCAL CONTENT IN SOUTH AFRICA'S AUTOMOTIVE INDUSTRY T. Mokgokong	342
36	RISK MANAGEMENT FRAMEWORKS OF GOVERNMENT HEALTHCARE INFRASTRUCTURE PROJECTS IN AFRICA P. Agede, S. Grobbelaar and G. Fanta	360
37	USING SYSTEM DYNAMICS MODELLING TO DETERMINE THE IMPACT OF CHARGING ELECTRIC VEHICLES ON THE LOAD PROFILE IN THE RESIDENTIAL SECTOR N.S. Pillay and A. Botha	380
38	CRAFTING OF A DECARBONISATION STRATEGY FOR THE SOUTH AFRICAN FOUNDRY INDUSTRY: A ROADMAP TOWARDS SUSTAINABLE METAL CASTING J.K. Kabasele and K.D. Nyembwe	394
43	DEVELOPMENT OF FUNCTIONAL PARTS IN RAPID SAND CASTING FOR HIGH-TECH APPLICATION - A REVIEW S.D. Oguntuyi, K.D. Nyembwe, M.B. Shongwe and T. Mojisola	409
44	QUALITY 4.0 MATURITY ASSESSMENT FOR SOUTH AFRICAN MANUFACTURING SECTORS N.G. Mhlongo and K.D. Nyembwe	422
46	DEVELOPMENT OF A DATA ANALYTICS TOOL FOR INTERNAL AUDITING PRACTICES: THE CASE STUDY OF A HARNESS-MAKING COMPANY IN SOUTH AFRICA T.H. Mabuza and B.F. Chiromo	443
47	SOUTH AFRICA'S MINING INDUSTRY EXPERT'S OPINION ON TECHNOLOGY IMPLEMENTATION STEPS B.S. Baloyi, J.H. Bührmann and O.C. Koekemoer	459

Ref[1]	Paper Title & Authors	Page
51	**DEVELOPING A DYNAMIC NEXT PURCHASE DATE PREDICTOR FOR INDIVIDUAL CUSTOMERS IN THE FAST-MOVING CONSUMER GOODS RETAIL SECTOR** K.S. Rice, J.F. Bekker and L.E. Burger	481
53	**THE ROLE OF DIGITAL TECHNOLOGIES IN PROCUREMENT** S.T. Mashabane and E. Van der Lingen	498
55	**ILLUMINATING FRAMEWORKS FOR MANAGING TECHNOLOGICAL INNOVATION: RECOGNISING CONSTRAINTS AND LIMITATIONS** E. Van der Lingen and M. Van Rooyen	514
56	**ASSESSING INFRASTRUCTURE CONDITION IN SOUTH AFRICA THROUGH TOPIC MODELLING OF ONLINE NEWS ARTICLES** A.A. Roux, L.E. Burger and C.J. MacRobert	533
57	**LIGHTING THE WAY TO PROFITABLE RECHARGING: A TECHNO-ECONOMIC ANALYSIS OF WORKPLACE SOLAR-POWERED ELECTRIC VEHICLE CHARGERS IN POTCHEFSTROOM, SOUTH AFRICA** A. Scholtz, O.C. Koekemoer and M. Roopa	549
58	**OPTIMISING STARTUP MANUFACTURER’S SUPPLY CHAIN: ANALYSIS AND INVENTORY SYSTEM DESIGN** P.J. Roux, O.C. Koekemoer and T.J. Kok	566
61	**THE ANALYSIS OF THE LOGISTICS SUPPORT SYSTEM IN ROAD TRANSPORT** N. Nemakonde, H. Steenkamp and N. Maibela	584
62	**APPLYING THE PDCA CYCLE TO SCOPE 3 GHG EMISSIONS REPORTING IN THE SOUTH AFRICAN MINING INDUSTRY** T. Mashila, C.S.L. Schutte, J.H. Van Laar and A.G.S. Gous	601
69	**APPLICATION OF FAILURE MODE AND EFFECTS ANALYSIS IN A ONE-PIECE FLOW MANUFACTURING SET UP: A SYSTEMATIC LITERATURE REVIEW** D.C. Ryumeko, P. Dube and B.F. Chiromo	620
74	**THE IMPACT OF RELIABILITY-CENTRED MAINTENANCE ON TOTAL COST OF OWNERSHIP OF MEDIUM VOLTAGE EXPLOSION-PROTECTED INDUCTION MOTORS** F. Smal and K. Visser	638
75	**AGILE SERVICE SYSTEMS ENGINEERING: A SYSTEMATIC APPROACH TO DESIGNING CUSTOMISED DIGITAL SOLUTIONS IN THE FINANCIAL SERVICES INDUSTRY** E. Mills and R. Oosthuizen	653
78	**TOWARDS A COMPREHENSIVE META MODEL FOR ENTERPRISE SYSTEM DYNAMICS** H. Hussain and M. De Vries	668
80	**IDENTIFYING IMPROVEMENT STRATEGIES FOR THE DIESEL REBATE PROCESS IN SOUTH AFRICAN MINES** N.M. Mudanalwo, A.G.S. Gous, C.S.L. Schutte and J.H. Van Laar	686

Ref[1]	Paper Title & Authors	Page
81	**ARTIFICIAL INTELLIGENCE INTEGRATION IN SYSTEMS ENGINEERING: NAVIGATING OPPORTUNITIES AND RISKS ACROSS THE SYSTEM LIFECYCLE** A. John, R. Oosthuizen and G. Fanta	706
83	**IMPACT OF FOUNDRY PROCESS VARIABLES ON THE FINANCIAL FEASIBILITY OF THE BINDER JETTING PROCESS** A. Msani and K.D. Nyembwe	723
84	**DEVELOPING A LEAPFROGGING MODEL FOR THE AFRICAN SIGNALLING SYSTEMS TO LEAPFROG TO THE LEVEL OF DEVELOPED COUNTRIES** S. Gumede and T.P. Letaba	741
89	**EVALUATING AND ENHANCING VEHICLE FLEET MAINTENANCE: LEVERAGING PREDICTIVE ANALYTICS AND SMOTE FOR OPERATIONAL EFFICIENCY AND COST SAVINGS** D. Rabinovitch and G.J. Oyewole	753
90	**AN EVALUATION OF THE RISK-BASED APPROACH IMPLEMENTATION IN ISO/IEC 17025:2017 CONFORMITY ASSESSMENTS - A CASE STUDY** L.C. Motsoeneng and S. Naidoo	770
94	**THE IMPACT OF THE BALANCED SCORECARD ON PRODUCT AND SERVICE INNOVATION IN SMALL MEDIUM ENTERPRISES** S.P. Sibisi and S. Naidoo	790
95	**A STRATEGY FOR CRITICAL ELECTRICAL SERVICE RESTORATION IN UNDERGROUND MINES USING GRAPH THEORY** W.H. Sterrenberg, B. Pascoe, J.F. Van Rensburg and J.H. Van Laar	809
97	**SYSTEM DYNAMICS MAINTENANCE MODELS - SYSTEMATIC LITERATURE REVIEW** S.D. Koloane, M.G. Kanakana-Katumba, R.W. Maladzhi and K. Mokgohloa	830
106	**THE IMPLEMENTATION OF CIRCULAR ECONOMY PRINCIPLES TO THE RAPID SAND-CASTING PROCESS** A.T. Motlhabane, K.D. Nyembwe and T. Mashifana	848
108	**OPTIMISING STORE OPERATIONS: ILLUMINATING INVENTORY MANAGEMENT FOR GLOBAL LEADERSHIP IN A MANUFACTURING ENVIRONMENT** M. Lewis and P.N. Zincume	864
113	**A CASE STUDY ON THE INTEGRATION OF PROJECT MANAGEMENT AND SYSTEM ENGINEERING IN A HIGH TECHNOLOGY COMPANY** N. Scribante	879
115	**A QUALITATIVE ASSESSMENT OF THE RAPID SAND CASTING PROCESS USING THE RESSOURCE EFFICIENCY CLEANER PRODUCTION FRAMEWORK** J.L. Chauke and K.D. Nyembwe	894
121	**INVESTIGATING THE DEFORMATION OF THE RIGHT-HAND SIDE BOX OUTER OF AN AUTOMOTIVE MANUFACTURER USING LEAN SIX SIGMA DMAIC METHODOLOGY** K.R. Ramdass, H. Phuluwa and T. Mokoti	903

Ref[1]	Paper Title & Authors	Page
122	**IMPLEMENTING RISK BASED INSPECTION AND MAINTENANCE IN THE POWER INDUSTRY** K.R. Ramdass, H. Phuluwa, N. Ndou and T. Newuwari	916
123	**DEVELOPMENT OF BERTH PERFORMANCE MEASUREMENT SYSTEM: AN OVERALL EQUIPMENT EFFECTIVENESS PERSPECTIVE** H. Phuluwa, K.R. Ramdass and T. Khatwane	928
124	**UTILISING VALUE STREAM MAPPING IN IDENTIFYING WASTE AND IMPROVEMENT STRATEGIES IN COMPONENT MANUFACTURING** K.R. Ramdass and K. Mokgohloa	939
127	**BENCHMARKING TOOL FOR SOUTH AFRICAN GOLD MINES' COMMINUTION CIRCUITS** N. Fernandes, C.S.L. Schutte, A.G.S. Gous and J.H. Van Laar	957
129	**COMPACT 3D PRINTED TURNTABLE DESIGN FOR INDUSTRIAL 3D SCANNING APPLICATIONS** G.J. Nel and R. Siriram	966
132	**INDUSTRY 5.0 CONCEPTS & COMPONENTS: A SCOPING LITERATURE REVIEW** W.E. Müller and L. Van Dyk	977
139	**A SYSTEMATIC LITERATURE REVIEW ON ASSET MAINTENANCE PRIORITISATION APPROACHES RELEVANT TO WATER INFRASTRUCTURE** P.G. Sibanda, W. Maisiri and L. Van Dyk	992
141	**AN INVESTIGATION INTO THE STATE OF ART OF QUANTITATIVE PERSPECTIVES ON SUSTAINABILITY INITIATIVES: A SYSTEMATIC REVIEW OF LITERATURE** J. Masefield, I.H. De Kock and J.L. Jooste	1009
124	**THE ROLE OF UNIVERSITIES IN PREPARING INDUSTRY TO MENTOR WORK-INTEGRATED LEARNING STUDENTS** S.L. Gqibani, A. Maile, S.G. Xaba, Z.A. Mkoko and M. Dlambulo	1025
145	**INVESTIGATING THE STATE-OF-THE-ART IMPACT ANALYSIS APPROACHES WITHIN THE CONTEXT OF BUILDING AUTOMATION AND CONTROL SYSTEMS FROM A FEASIBILITY PERSPECTIVE: A STRUCTURED LITERATURE REVIEW** S.P. Nash, W.L. Jooste and I.H. De Kock	1039
150	**STRATEGIC INTEGRATION OF PLANT MAINTENANCE SYSTEMS: A SYSTEMS THINKING APPROACH FOR ENHANCED PERFORMANCE AND SUSTAINABILITY** F.E. Mundoza, R. Oosthuizen and R.H. Peach	1060
151	**IMPROVING THE QUALITY OF CONSTRUCTION PROJECTS IN SOUTH AFRICA USING BUILDING INFORMATION MODELLING** Y.S. Maphosa, P.N. Zincume and J.L. Jooste	1076
152	**SUSTAINABILITY OF LEAN IN SOUTH AFRICAN PUBLIC HOSPITALS** R.S. Wagner, T. Hattingh and H. Meijer	1092
154	**RISK ASSESSMENT AND MITIGATION STRATEGIES FOR FALL OF GROUND INCIDENTS AT SIBANYE-STILLWATER GOLD MINE** M. Matloga and A.F. Mulaba-Bafubiandi	1108

Ref[1] **Paper Title & Authors** **Page**

155 **ANALYSIS AND RECOMMENDATIONS ON BUSINESS IMPROVEMENT TECHNIQUES AS APPLIED IN SOUTH AFRICAN COLLIERIES** 1122
D. Monoge, A.F. Mulaba-Bafubiandi and N. Madonsela

156 **OPTIMIZING QUALITY IN THE AUTOMOTIVE SECTOR: IDENTIFYING IMPROVEMENT STRATEGIES FOR REDUCING DENTS** 1130
T.D. Naledzani, B.N. Mushwana and K. Letlhake

158 **PARAMETRIC STUDY OF THE QUEUING MODEL IN TELEMEDICINE** 1138
D. Tshiamala and L.K. Tartibu

159 **A REVIEW OF POTENTIAL CHALLENGES AND OPPORTUNITIES OF BUSINESS PROCESS REENGINEERING IN THE ERA OF INDUSTRY 4.0** 1157
B. Masokoameng, V. Mofokeng and K.S. Nyakala

160 **A SYSTEMATIC LITERATURE REVIEW FOR EXPLORING THE SUSTAINABILITY IMPACT OF ANIMAL-SOURCE FOOD SUPPLY CHAINS** 1170
M. Badenhorst, I.H. De Kock, P.N. Zincume

161 **SHINING LIGHT ON 20 KEYS IMPLEMENTATION AT A SOUTH AFRICAN AGRICULTURAL COMPANY USING FOCUS GROUPS** 1188
D. Kotzé, M. Roopa and R. Coetzee

163 **IMPACT OF TOTAL PRODUCTIVE MAINTENANCE ON CONVEYOR BELT RELIABILITY** 1202
R.P. Mutyavavire and M.E. Maditsi

164 **ENHANCING EMERGENCY MEDICAL SERVICE EFFICIENCY: OPTIMISING AMBULANCE RESPONSE TIME IN GAUTENG PROVINCE** 1215
M.K. Dube and R.P. Mutyavavire

166 **STATISTICAL ANALYSIS OF PROPERTIES OF SOUTH AFRICAN FOUNDRY CHROMITE SAND USED FOR ADDITIVE MANUFACTURING APPLICATIONS** 1227
N.V. Tshabalala and K.D. Nyembwe

176 **BUILDING A SUSTAINABLE HIGHER EDUCATION MODEL FOR SOUTH AFRICA** 1242
T.K. Ramasu and M.G. Kanakana-Katumba

179 **FRAMEWORK FOR DEVELOPING PEDAGOGY SKILLS FOR TEACHING AND LEARNING IN THE FOURTH INDUSTRIAL REVOLUTION (4IR): A SOUTH AFRICAN PERSPECTIVE** 1254
T.M. Tshabalala

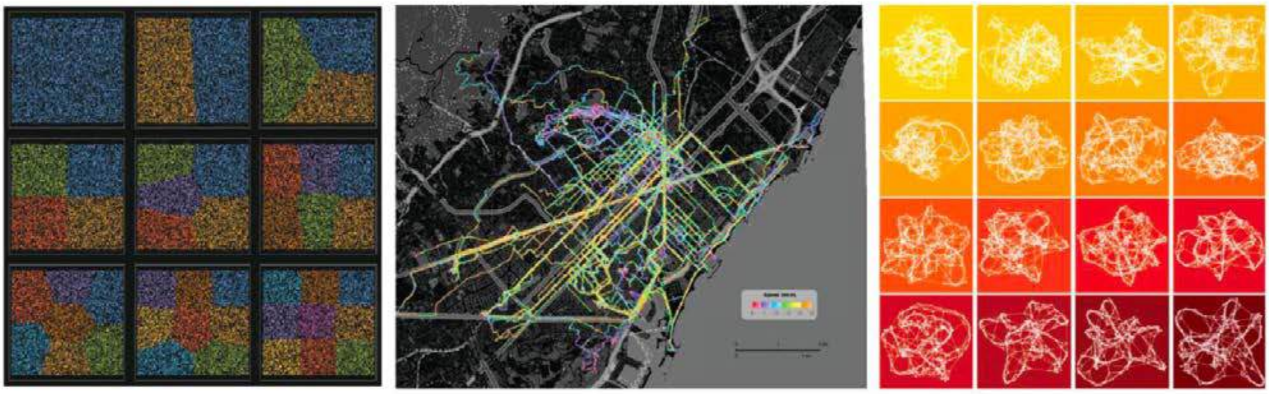
181 **AN OVERVIEW OF FUZZY LOGIC TRAFFIC SIGNAL CONTROLLER** 1267
Z. Mpanza and R.P. Mutyavavire

184 **THE ROLE OF INDUSTRY 4.0 TECHNOLOGIES IN SUCCESSFUL ENTERPRISE RESOURCE PLANNING (ERP) IMPLEMENTATION OF PROJECTS IN SELECTED SOUTH AFRICAN ORGANISATIONS** 1280
K. Mphahlele and B. Emwanu

186 **AN EXAMINATION OF BARRIERS AND SUPPORT SYSTEMS FOR SMALL AND MEDIUM ENTERPRISES IN SOUTH AFRICA'S COAL MINING SECTOR** 1296
H. Ncube and Z. Mpanza

197 **DYNAMIC CONTROL OF DEEP-LEVEL MINE COOLING SYSTEMS USING ARTIFICIAL INTELLIGENCE** 1306
M.C. Furumele, J.H. Marais and J.H. Van Laar

Ref[1]	Paper Title & Authors	Page
198	**COST-TO-SERVE AND PROFITABILITY ANALYSIS OF PRODUCTS AND CUSTOMERS IN A SUPPLY CHAIN** W.L. Bean and D. Petrarolo	1324
199	**A FRAMEWORK FOR INDUSTRIAL CLUSTER-DRIVEN ADOPTION OF INDUSTRY 4.0 TECHNOLOGIES** N. Jahangard, L.K. Tartibu and M. Okwu	1338
201	**ENERGY INNOVATION OPPORTUNITIES IN HIGH ENERGY CONSUMING SECTORS IN SOUTH AFRICA** T.S. Kamba and L. Pretorius	1353
206	**MAINTENANCE PLANNING EFFECT ON PLANT'S HEALTH** S.D. Koloane, M.G. Kanakana-Katumba, R.W. Maladzhi and K. Mokgohloa	1363
207	**ELECTROSTATIC PRECIPITATORS DUST REMOVAL SYSTEM - SYSTEMATIC LITERATURE REVIEW** S.D. Koloane, M.G. Kanakana-Katumba, R.W. Maladzhi and K. Mokgohloa	1386
210	**DEVELOPING A PRIMARILY QUANTITATIVE INFRASTRUCTURE RISK CATEGORISATION METHOD** D.P. Goncalves	1407
212	**DIGITAL TWIN ABILITIES IN CELLULAR MANUFACTURING: ILLUMINATING PATHWAYS TO SUCCESS** M. Sikibi, T. Kunene and L.K. Tartibu	1421
218	**CONCEPTUAL FRAMEWORK TO ENHANCE GROWTH AND COMPETITIVENESS OF LOWER-TIER AUTOMOTIVE SMMES: A REVIEW** A.C. Pillay and B.F. Chiromo	1433
222	**THE IMPACT OF AUTOMATION ON EMPLOYMENT IN SMALL AND MEDIUM ENTERPRISES (SMES): A SYSTEMATIC LITERATURE REVIEW** S. Ubisi, V. Mofokeng and K.S. Nyakala	1444
226	**ECONOMIC SUSTAINABILITY ASSESSMENT OF ENERGY SOURCES FOR DECENTRALIZED GENERATION** M.J.B. Kabeyi, K.C. Nwala and O.A. Olanrewaju	1457

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Alphabetic Author List

Authors	Paper Title	Ref[1]
Agede, P.	RISK MANAGEMENT FRAMEWORKS OF GOVERNMENT HEALTHCARE INFRASTRUCTURE PROJECTS IN AFRICA	36
Alberts, M.F.	THE APPLICATION OF OPTIMISATION TECHNIQUES IN CRICKET: A SYSTEMATIC LITERATURE REVIEW	25
Badenhorst, M.	A SYSTEMATIC LITERATURE REVIEW FOR EXPLORING THE SUSTAINABILITY IMPACT OF ANIMAL-SOURCE FOOD SUPPLY CHAINS	160
Baloyi, B.S.	SOUTH AFRICA'S MINING INDUSTRY EXPERT'S OPINION ON TECHNOLOGY IMPLEMENTATION STEPS	47
Bareki, K.K.	THE SOCIO-ECONOMIC EFFECTS OF AIRBNB AS A DISRUPTIVE INNOVATION ON BUSINESS AND SOCIETY	22
Bean, W.L.	COST-TO-SERVE AND PROFITABILITY ANALYSIS OF PRODUCTS AND CUSTOMERS IN A SUPPLY CHAIN	198
Bekker, J.F.	DEVELOPING A DYNAMIC NEXT PURCHASE DATE PREDICTOR FOR INDIVIDUAL CUSTOMERS IN THE FAST-MOVING CONSUMER GOODS RETAIL SECTOR	51
Bisschoff, R.A.D.P.	THE DEVELOPMENT OF A DDDM IMPLEMENTATION FRAMEWORK FOR THE SOUTH AFRICAN MINING INDUSTRY	34
Bisset, C.	A SIMULATION-BASED APPROACH TO ILLUMINATE INVENTORY CONTROL DECISIONS: POLICY IDENTIFICATION AND OPTIMISATION FOR STAKEHOLDER INFORMED STRATEGIES	9
Bisset, C.	OPTIMISING UNDERGROUND MINE TRAIN SCHEDULING: A MIXED-INTEGER LINEAR PROGRAMMING APPROACH	10
Bisset, C.	THE APPLICATION OF OPTIMISATION TECHNIQUES IN CRICKET: A SYSTEMATIC LITERATURE REVIEW	25
Bisset, C.	DEVELOPING MACHINE LEARNING-BASED MODELS FOR OPTIMAL MAINTENANCE SCHEDULING WITHIN THE FOOD INDUSTRY	26
Bisset, C.	UTILISING DATABASE MANAGEMENT SYSTEMS AND STATISTICAL PROCESS CONTROL TO ELEVATE QUALITY ASSURANCE FOR AGRICULTURAL PERISHABLES	27
Botha, A.	USING SYSTEM DYNAMICS MODELLING TO DETERMINE THE IMPACT OF CHARGING ELECTRIC VEHICLES ON THE LOAD PROFILE IN THE RESIDENTIAL SECTOR	37
Bührmann, J.H.	SOUTH AFRICA'S MINING INDUSTRY EXPERT'S OPINION ON TECHNOLOGY IMPLEMENTATION STEPS	47
Burger, L.E.	DEVELOPING A DYNAMIC NEXT PURCHASE DATE PREDICTOR FOR INDIVIDUAL CUSTOMERS IN THE FAST-MOVING CONSUMER GOODS RETAIL SECTOR	51
Burger, L.E.	ASSESSING INFRASTRUCTURE CONDITION IN SOUTH AFRICA THROUGH TOPIC MODELLING OF ONLINE NEWS ARTICLES	56
Chauke, J.L.	A QUALITATIVE ASSESSMENT OF THE RAPID SAND CASTING PROCESS USING THE RESSOURCE EFFICIENCY CLEANER PRODUCTION FRAMEWORK.	115
Chiromo, B.F.	CONCEPTUAL FRAMEWORK TO ENHANCE GROWTH AND COMPETITIVENESS OF LOWER-TIER AUTOMOTIVE SMMES: A REVIEW	218

---

[1] *The Reference Number is a unique paper reference that is used throughout the conference to identify the paper. This is also used as a page number prefix in the proceedings, and papers are sorted according to this number in the proceedings.*

Authors	Paper Title	Ref[1]
Chiromo, B.F.	DEVELOPMENT OF A DATA ANALYTICS TOOL FOR INTERNAL AUDITING PRACTICES: THE CASE STUDY OF A HARNESS-MAKING COMPANY IN SOUTH AFRICA	46
Chiromo, B.F.	APPLICATION OF FAILURE MODE AND EFFECTS ANALYSIS IN A ONE-PIECE FLOW MANUFACTURING SET UP: A SYSTEMATIC LITERATURE REVIEW	69
Coetzee, R.	SHINING LIGHT ON 20 KEYS IMPLEMENTATION AT A SOUTH AFRICAN AGRICULTURAL COMPANY USING FOCUS GROUPS	161
Coetzer, R.	THE APPLICATION OF OPTIMISATION TECHNIQUES IN CRICKET: A SYSTEMATIC LITERATURE REVIEW	25
Cuyler, I.	THE SOCIO-ECONOMIC EFFECTS OF AIRBNB AS A DISRUPTIVE INNOVATION ON BUSINESS AND SOCIETY	22
Dau, D.	ENHANCING DECISION-MAKING IN SOUTH AFRICAN SMMES THROUGH BUSINESS INTELLIGENCE	23
De Kock, I.H.	AN INVESTIGATION INTO THE STATE OF ART OF QUANTITATIVE PERSPECTIVES ON SUSTAINABILITY INITIATIVES: A SYSTEMATIC REVIEW OF LITERATURE	141
De Kock, I.H.	INVESTIGATING THE STATE-OF-THE-ART IMPACT ANALYSIS APPROACHES WITHIN THE CONTEXT OF BUILDING AUTOMATION AND CONTROL SYSTEMS FROM A FEASIBILITY PERSPECTIVE: A STRUCTURED LITERATURE REVIEW	145
De Kock, I.H.	A SYSTEMATIC LITERATURE REVIEW FOR EXPLORING THE SUSTAINABILITY IMPACT OF ANIMAL-SOURCE FOOD SUPPLY CHAINS	160
De Vries, M.	TOWARDS A COMPREHENSIVE META MODEL FOR ENTERPRISE SYSTEM DYNAMICS	78
Dlambulo, M.	THE ROLE OF UNIVERSITIES IN PREPARING INDUSTRY TO MENTOR WORK-INTEGRATED LEARNING STUDENTS	142
Du Plessis, C.	A SIMULATION-BASED APPROACH TO ILLUMINATE INVENTORY CONTROL DECISIONS: POLICY IDENTIFICATION AND OPTIMISATION FOR STAKEHOLDER INFORMED STRATEGIES	9
Du Plessis, C.	DEVELOPING MACHINE LEARNING-BASED MODELS FOR OPTIMAL MAINTENANCE SCHEDULING WITHIN THE FOOD INDUSTRY	26
Du Plessis, C.	UTILISING DATABASE MANAGEMENT SYSTEMS AND STATISTICAL PROCESS CONTROL TO ELEVATE QUALITY ASSURANCE FOR AGRICULTURAL PERISHABLES	27
Du Toit, C.	INCORPORATING BUSINESS INTELLIGENCE MANAGEMENT INTO THE ENGINEERING STEEL INDUSTRY TO ENHANCE ITS ECONOMIC RESILIENCE	32
Dube, M.K.	ENHANCING EMERGENCY MEDICAL SERVICE EFFICIENCY: OPTIMISING AMBULANCE RESPONSE TIME IN GAUTENG PROVINCE	164
Dube, P.	APPLICATION OF FAILURE MODE AND EFFECTS ANALYSIS IN A ONE-PIECE FLOW MANUFACTURING SET UP: A SYSTEMATIC LITERATURE REVIEW	69
Duvenhage, T.J.	DEVELOPING AN ENTERPRISE RISK MANAGEMENT (ERM) MODEL TO INCLUDE PROJECT RISK MANAGEMENT, CASE STUDY: CONSULTING ENGINEERING, WINDHOEK NAMIBIA	15
Emwanu, B.	THE ROLE OF INDUSTRY 4.0 TECHNOLOGIES IN SUCCESSFUL ENTERPRISE RESOURCE PLANNING (ERP) IMPLEMENTATION OF PROJECTS IN SELECTED SOUTH AFRICAN ORGANISATIONS	184
Fanta, G.	RISK MANAGEMENT FRAMEWORKS OF GOVERNMENT HEALTHCARE INFRASTRUCTURE PROJECTS IN AFRICA	36
Fanta, G.	ARTIFICIAL INTELLIGENCE INTEGRATION IN SYSTEMS ENGINEERING: NAVIGATING OPPORTUNITIES AND RISKS ACROSS THE SYSTEM LIFECYCLE	81

Authors	Paper Title	Ref[1]
Fernandes, N.	BENCHMARKING TOOL FOR SOUTH AFRICAN GOLD MINES’ COMMINUTION CIRCUITS	127
Furumele, M.C.	DYNAMIC CONTROL OF DEEP-LEVEL MINE COOLING SYSTEMS USING ARTIFICIAL INTELLIGENCE	197
Goncalves, D.P.	DEVELOPING A PRIMARILY QUANTITATIVE INFRASTRUCTURE RISK CATEGORISATION METHOD	210
Gous, A.G.S.	APPLYING THE PDCA CYCLE TO SCOPE 3 GHG EMISSIONS REPORTING IN THE SOUTH AFRICAN MINING INDUSTRY	62
Gous, A.G.S.	IDENTIFYING IMPROVEMENT STRATEGIES FOR THE DIESEL REBATE PROCESS IN SOUTH AFRICAN MINES	80
Gous, A.G.S.	BENCHMARKING TOOL FOR SOUTH AFRICAN GOLD MINES’ COMMINUTION CIRCUITS	127
Gqibani, S.L.	THE ROLE OF UNIVERSITIES IN PREPARING INDUSTRY TO MENTOR WORK-INTEGRATED LEARNING STUDENTS	142
Grobbelaar, S.	ASSESSING MAINTENANCE 4.0 MATURITY: A CASE STUDY OF A SOUTH AFRICAN MINING COMPANY	14
Grobbelaar, S.	DEVELOPING AN ENTERPRISE RISK MANAGEMENT (ERM) MODEL TO INCLUDE PROJECT RISK MANAGEMENT, CASE STUDY: CONSULTING ENGINEERING, WINDHOEK NAMIBIA	15
Grobbelaar, S.	THE SUITABILITY OF INCREMENTAL INNOVATION FOR COMPETITIVE DIFFERENTIATION: A REVIEW OF THE SMARTPHONE INDUSTRY	16
Grobbelaar, S.	THE SOCIO-ECONOMIC EFFECTS OF AIRBNB AS A DISRUPTIVE INNOVATION ON BUSINESS AND SOCIETY	22
Grobbelaar, S.	TOPIC MODELLING OF ACADEMIC PUBLICATIONS IN TIMBER CONSTRUCTION AND ENGINEERED WOOD	24
Grobbelaar, S.	INCORPORATING BUSINESS INTELLIGENCE MANAGEMENT INTO THE ENGINEERING STEEL INDUSTRY TO ENHANCE ITS ECONOMIC RESILIENCE	32
Grobbelaar, S.	EVALUATION OF THE SOUTH AFRICAN SAWMILL INDUSTRY’S NATIONAL COMPETITIVE ADVANTAGE USING PORTER’S DIAMOND MODEL	33
Grobbelaar, S.	THE DEVELOPMENT OF A DDDM IMPLEMENTATION FRAMEWORK FOR THE SOUTH AFRICAN MINING INDUSTRY	34
Grobbelaar, S.	RISK MANAGEMENT FRAMEWORKS OF GOVERNMENT HEALTHCARE INFRASTRUCTURE PROJECTS IN AFRICA	36
Gumede, S.	DEVELOPING A LEAPFROGGING MODEL FOR THE AFRICAN SIGNALLING SYSTEMS TO LEAPFROG TO THE LEVEL OF DEVELOPED COUNTRIES	84
Hattingh, T.	SUSTAINABILITY OF LEAN IN SOUTH AFRICAN PUBLIC HOSPITALS	152
Hussain, H.	TOWARDS A COMPREHENSIVE META MODEL FOR ENTERPRISE SYSTEM DYNAMICS	78
Jahangard, N.	A FRAMEWORK FOR INDUSTRIAL CLUSTER-DRIVEN ADOPTION OF INDUSTRY 4.0 TECHNOLOGIES	199
John, A.	ARTIFICIAL INTELLIGENCE INTEGRATION IN SYSTEMS ENGINEERING: NAVIGATING OPPORTUNITIES AND RISKS ACROSS THE SYSTEM LIFECYCLE	81
Jooste, J.L.	AN INVESTIGATION INTO THE STATE OF ART OF QUANTITATIVE PERSPECTIVES ON SUSTAINABILITY INITIATIVES: A SYSTEMATIC REVIEW OF LITERATURE	141
Jooste, J.L.	IMPROVING THE QUALITY OF CONSTRUCTION PROJECTS IN SOUTH AFRICA USING BUILDING INFORMATION MODELLING	151
Jooste, W.L.	INVESTIGATING THE STATE-OF-THE-ART IMPACT ANALYSIS APPROACHES WITHIN THE CONTEXT OF BUILDING AUTOMATION AND CONTROL SYSTEMS FROM A FEASIBILITY PERSPECTIVE: A STRUCTURED LITERATURE REVIEW	145

Authors	Paper Title	Ref[1]
Kabasele, J.K.	CRAFTING OF A DECARBONISATION STRATEGY FOR THE SOUTH AFRICAN FOUNDRY INDUSTRY: A ROADMAP TOWARDS SUSTAINABLE METAL CASTING	38
Kabeyi, M.J.B.	ECONOMIC SUSTAINABILITY ASSESSMENT OF ENERGY SOURCES FOR DECENTRALIZED GENERATION	226
Kamba, T.S.	ENERGY INNOVATION OPPORTUNITIES IN HIGH ENERGY CONSUMING SECTORS IN SOUTH AFRICA	201
Kanakana-Katumba, M.G.	SYSTEM DYNAMICS MAINTENANCE MODELS - SYSTEMATIC LITERATURE REVIEW	97
Kanakana-Katumba, M.G.	BUILDING A SUSTAINABLE HIGHER EDUCATION MODEL FOR SOUTH AFRICA	176
Kanakana-Katumba, M.G.	MAINTENANCE PLANNING EFFECT ON PLANT’S HEALTH	206
Kanakana-Katumba, M.G.	ELECTROSTATIC PRECIPITATORS DUST REMOVAL SYSTEM – SYSTEMATIC LITERATURE REVIEW	207
Khatwane, T.	DEVELOPMENT OF BERTH PERFORMANCE MEASUREMENT SYSTEM: AN OVERALL EQUIPMENT EFFECTIVENESS PERSPECTIVE	123
Koekemoer, O.C.	LIGHTING THE WAY TO PROFITABLE RECHARGING: A TECHNO-ECONOMIC ANALYSIS OF WORKPLACE SOLAR-POWERED ELECTRIC VEHICLE CHARGERS IN POTCHEFSTROOM, SOUTH AFRICA	57
Koekemoer, O.C.	SOUTH AFRICA'S MINING INDUSTRY EXPERT'S OPINION ON TECHNOLOGY IMPLEMENTATION STEPS	47
Koekemoer, O.C.	OPTIMISING STARTUP MANUFACTURER’S SUPPLY CHAIN: ANALYSIS AND INVENTORY SYSTEM DESIGN	58
Kok, T.J.	OPTIMISING STARTUP MANUFACTURER’S SUPPLY CHAIN: ANALYSIS AND INVENTORY SYSTEM DESIGN	58
Koloane, S.D.	SYSTEM DYNAMICS MAINTENANCE MODELS - SYSTEMATIC LITERATURE REVIEW	97
Koloane, S.D.	MAINTENANCE PLANNING EFFECT ON PLANT’S HEALTH	206
Koloane, S.D.	ELECTROSTATIC PRECIPITATORS DUST REMOVAL SYSTEM – SYSTEMATIC LITERATURE REVIEW	207
Kotzé, D.	SHINING LIGHT ON 20 KEYS IMPLEMENTATION AT A SOUTH AFRICAN AGRICULTURAL COMPANY USING FOCUS GROUPS	161
Kunene, T.	DIGITAL TWIN ABILITIES IN CELLULAR MANUFACTURING: ILLUMINATING PATHWAYS TO SUCCESS	212
Letaba, T.P.	DEVELOPING A LEAPFROGGING MODEL FOR THE AFRICAN SIGNALLING SYSTEMS TO LEAPFROG TO THE LEVEL OF DEVELOPED COUNTRIES	84
Letlhake, K.	OPTIMIZING QUALITY IN THE AUTOMOTIVE SECTOR: IDENTIFYING IMPROVEMENT STRATEGIES FOR REDUCING DENTS	156
Lewis, M.	OPTIMISING STORE OPERATIONS: ILLUMINATING INVENTORY MANAGEMENT FOR GLOBAL LEADERSHIP IN A MANUFACTURING ENVIRONMENT	108
Luies, R.	OPTIMISING UNDERGROUND MINE TRAIN SCHEDULING: A MIXED-INTEGER LINEAR PROGRAMMING APPROACH	10
Mabe, K.	ASSESSING MAINTENANCE 4.0 MATURITY: A CASE STUDY OF A SOUTH AFRICAN MINING COMPANY	14
Mabuza, T.H.	DEVELOPMENT OF A DATA ANALYTICS TOOL FOR INTERNAL AUDITING PRACTICES: THE CASE STUDY OF A HARNESS-MAKING COMPANY IN SOUTH AFRICA	46
MacRobert, C.J.	ASSESSING INFRASTRUCTURE CONDITION IN SOUTH AFRICA THROUGH TOPIC MODELLING OF ONLINE NEWS ARTICLES	56

Authors	Paper Title	Ref[1]
Maditsi, M.E.	IMPACT OF TOTAL PRODUCTIVE MAINTENANCE ON CONVEYOR BELT RELIABILITY	163
Madonsela, N.	ANALYSIS AND RECOMMENDATIONS ON BUSINESS IMPROVEMENT TECHNIQUES AS APPLIED IN SOUTH AFRICAN COLLIERIES	155
Mahlalela, T.	THE SOCIO-ECONOMIC EFFECTS OF AIRBNB AS A DISRUPTIVE INNOVATION ON BUSINESS AND SOCIETY	22
Maibela, N.	THE ANALYSIS OF THE LOGISTICS SUPPORT SYSTEM IN ROAD TRANSPORT	61
Maile, A.	THE ROLE OF UNIVERSITIES IN PREPARING INDUSTRY TO MENTOR WORK-INTEGRATED LEARNING STUDENTS	142
Maisiri, W.	A SYSTEMATIC LITERATURE REVIEW ON ASSET MAINTENANCE PRIORITISATION APPROACHES RELEVANT TO WATER INFRASTRUCTURE	139
Maladzhi, R.W.	SYSTEM DYNAMICS MAINTENANCE MODELS - SYSTEMATIC LITERATURE REVIEW	97
Maladzhi, R.W.	MAINTENANCE PLANNING EFFECT ON PLANT’S HEALTH	206
Maladzhi, R.W.	ELECTROSTATIC PRECIPITATORS DUST REMOVAL SYSTEM – SYSTEMATIC LITERATURE REVIEW	207
Mangaroo-Pillay, M.	LEAN 4.0 IN SOUTH AFRICA: ILLUMINATING THE PATH AHEAD	7
Maphosa, Y.S.	IMPROVING THE QUALITY OF CONSTRUCTION PROJECTS IN SOUTH AFRICA USING BUILDING INFORMATION MODELLING	151
Marais, J.H.	DYNAMIC CONTROL OF DEEP-LEVEL MINE COOLING SYSTEMS USING ARTIFICIAL INTELLIGENCE	197
Masefield, J.	AN INVESTIGATION INTO THE STATE OF ART OF QUANTITATIVE PERSPECTIVES ON SUSTAINABILITY INITIATIVES: A SYSTEMATIC REVIEW OF LITERATURE	141
Mashabane, S.T.	THE ROLE OF DIGITAL TECHNOLOGIES IN PROCUREMENT	53
Mashayamombe, T.	COMPARISON OF ARCHIMEDES AND MICROSCOPIC IMAGING METHODS FOR THE MEASUREMENT OF RELATIVE DENSITY OF 304SS ADDITIVELY MANUFACTURED PARTS	8
Mashifana, T.	THE IMPLEMENTATION OF CIRCULAR ECONOMY PRINCIPLES TO THE RAPID SAND-CASTING PROCESS	106
Mashila, T.	APPLYING THE PDCA CYCLE TO SCOPE 3 GHG EMISSIONS REPORTING IN THE SOUTH AFRICAN MINING INDUSTRY	62
Masokoameng, B.	A REVIEW OF POTENTIAL CHALLENGES AND OPPORTUNITIES OF BUSINESS PROCESS REENGINEERING IN THE ERA OF INDUSTRY 4.0	159
Matloga, M.	RISK ASSESSMENT AND MITIGATION STRATEGIES FOR FALL OF GROUND INCIDENTS AT SIBANYE-STILLWATER GOLD MINE	154
Matope, S.	COMPARISON OF ARCHIMEDES AND MICROSCOPIC IMAGING METHODS FOR THE MEASUREMENT OF RELATIVE DENSITY OF 304SS ADDITIVELY MANUFACTURED PARTS	8
Meijer, H.	SUSTAINABILITY OF LEAN IN SOUTH AFRICAN PUBLIC HOSPITALS	152
Mhlongo, N.G.	QUALITY 4.0 MATURITY ASSESSMENT FOR SOUTH AFRICAN MANUFACTURING SECTORS	44
Mills, E.	AGILE SERVICE SYSTEMS ENGINEERING: A SYSTEMATIC APPROACH TO DESIGNING CUSTOMISED DIGITAL SOLUTIONS IN THE FINANCIAL SERVICES INDUSTRY	75
Mkoko, Z.A.	THE ROLE OF UNIVERSITIES IN PREPARING INDUSTRY TO MENTOR WORK-INTEGRATED LEARNING STUDENTS	142
Mnguni, N.	TOPIC MODELLING OF ACADEMIC PUBLICATIONS IN TIMBER CONSTRUCTION AND ENGINEERED WOOD	24

Authors	Paper Title	Ref[1]
Mofokeng, V.	A REVIEW OF POTENTIAL CHALLENGES AND OPPORTUNITIES OF BUSINESS PROCESS REENGINEERING IN THE ERA OF INDUSTRY 4.1	159
Mofokeng, V.	THE IMPACT OF AUTOMATION ON EMPLOYMENT IN SMALL AND MEDIUM ENTERPRISES (SMES): A SYSTEMATIC LITERATURE REVIEW	222
Mojisola, T.	DEVELOPMENT OF FUNCTIONAL PARTS IN RAPID SAND CASTING FOR HIGH-TECH APPLICATION - A REVIEW	43
Mokgohloa, K.	SYSTEM DYNAMICS MAINTENANCE MODELS - SYSTEMATIC LITERATURE REVIEW	97
Mokgohloa, K.	UTILISING VALUE STREAM MAPPING IN IDENTIFYING WASTE AND IMPROVEMENT STRATEGIES IN COMPONENT MANUFACTURING	124
Mokgohloa, K.	MAINTENANCE PLANNING EFFECT ON PLANT’S HEALTH	206
Mokgohloa, K.	ELECTROSTATIC PRECIPITATORS DUST REMOVAL SYSTEM - SYSTEMATIC LITERATURE REVIEW	207
Mokgokong, T.	INDUSTRIAL POLICY IS A KEY DRIVER OF LOCAL CONTENT IN SOUTH AFRICA'S AUTOMOTIVE INDUSTRY.	35
Mokgoro, P.	THE SUITABILITY OF INCREMENTAL INNOVATION FOR COMPETITIVE DIFFERENTIATION: A REVIEW OF THE SMARTPHONE INDUSTRY	16
Mokoti, T.	INVESTIGATING THE DEFORMATION OF THE RIGHT-HAND SIDE BOX OUTER OF AN AUTOMOTIVE MANUFACTURER USING LEAN SIX SIGMA DMAIC METHODOLOGY	121
Monoge, D.	ANALYSIS AND RECOMMENDATIONS ON BUSINESS IMPROVEMENT TECHNIQUES AS APPLIED IN SOUTH AFRICAN COLLIERIES	155
Motlhabane, A.T.	THE IMPLEMENTATION OF CIRCULAR ECONOMY PRINCIPLES TO THE RAPID SAND-CASTING PROCESS	106
Motsoeneng, L.C.	AN EVALUATION OF THE RISK-BASED APPROACH IMPLEMENTATION IN ISO/IEC 17025:2017 CONFORMITY ASSESSMENTS - A CASE STUDY	90
Mpanza, Z.	AN OVERVIEW OF FUZZY LOGIC TRAFFIC SIGNAL CONTROLLER	181
Mpanza, Z.	AN EXAMINATION OF BARRIERS AND SUPPORT SYSTEMS FOR SMALL AND MEDIUM ENTERPRISES IN SOUTH AFRICA'S COAL MINING SECTOR	186
Mphahlele, K.	THE ROLE OF INDUSTRY 4.0 TECHNOLOGIES IN SUCCESSFUL ENTERPRISE RESOURCE PLANNING (ERP) IMPLEMENTATION OF PROJECTS IN SELECTED SOUTH AFRICAN ORGANISATIONS	184
Msani, A.	IMPACT OF FOUNDRY PROCESS VARIABLES ON THE FINANCIAL FEASIBILITY OF THE BINDER JETTING PROCESS	83
Mudanalwo, N.M.	IDENTIFYING IMPROVEMENT STRATEGIES FOR THE DIESEL REBATE PROCESS IN SOUTH AFRICAN MINES	80
Mulaba-Bafubiandi, A.F.	RISK ASSESSMENT AND MITIGATION STRATEGIES FOR FALL OF GROUND INCIDENTS AT SIBANYE-STILLWATER GOLD MINE	154
Mulaba-Bafubiandi, A.F.	ANALYSIS AND RECOMMENDATIONS ON BUSINESS IMPROVEMENT TECHNIQUES AS APPLIED IN SOUTH AFRICAN COLLIERIES	155
Müller, W.E.	INDUSTRY 5.0 CONCEPTS & COMPONENTS: A SCOPING LITERATURE REVIEW	132
Mundoza, F.E.	STRATEGIC INTEGRATION OF PLANT MAINTENANCE SYSTEMS: A SYSTEMS THINKING APPROACH FOR ENHANCED PERFORMANCE AND SUSTAINABILITY	150
Mushwana, B.N.	OPTIMIZING QUALITY IN THE AUTOMOTIVE SECTOR: IDENTIFYING IMPROVEMENT STRATEGIES FOR REDUCING DENTS	156
Mutyavavire, R.P.	AN OVERVIEW OF FUZZY LOGIC TRAFFIC SIGNAL CONTROLLER	181
Mutyavavire, R.P.	IMPACT OF TOTAL PRODUCTIVE MAINTENANCE ON CONVEYOR BELT RELIABILITY	163

Authors	Paper Title	Ref[1]
Mutyavavire, R.P.	ENHANCING EMERGENCY MEDICAL SERVICE EFFICIENCY: OPTIMISING AMBULANCE RESPONSE TIME IN GAUTENG PROVINCE	164
Naidoo, S.	AN EVALUATION OF THE RISK-BASED APPROACH IMPLEMENTATION IN ISO/IEC 17025:2017 CONFORMITY ASSESSMENTS – A CASE STUDY	90
Naidoo, S.	THE IMPACT OF THE BALANCED SCORECARD ON PRODUCT AND SERVICE INNOVATION IN SMALL MEDIUM ENTERPRISES	94
Naledzani, T.D.	OPTIMIZING QUALITY IN THE AUTOMOTIVE SECTOR: IDENTIFYING IMPROVEMENT STRATEGIES FOR REDUCING DENTS	156
Nash, S.P.	INVESTIGATING THE STATE-OF-THE-ART IMPACT ANALYSIS APPROACHES WITHIN THE CONTEXT OF BUILDING AUTOMATION AND CONTROL SYSTEMS FROM A FEASIBILITY PERSPECTIVE: A STRUCTURED LITERATURE REVIEW	145
Ncube, H.	AN EXAMINATION OF BARRIERS AND SUPPORT SYSTEMS FOR SMALL AND MEDIUM ENTERPRISES IN SOUTH AFRICA'S COAL MINING SECTOR	186
Ndou, N.	IMPLEMENTING RISK BASED INSPECTION AND MAINTENANCE IN THE POWER INDUSTRY	122
Nel, G.J.	COMPACT 3D PRINTED TURNTABLE DESIGN FOR INDUSTRIAL 3D SCANNING APPLICATIONS	129
Nemakonde, N.	THE ANALYSIS OF THE LOGISTICS SUPPORT SYSTEM IN ROAD TRANSPORT	61
Newuwari, T.	IMPLEMENTING RISK BASED INSPECTION AND MAINTENANCE IN THE POWER INDUSTRY	122
Nkosi, M.	THE SOCIO-ECONOMIC EFFECTS OF AIRBNB AS A DISRUPTIVE INNOVATION ON BUSINESS AND SOCIETY	22
Nkuna, T.	THE SOCIO-ECONOMIC EFFECTS OF AIRBNB AS A DISRUPTIVE INNOVATION ON BUSINESS AND SOCIETY	22
Nwala, K.C.	ECONOMIC SUSTAINABILITY ASSESSMENT OF ENERGY SOURCES FOR DECENTRALIZED GENERATION	226
Nyakala, K.S.	A REVIEW OF POTENTIAL CHALLENGES AND OPPORTUNITIES OF BUSINESS PROCESS REENGINEERING IN THE ERA OF INDUSTRY 4.2	159
Nyakala, K.S.	THE IMPACT OF AUTOMATION ON EMPLOYMENT IN SMALL AND MEDIUM ENTERPRISES (SMES): A SYSTEMATIC LITERATURE REVIEW	222
Nyembwe, K.D.	DEVELOPMENT OF FUNCTIONAL PARTS IN RAPID SAND CASTING FOR HIGH-TECH APPLICATION – A REVIEW	43
Nyembwe, K.D.	IMPACT OF FOUNDRY PROCESS VARIABLES ON THE FINANCIAL FEASIBILITY OF THE BINDER JETTING PROCESS	83
Nyembwe, K.D.	CRAFTING OF A DECARBONISATION STRATEGY FOR THE SOUTH AFRICAN FOUNDRY INDUSTRY: A ROADMAP TOWARDS SUSTAINABLE METAL CASTING	38
Nyembwe, K.D.	QUALITY 4.0 MATURITY ASSESSMENT FOR SOUTH AFRICAN MANUFACTURING SECTORS	44
Nyembwe, K.D.	THE IMPLEMENTATION OF CIRCULAR ECONOMY PRINCIPLES TO THE RAPID SAND-CASTING PROCESS	106
Nyembwe, K.D.	A QUALITATIVE ASSESSMENT OF THE RAPID SAND CASTING PROCESS USING THE RESSOURCE EFFICIENCY CLEANER PRODUCTION FRAMEWORK.	115
Nyembwe, K.D.	STATISTICAL ANALYSIS OF PROPERTIES OF SOUTH AFRICAN FOUNDRY CHROMITE SAND USED FOR ADDITIVE MANUFACTURING APPLICATIONS.	166
Oguntuyi, S.D.	DEVELOPMENT OF FUNCTIONAL PARTS IN RAPID SAND CASTING FOR HIGH-TECH APPLICATION – A REVIEW	43
Okwu, M.	A FRAMEWORK FOR INDUSTRIAL CLUSTER-DRIVEN ADOPTION OF INDUSTRY 4.0 TECHNOLOGIES	199

Authors	Paper Title	Ref[1]
Olanrewaju, O.A.	ECONOMIC SUSTAINABILITY ASSESSMENT OF ENERGY SOURCES FOR DECENTRALIZED GENERATION	226
Oosthuizen, R.	TOPIC MODELLING OF ACADEMIC PUBLICATIONS IN TIMBER CONSTRUCTION AND ENGINEERED WOOD	24
Oosthuizen, R.	DEVELOPING MACHINE LEARNING-BASED MODELS FOR OPTIMAL MAINTENANCE SCHEDULING WITHIN THE FOOD INDUSTRY	26
Oosthuizen, R.	AGILE SERVICE SYSTEMS ENGINEERING: A SYSTEMATIC APPROACH TO DESIGNING CUSTOMISED DIGITAL SOLUTIONS IN THE FINANCIAL SERVICES INDUSTRY	75
Oosthuizen, R.	ARTIFICIAL INTELLIGENCE INTEGRATION IN SYSTEMS ENGINEERING: NAVIGATING OPPORTUNITIES AND RISKS ACROSS THE SYSTEM LIFECYCLE	81
Oosthuizen, R.	STRATEGIC INTEGRATION OF PLANT MAINTENANCE SYSTEMS: A SYSTEMS THINKING APPROACH FOR ENHANCED PERFORMANCE AND SUSTAINABILITY	150
Oyewole, G.J.	EVALUATING AND ENHANCING VEHICLE FLEET MAINTENANCE: LEVERAGING PREDICTIVE ANALYTICS AND SMOTE FOR OPERATIONAL EFFICIENCY AND COST SAVINGS	89
Pascoe, B.	A STRATEGY FOR CRITICAL ELECTRICAL SERVICE RESTORATION IN UNDERGROUND MINES USING GRAPH THEORY	95
Peach, R.H.	ASSESSING MAINTENANCE 4.0 MATURITY: A CASE STUDY OF A SOUTH AFRICAN MINING COMPANY	14
Peach, R.H.	STRATEGIC INTEGRATION OF PLANT MAINTENANCE SYSTEMS: A SYSTEMS THINKING APPROACH FOR ENHANCED PERFORMANCE AND SUSTAINABILITY	150
Petrarolo, D.	COST-TO-SERVE AND PROFITABILITY ANALYSIS OF PRODUCTS AND CUSTOMERS IN A SUPPLY CHAIN	198
Phuluwa, H.	INVESTIGATING THE DEFORMATION OF THE RIGHT-HAND SIDE BOX OUTER OF AN AUTOMOTIVE MANUFACTURER USING LEAN SIX SIGMA DMAIC METHODOLOGY	121
Phuluwa, H.	IMPLEMENTING RISK BASED INSPECTION AND MAINTENANCE IN THE POWER INDUSTRY	122
Phuluwa, H.	DEVELOPMENT OF BERTH PERFORMANCE MEASUREMENT SYSTEM: AN OVERALL EQUIPMENT EFFECTIVENESS PERSPECTIVE	123
Pillay, A.C.	CONCEPTUAL FRAMEWORK TO ENHANCE GROWTH AND COMPETITIVENESS OF LOWER-TIER AUTOMOTIVE SMMES: A REVIEW	218
Pillay, N.S.	USING SYSTEM DYNAMICS MODELLING TO DETERMINE THE IMPACT OF CHARGING ELECTRIC VEHICLES ON THE LOAD PROFILE IN THE RESIDENTIAL SECTOR	37
Pretorius, L.	ENERGY INNOVATION OPPORTUNITIES IN HIGH ENERGY CONSUMING SECTORS IN SOUTH AFRICA	201
Rabinovitch, D.	EVALUATING AND ENHANCING VEHICLE FLEET MAINTENANCE: LEVERAGING PREDICTIVE ANALYTICS AND SMOTE FOR OPERATIONAL EFFICIENCY AND COST SAVINGS	89
Ramasu, T.K.	BUILDING A SUSTAINABLE HIGHER EDUCATION MODEL FOR SOUTH AFRICA	176
Ramdass, K.R.	INVESTIGATING THE DEFORMATION OF THE RIGHT-HAND SIDE BOX OUTER OF AN AUTOMOTIVE MANUFACTURER USING LEAN SIX SIGMA DMAIC METHODOLOGY	121
Ramdass, K.R.	IMPLEMENTING RISK BASED INSPECTION AND MAINTENANCE IN THE POWER INDUSTRY	122

Authors	Paper Title	Ref[1]
Ramdass, K.R.	DEVELOPMENT OF BERTH PERFORMANCE MEASUREMENT SYSTEM: AN OVERALL EQUIPMENT EFFECTIVENESS PERSPECTIVE	123
Ramdass, K.R.	UTILISING VALUE STREAM MAPPING IN IDENTIFYING WASTE AND IMPROVEMENT STRATEGIES IN COMPONENT MANUFACTURING	124
Rice, K.S.	DEVELOPING A DYNAMIC NEXT PURCHASE DATE PREDICTOR FOR INDIVIDUAL CUSTOMERS IN THE FAST-MOVING CONSUMER GOODS RETAIL SECTOR	51
Roopa, M.	AN INDUSTRIAL ENGINEERING LIGHTHOUSE MODEL FOR TRANSDISCIPLINARY PROBLEM SOLVING AND SUSTAINABLE DEVELOPMENT IN SOUTH AFRICA	30
Roopa, M.	LIGHTING THE WAY TO PROFITABLE RECHARGING: A TECHNO-ECONOMIC ANALYSIS OF WORKPLACE SOLAR-POWERED ELECTRIC VEHICLE CHARGERS IN POTCHEFSTROOM, SOUTH AFRICA	57
Roopa, M.	SHINING LIGHT ON 20 KEYS IMPLEMENTATION AT A SOUTH AFRICAN AGRICULTURAL COMPANY USING FOCUS GROUPS	161
Roux, A.A.	ASSESSING INFRASTRUCTURE CONDITION IN SOUTH AFRICA THROUGH TOPIC MODELLING OF ONLINE NEWS ARTICLES	56
Roux, P.J.	OPTIMISING STARTUP MANUFACTURER'S SUPPLY CHAIN: ANALYSIS AND INVENTORY SYSTEM DESIGN	58
Ryumeko, D.C.	APPLICATION OF FAILURE MODE AND EFFECTS ANALYSIS IN A ONE-PIECE FLOW MANUFACTURING SET UP: A SYSTEMATIC LITERATURE REVIEW	69
Scholtz, A.	LIGHTING THE WAY TO PROFITABLE RECHARGING: A TECHNO-ECONOMIC ANALYSIS OF WORKPLACE SOLAR-POWERED ELECTRIC VEHICLE CHARGERS IN POTCHEFSTROOM, SOUTH AFRICA	57
Schutte, C.S.L.	APPLYING THE PDCA CYCLE TO SCOPE 3 GHG EMISSIONS REPORTING IN THE SOUTH AFRICAN MINING INDUSTRY	62
Schutte, C.S.L.	IDENTIFYING IMPROVEMENT STRATEGIES FOR THE DIESEL REBATE PROCESS IN SOUTH AFRICAN MINES	80
Schutte, C.S.L.	BENCHMARKING TOOL FOR SOUTH AFRICAN GOLD MINES' COMMINUTION CIRCUITS	127
Scribante, N.	A CASE STUDY ON THE INTEGRATION OF PROJECT MANAGEMENT AND SYSTEM ENGINEERING IN A HIGH TECHNOLOGY COMPANY	113
Semuli, S.	THE SUITABILITY OF INCREMENTAL INNOVATION FOR COMPETITIVE DIFFERENTIATION: A REVIEW OF THE SMARTPHONE INDUSTRY	16
Shongwe, M.B.	DEVELOPMENT OF FUNCTIONAL PARTS IN RAPID SAND CASTING FOR HIGH-TECH APPLICATION – A REVIEW	43
Sibanda, P.G.	A SYSTEMATIC LITERATURE REVIEW ON ASSET MAINTENANCE PRIORITISATION APPROACHES RELEVANT TO WATER INFRASTRUCTURE	139
Sibisi, S.P.	THE IMPACT OF THE BALANCED SCORECARD ON PRODUCT AND SERVICE INNOVATION IN SMALL MEDIUM ENTERPRISES	94
Sikibi, M.	DIGITAL TWIN ABILITIES IN CELLULAR MANUFACTURING: ILLUMINATING PATHWAYS TO SUCCESS	212
Siriram, R.	COMPACT 3D PRINTED TURNTABLE DESIGN FOR INDUSTRIAL 3D SCANNING APPLICATIONS	129
Smal, F.	THE IMPACT OF RELIABILITY-CENTRED MAINTENANCE ON TOTAL COST OF OWNERSHIP OF MEDIUM VOLTAGE EXPLOSION-PROTECTED INDUCTION MOTORS	74
Snyman, H.J.	OPTIMISING UNDERGROUND MINE TRAIN SCHEDULING: A MIXED-INTEGER LINEAR PROGRAMMING APPROACH	10

Authors	Paper Title	Ref[1]
Steenkamp, H.	ENHANCING DECISION-MAKING IN SOUTH AFRICAN SMMES THROUGH BUSINESS INTELLIGENCE	23
Steenkamp, H.	THE ANALYSIS OF THE LOGISTICS SUPPORT SYSTEM IN ROAD TRANSPORT	61
Sterrenberg, W.H.	A STRATEGY FOR CRITICAL ELECTRICAL SERVICE RESTORATION IN UNDERGROUND MINES USING GRAPH THEORY	95
Tartibu, L.K.	DIGITAL TWIN ABILITIES IN CELLULAR MANUFACTURING: ILLUMINATING PATHWAYS TO SUCCESS	212
Tartibu, L.K.	PARAMETRIC STUDY OF THE QUEUING MODEL IN TELEMEDICINE	158
Tartibu, L.K.	A FRAMEWORK FOR INDUSTRIAL CLUSTER-DRIVEN ADOPTION OF INDUSTRY 4.0 TECHNOLOGIES	199
Toro, S.	THE SUITABILITY OF INCREMENTAL INNOVATION FOR COMPETITIVE DIFFERENTIATION: A REVIEW OF THE SMARTPHONE INDUSTRY	16
Tshabalala, N.V.	STATISTICAL ANALYSIS OF PROPERTIES OF SOUTH AFRICAN FOUNDRY CHROMITE SAND USED FOR ADDITIVE MANUFACTURING APPLICATIONS.	166
Tshabalala, T.M.	FRAMEWORK FOR DEVELOPING PEDAGOGY SKILLS FOR TEACHING AND LEARNING IN THE FOURTH INDUSTRIAL REVOLUTION (4IR): A SOUTH AFRICAN PERSPECTIVE	179
Tshavhungwe, V.	EVALUATION OF THE SOUTH AFRICAN SAWMILL INDUSTRY’S NATIONAL COMPETITIVE ADVANTAGE USING PORTER’S DIAMOND MODEL	33
Tshiamala, D.	PARAMETRIC STUDY OF THE QUEUING MODEL IN TELEMEDICINE	158
Ubisi, S.	THE IMPACT OF AUTOMATION ON EMPLOYMENT IN SMALL AND MEDIUM ENTERPRISES (SMES): A SYSTEMATIC LITERATURE REVIEW	222
Van Der Lingen, E.	THE ROLE OF DIGITAL TECHNOLOGIES IN PROCUREMENT	53
Van der Lingen, E.	ILLUMINATING FRAMEWORKS FOR MANAGING TECHNOLOGICAL INNOVATION: RECOGNISING CONSTRAINTS AND LIMITATIONS	55
Van der Merwe, J.	UTILISING DATABASE MANAGEMENT SYSTEMS AND STATISTICAL PROCESS CONTROL TO ELEVATE QUALITY ASSURANCE FOR AGRICULTURAL PERISHABLES	27
Van Dyk, L.	INDUSTRY 5.0 CONCEPTS & COMPONENTS: A SCOPING LITERATURE REVIEW	132
Van Dyk, L.	A SYSTEMATIC LITERATURE REVIEW ON ASSET MAINTENANCE PRIORITISATION APPROACHES RELEVANT TO WATER INFRASTRUCTURE	139
Van Laar, J.H.	APPLYING THE PDCA CYCLE TO SCOPE 3 GHG EMISSIONS REPORTING IN THE SOUTH AFRICAN MINING INDUSTRY	62
Van Laar, J.H.	IDENTIFYING IMPROVEMENT STRATEGIES FOR THE DIESEL REBATE PROCESS IN SOUTH AFRICAN MINES	80
Van Laar, J.H.	A STRATEGY FOR CRITICAL ELECTRICAL SERVICE RESTORATION IN UNDERGROUND MINES USING GRAPH THEORY	95
Van Laar, J.H.	BENCHMARKING TOOL FOR SOUTH AFRICAN GOLD MINES’ COMMINUTION CIRCUITS	127
Van Laar, J.H.	DYNAMIC CONTROL OF DEEP-LEVEL MINE COOLING SYSTEMS USING ARTIFICIAL INTELLIGENCE	197
Van Rensburg, J.F.	A STRATEGY FOR CRITICAL ELECTRICAL SERVICE RESTORATION IN UNDERGROUND MINES USING GRAPH THEORY	95
Van Rooyen, M.	ILLUMINATING FRAMEWORKS FOR MANAGING TECHNOLOGICAL INNOVATION: RECOGNISING CONSTRAINTS AND LIMITATIONS	55
Visser, K.	THE IMPACT OF RELIABILITY-CENTRED MAINTENANCE ON TOTAL COST OF OWNERSHIP OF MEDIUM VOLTAGE EXPLOSION-PROTECTED INDUCTION MOTORS	74

Authors	Paper Title	Ref[1]
Wagener, R.	A SIMULATION-BASED APPROACH TO ILLUMINATE INVENTORY CONTROL DECISIONS: POLICY IDENTIFICATION AND OPTIMISATION FOR STAKEHOLDER INFORMED STRATEGIES	9
Wagner, R.S.	SUSTAINABILITY OF LEAN IN SOUTH AFRICAN PUBLIC HOSPITALS	152
Xaba, S.G.	THE ROLE OF UNIVERSITIES IN PREPARING INDUSTRY TO MENTOR WORK-INTEGRATED LEARNING STUDENTS	142
Zincume, P.N.	OPTIMISING STORE OPERATIONS: ILLUMINATING INVENTORY MANAGEMENT FOR GLOBAL LEADERSHIP IN A MANUFACTURING ENVIRONMENT	108
Zincume, P.N.	IMPROVING THE QUALITY OF CONSTRUCTION PROJECTS IN SOUTH AFRICA USING BUILDING INFORMATION MODELLING	151
Zincume, P.N.	A SYSTEMATIC LITERATURE REVIEW FOR EXPLORING THE SUSTAINABILITY IMPACT OF ANIMAL-SOURCE FOOD SUPPLY CHAINS	160
Zitha, M.	THE SUITABILITY OF INCREMENTAL INNOVATION FOR COMPETITIVE DIFFERENTIATION: A REVIEW OF THE SMARTPHONE INDUSTRY	16

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LEAN 4.0 IN SOUTH AFRICA: ILLUMINATING THE PATH AHEAD

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ABSTRACT

South African stands on the brink of change, as technological advancements reshape the thoughts and ideas within the international manufacturing community. Digitalisation has offered a range of tools and techniques to guide in the technological advancement journey. However, Lean 4.0 provides an opportunity to integrate the technological development of Industry 4.0, with the benefits of Lean philosophy, in order to illuminate the path ahead. This study makes use of a systematic literature review to scope, benefits, barriers and enables of Lean 4.0. It was found while there are various trade-offs of Lean 4.0, there is a huge room for adoption in South Africa. The findings provide a guideline for applying Lean 4.0 in South African industries, in order to enhance global competitive advantage.

Keywords: Lean 4.0; Lean Philosophy; Industry 4.0; Systematic literature review; South Africa

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1 INTRODUCTION

South African stands on the brink of change, as technological advancements reshape the thoughts and ideas within the international manufacturing community. The manufacturing industry continues to implement state-of-the-art technologies with their organisations, as Industry 4.0 has taken off with a boom. However, third world countries are left wondering how to catch up and enhance their competitive advantage on a global scale. Figure 1 illustrates the breakdown of the phases of industrialisations.

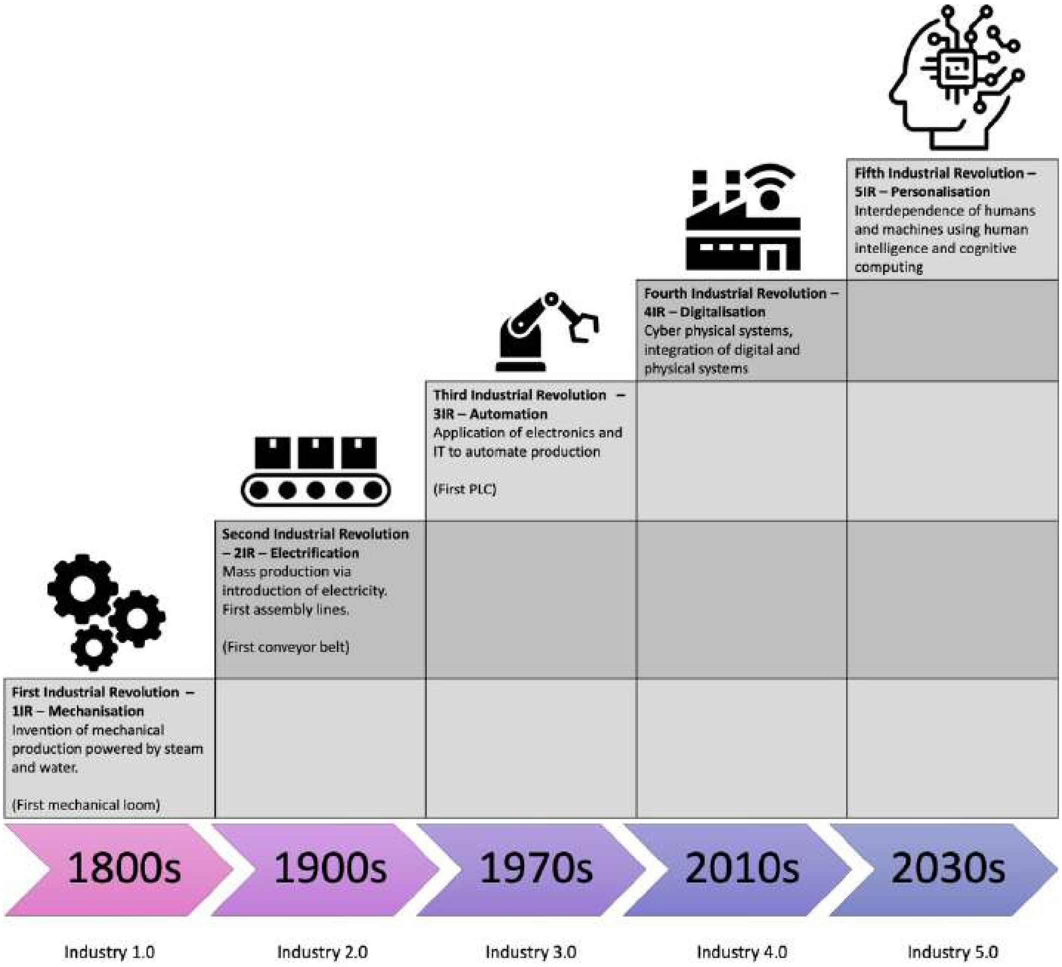

Figure 1: Phases of Industrialisation (Adapted from [1])

Industry 4.0 (I4.0) was first introduced in 2011 by the German Federal Government as their strategic aim for digitalising the manufacturing industry, where humans and machines are interconnected by extensive communication networks [2]. The concept of Industry 4.0 is explained in different ways, Saad et al. [3] states it is "the application of cyber-physical systems (CPS) in industries, allowing real-time integration while making the value chain more productive, intelligent and agile". While there are various definitions of Industry 4.0 available in literature, there is consensus on its value in terms of improved productivity, speed, flexibility and quality over the whole value chain [4].

In literature Industry 4.0 and the Fourth Industrial Revolution are often used as interchangeable terms, however, is imperative to note the difference between them, as it holds significant implications for sustainability. As can be seen in figure 1, since the mid 2010s, the world has been in the Fourth Industrial Revolution (4IR), which is significantly driven by Industry 4.0 [5]. Moreover, Digitalisation is at the core of I4.0 and 4IR, as the use of technologies to improve and transform business process [5].

There has been global recognised for the concepts and technologies that I4.0 brings with it, like [3, 4]:

- **Autonomous robots**:
    - **Collaborative robots (Cobots)** - An approach which allows the direct physical interaction between humans and robots without need for physical guarding
    - **Automated guided vehicles (AGV)** - Mobile robots used to transport goods around
    - **Autonomous mobile robots (AMR)** - Robots that transport, handle materials, patrol and collaborate with operators, while making autonomous decisions
- **Simulation**:
    - **Digital twin (DT)** - Digital representations of a system to reflect and perform real-time optimisations, decisions and predictive maintenance
    - **Real-time data and synchronisation -** The collection and complete evaluation of data from several sources to support real-time decision making
- **Horizontal, vertical, and end-to-end system integration:**
    - **Integration across the value chain -** Horizontal integration of organizations with their suppliers to improve the raw material and final product delivery across the entire supply chain
    - **Integration within the organisation -** Vertical integration entails advanced ICT systems that integrate across all levels of the company to aid in decision making
- **Industrial Internet of Things (IIoT):**
    - **Auto ID and data capture (RFID,NFC,DMC) - A**n individual tag that aids machines and technology in identifying and recording an objects movement, such as radio frequency identification system (RFID) tags
    - **Sensors and actuators -** Centers, controllers and actuators interconnect the local network
    - **Internet of things (IoT)** - Internet networking that integrates humans with machines in real time
    - **Cyber-physical systems (CPS)** - Allows for the production system to be modular such that it ensures profitable
- **Cloud computing (CC):**
    - **Cloud systems for data storage, processing and analysis** - Integrated computing and communication between hierarchies of an organization with the technology levels
- **Additive manufacturing (AM):**
    - **3D printing** - Additive manufacturing is enabled 3D printing small batches of customized products at relatively low costs
- **Augmented reality (AR)** - A set of communication systems that allow humans to interact with smart technology
- **Virtual reality (VR)** - A simulation of reality
- **Big data analytics (BDA)**:
    - **Big Data (BD**) - Characterised by large volumes, variety and velocity of data across a large range of networks where analytics are used to inform decisions and support them
    - **Artificial Intelligence (AI)** - Corresponding tasks that are carried out by machines which normally require human interference
    - **Machine Learning (ML)** - Computing program that is capable of learning from experience to improve

Furthermore, a study by Hoyer et al. [6], they reviewed 64 articles on Industry 4.0, and found that they are various factors to consider prior to Industry 4.0 implementations like political support, IT standardisation and security, corporate and institutional cooperation, funding, available knowledge and education, industry sector, strategic consideration, perceived benefits and company size. As a result of these factors, a large amount of Industry 4.0 research explores overcoming the challenges of implementation.

While there is a huge drive for digital transformation within South Africa, research reports that almost 70% of digital transformation processes fail due to a lack of strategy and long-term thinking [7]. To address this issue, Lean 4.0 is aiding organisations to add value during their digital transformation [7].

Lean 4.0 is the integration of Lean philosophy and Industry 4.0 [8]. Rossi et al. [7] explained that “Lean is seen as an important agent in the implementation of Industry 4.0 and highlights Lean concepts such as standardization of work, organization, and transparency as bridges to allow a more effective digital consolidation. In fact, there is a contribution from Industry 4.0 in improving Lean, mainly through integrated information and communication systems, supplying conventional practices and reducing production waste”. Furthermore, both Lean philosophy and Industry 4.0 aim to reduce the cost of production, enhance productivity and improve efficiencies within an organisation [4].

Lean philosophy is all encompassing management approach that is associated with business improvement and eliminating wastes, while focusing on people’s development and the creation of a problem-solving culture [3]. Although Lean has its origins within the manufacturing industry, it has been widely adopted and researched in various other industries, like healthcare, environmental sustainability and so on. This speaks to the well-established nature of the research field around Lean, in contrast to the emerging and evolving research on Industry 4.0 [4].

The current body of research on Lean 4.0 highlights the growing interest on the organisational benefits and value of the overlap of Lean and Industry 4.0; however, it is important to note that opposing views on this have been published [4, 7]. Researchers argue that the incompatibilities between these two approaches can be attributed to Lean having a low-tech, human-centric philosophy in contrast to Industry 4.0’s tech-driven philosophy, with people playing a secondary role [4, 9, 10, 11, 12]. Nevertheless, researchers have maintained that the combination of these approaches contribute to higher organisational performance [4, 12, 13, 14]. Authors explain that Industry 4.0 enhances Lean by providing technological capabilities, whilst Lean facilitate the Industry 4.0 implementation [4, 12, 13, 14]. This trade off could offer South African manufacturing organisations the opportunity to improve their competitive advantage.

However, at the time of writing this paper, only one study is present in literature about Lean 4.0 in South Africa [15]. This is study explores the use of Lean 4.0 and Quality 4.0 to eliminate waste in a FMCG packaging organisation in South Africa, where it was found that the use of Lean 4.0 allowed for proper control over the production [15]. The lack of studies in South Africa emphasises the gap in literature and opportunity to explore Lean 4.0 in the South African context.

Against this background and to contribute to the Lean 4.0 discussion, this research study intends to explore the scope of Lean 4.0 literature. This research study aims to collect and document available literature on the scope, benefits, barriers and enables of Lean 4.0, in order to provide a guidance framework for implementation in South Africa.

2 RESEARCH METHOD

In order to achieve the aim, a systematic literature review (SLR) was conducted to collect data. This took the form of a scoping SLR, which allowed for the investigation of the definitions, benefits, barriers and enables of Lean 4.0 [16]. This study was guided by the SLR method proposed by Albliwi et. Al. [17], which is detailed in the steps and sections that follow:

- **Step 1: Develop a research purpose and/or objective** - Clearly state the goal of the SLR
- **Step 2: Develop research protocol** - Create a research protocol that includes the purpose, inclusion criteria, exclusion criteria, databases, keywords and quality assessment criteria
- **Step 3: Establish relevance criteria** - State the reasoning for if a resource is relevant to this study
- **Step 4: Search and retrieve the literature** - Conduct searches on applicable scientific databases to find literature
- **Step 5: Selection of studies** - Use the inclusion and exclusion criteria to select studies
- **Step 6: Quality assessment for relevant studies** - Assess the quality of each paper
- **Step 7: Data extraction** - Extract relevant information from the papers
- **Step 8: Analysis and synthesis of findings** - Analyse and synthesise the data from the papers in order to find themes and patterns
- **Step 9: Report** - Report the review in detailed results
- **Step 10: Dissemination** - Publish the SLR

The outcomes of step 1- 6 are discussed in the sub-sections to follow (section 2.1 - 2.6), while the findings of the study (step 7 and 8) are documented in section 3. Steps 9 and 10 are addressed by publishing this research paper.

2.1 Step 1: Develop a research purposed and/or objective

The purpose of this study was to collect and document available literature on the scope, benefits, barriers and enables of Lean 4.0, in order to provide a guideline for implementation in South Africa.

2.2 Step 2: Develop a research protocol

A research protocol was developed, as depicted in table 1.

Table 1: Research review protocol (Structure adapted from Xiao et al. [16])

Purpose of the study	• To collect and document available literature on the scope, benefits, barriers and enables of Lean 4.0
Inclusion criteria	• Literature that contains “Lean 4.0” in the title, abstract or keywords • Literature that discusses the definition, barrier, enablers and benefits of Lean 4.0
Exclusion criteria	• Non-English studies • Lean-X focused studies (e.g. Lean Six Sigma, Lean Supply chain)
Search databases	• Science direct • Scopus • Web of Science • Emerald Insight
Keywords	• “Lean 4.0”
Quality assessment criteria	• All duplicate literature must be removed • Literature must be checked for relevance • Literature must be checked for correct understanding and interpretation of Lean • Studies must be scientific • Studies must have transparent data collection

2.3 Step 3: Establish relevance criteria

The field of Lean 4.0 is relatively new, with the first research emerging in the 2010s. Ergo, to expand the net cast for inclusion, the following relevance criteria was developed for the inclusion of studies:

- Literature that contains “Lean 4.0” in the title, abstract or keywords
- Literature that discusses the definition, barrier, enablers and benefits of Lean 4.0
- Non-English studies should be excluded
- Lean-X focused studies (e.g. Lean Six Sigma, Lean Supply chain) will be excluded due to the specific nature of their applications and development of 4.0 sub-groups (e.g. Lean six sigma 4.0)

2.4 Step 4: Search and retrieve the literature

During step 4, the search and retrieval of literature was conducted using the databases stipulated in table 1, which resulted in a total of 118 papers. Figure 2’s identification section illustrates the breakdown of papers during this step.

2.5 Step 5: Selection of studies

The duplicates and retraction notices were removed from the search results. This resulted in 93 papers passing the screening process, as shown in figure 2’s screening section. Thereafter, the several studies were removed as they did not discuss the definitions, benefits, or issues of Lean 4.0. Some studies were removed as they explored the history of Lean and did not have details of Lean 4.0. Some studies were in German or Spanish and did not have an English version, thus were excluded. Some studies explored Lean Six Sigma or only focused Lean supply chain and were excluded. Lastly studies explored one case study of the use of IoT, visual management or TPM were also excluded. After the exclusion process only 16 studies were eligible for inclusion, as denoted in figure 2’s eligibility section.

2.6 Step 6: Quality assessment for relevant studies

All 16 studies were assessed using the quality criteria presented in table 1 and met the requirements to be included as part of the SLR, as illustrated in figure 2.

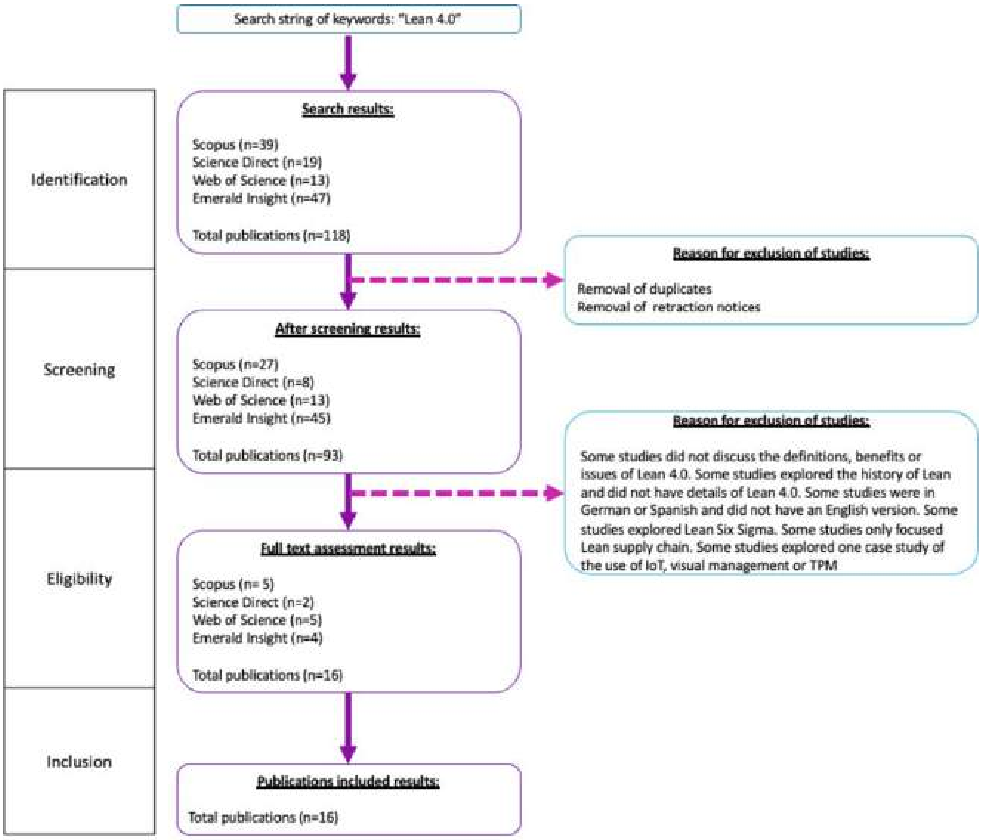

Figure 2: Selection process chart (As per PRISMA guidelines)

3 FINDINGS

The findings (step 7 and 8) from following the SLR methodology are discussed in the following sub-sections.

3.1 Step 7: Data extraction

After finalising the list of studies to be included, their full texts were studies and data was extracted. Appendix A contains a table that indicates the studies included along with data present in each paper. It is imperative to note that while the SLR was not limited to any specific industry, the results showed an overwhelming majority within the manufacturing industry. This can be attributed to the fact that both Industry 4.0 technologies and Lean have a large footprint in the manufacturing industry. Moreover, it can be ascribed to the large influx of research within the manufacturing sector in the past few years. Nevertheless, this highlights the gap in the research for studies from the other sectors and showcases the opportunity for future research to fill this gap.

3.2 Step 8: Analysis and synthesis of findings

After reading the full texts, the data was extracted, analysed and synthesised in the following sub-sections.

3.2.1 Annual distribution of studies

Although the research protocol did not limit a specific timeframe for data collection, the studies selected revealed that the earliest mentions of Lean 4.0 go back to 2018. While most of the publications were in 2022. This peak in publications is attributed to the changes brought on from the COVID-19 pandemic, which forced researchers to investigate how technology can help to make things more remote. The decline in studies in 2024 is due to data collection taking place in January of 2024, ergo various studies are yet to be published. Figure 3 illustrates the specific breakdown per year of publication.

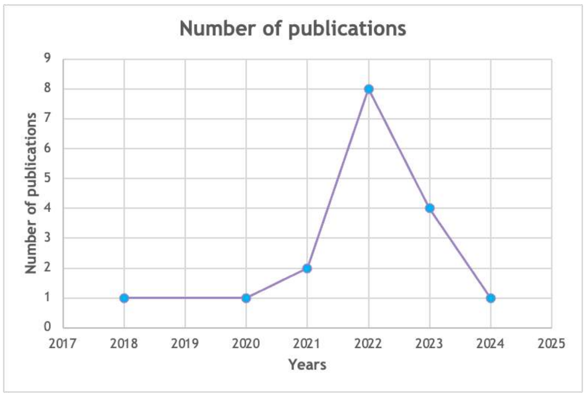

Figure 3: Line graph of the number of publications per year

3.2.2 *Keywords*

An analysis of the keywords in the studies showed that the most common keyword was Lean followed by Industry 4.0. This was to be expected given the nature of the topic of the SLR. However, other prevalent keywords were manufacturing, management, production, technologies, and target, which all align with Lean research. It is noteworthy that keywords like transformation, implementation and regulatory also came up, thus highlighting the importance of handling the implementation of Lean 4.0 correctly. A wordcloud was generated from the keywords to illustrate the frequency of use of the words, which is depicted in figure 4.

Figure 4: Wordcloud of the keywords

3.2.3 *Countries of study*

When looking at the country of origin of each study, it was clear that the studies were distributed throughout the globe. However, it was Germany and India that produced the majority of the papers. This is not surprising given that Industry 4.0 research is common in these countries. Some studies offered insights from a third world country perspective, which could be immensely valuable to South African organisations. Figure 5 showcases the frequency of publications per country.

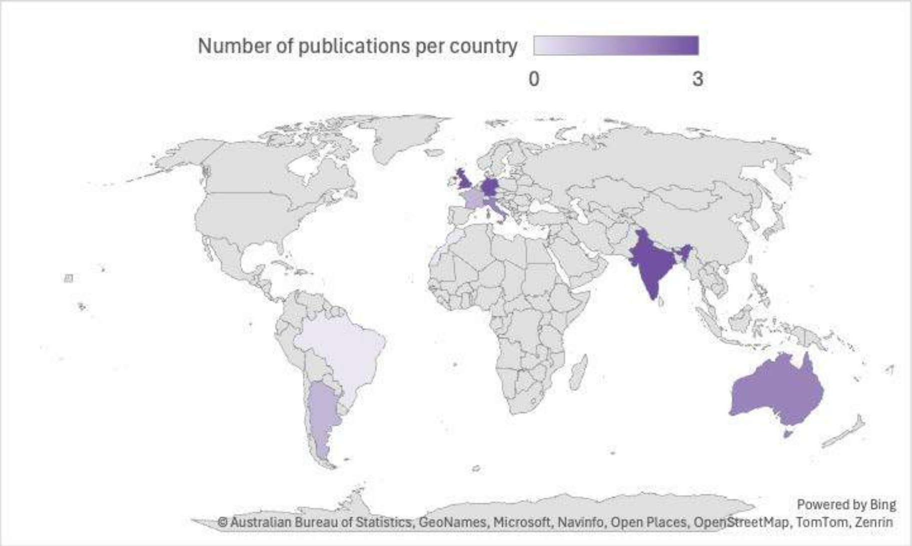

Figure 5: A world map indicating the number of publications per country

3.2.4 *Industry 4.0 technologies/concepts and Lean 4.0 tools/concepts*

The studies explored which Industry 4.0 technologies/concepts can be used for to enhance which Lean 4.0 tools/concepts. Table 2 was created to illustrate the relationship between them, and appendix B illustrates this using a Sankey chart.

Table 2: Relationship between Industry 4.0 concepts and Lean concepts

Lean concepts	Industry 4.0 concepts														
	Cobots	AGV	AMR	DT	Simulation	IIoT	IoT	CPS	CC	AM	AR	VR	BD	AI	ML
5S				X	X				X	X	X	X	X	X	X
Andon				X	X				X		X	X	X	X	X
Automation	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Cellular manufacturing	X			X	X				X	X	X	X	X	X	X
Communication of Info	X	X	X			X	X	X	X		X	X	X	X	
Continuous improvement	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Eliminating waste				X	X				X	X	X	X	X	X	X
Empowering employees									X		X	X	X	X	X
Flexibility				X	X	X	X	X	X	X	X	X	X	X	X
Hejiunka				X	X	X	X	X	X		X	X	X	X	X
Human resource improvement									X	X	X	X	X	X	X
Jidoka	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
JIT	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Kanban				X	X				X	X	X	X	X	X	X
Kaizen	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Lean thinking				X	X				X		X	X			
Poka-yoke				X	X				X	X	X	X	X	X	X
Problem solving culture	X	X	X	X	X				X		X	X	X	X	X
Pull	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Quality control				X	X	X	X	X	X		X	X	X	X	X
Respect for people									X	X	X	X	X	X	X
SMED	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Standardisation of work						X	X	X	X		X	X	X	X	X
Takt time				X	X	X	X						X		
TPM				X	X	X	X	X	X	X	X	X	X	X	X
Visual management					X	X					X	X			
VSM				X	X				X	X		X	X	X	X

From table 2, not all Industry 4.0 concepts correlate with all Lean concepts. Subsequently, various authors [18, 8, 19, 20, 21, 22, 23, 24, 25, 26] [27, 28, 3, 29, 30, 31, 7]have created context-specific variations for several Lean 4.0 concepts, to carry the same neologism of "X 4.0" such as:

- **Jidoka 4.0** - Real-time monitoring and compliance of machines and users regarding inconsistencies in the process
- **JIT 4.0** - Real-time tracking and mapping of pull in the digital space across the entire supply chain
- **Kaizen 4.0** - Using smart sensors to focus on production flow improvement and employee training
- **Kanban 4.0** - Real-time monitoring, analysis, and traceability labels of products in productions
- **Lean thinking 4.0** - Training employees to identify Lean solutions in a digital innovation space, along with using Industry 4.0 concepts to reduce wastes
- **Poka-yoke 4.0** - Real-time promotion of error-proofing the production process using digital technologies

- **TPM 4.0** - Utilising digital technology to implement maintenance plans that integrate various sectors. This allows for analysis of trends in machine failure history and downtimes
- **Visual management 4.0** - Using digital processing mapping that incorporates historical data and demand forecasting to showcase process vulnerability and progression towards a goal
- **VSM 4.0** - Control and management of daily production operations in order to integrate the entire value stream of the suppliers, organisation and customers

Moreover, another interesting find from the SLR articles was that of Cifone et al. [8], where they discussed the eight digital waste reduction mechanisms. These mechanisms allow organisations to use industry 4.0 technology to reduce the eight Lean wastes (Transport, inventory, motion, waiting, overproduction, overprocessing, defects, underutilised employee skills). Table 3 outlines the mechanism's definition along with an example, as covered by Cifone et al. [8].

Table 3: Eight mechanisms to reduce waste (Adapted from Cifone et al. [8])

#	Mechanism	Definition	Example
1	Visibility	Exploit technologies to improve planning phase. Use real-time data for improved visibility.	Advance analytics to improve forecasting. IoT to automate production line balancing.
2	Precision of execution	Exploit technologies to improve accuracy and reliability in the process.	AGV and AMR to reduce human error. AM to produce products that are complex in design.
3	Speed of execution	Exploit technologies to speed up processes.	AGV and AMR with route planning utilisation to reduce transport and waiting. Robotics to reduce setup time while synchronising operations.
4	Feedback	Exploit technologies for real-time feedback systems for identifying errors and defects in the process.	VR and AR to identify errors and defects. IoT for a self-correcting system.
5	Engagement	Exploit technologies to enhance and enrich employees' jobs.	Use of robots to reduce motion from operators and improve ergonomics. VR and AR training opportunities.
6	Flexibility in time	Exploit technologies to customise outputs and link production to actual demand.	AM to produce smaller batch sizes. Advanced analytics to follow customer requirements.
7	Flexibility in space	Exploit technologies to design and manage assets that enable an enhanced responsive system and production.	Use IoT to assistance in location associated decisions. Use simulations and robotics to create an improved layout.
8	Prevention	Exploit technologies to anticipate defects, intervention needs and plan preventative maintenance.	Predicative tools designed using advanced analytics. AM to create ad hoc space parts.

3.2.5 Barriers to Lean 4.0

During Lean implementations it is important to understand what the barriers to successful implementations are, in order to mitigate them and increase the chances of a successful adoption. From the 16 studies reviewed during the SLR, the following barriers or inhibitors were identified and extracted:

- Different focus areas of Lean and Industry 4.0
- Equipment or technology failure
- Financial challenges
- Hyper-connectedness introduces risk in digital security

- Improper change management
- Labour force inefficiencies
- Lack of buy-in from team members
- Lack of leadership
- Lack of proof and success stories
- Lack of support from suppliers, customers, and government
- Lack of understanding of the technologies and lack of training
- Non-alignment with the strategic goals of the company (lack of long-term vision)
- Unclear how to adopt new technologies

3.2.6 Enablers of Lean 4.0

In a similar vein, it is important to place emphasis on the enablers of success adoptions of Lean 4.0. From the 16 studies reviewed during the SLR, the following enablers or success factors were identified and extracted:

- Cross functional teams
- Employee buy-in
- Financial support
- Improved analysis and understanding of systems
- Integration between different systems, tools and ideas
- Lean philosophy must be implemented first, then Industry 4.0 concepts can be introduced
- Lean thinking, continuous improvement and problem solving culture
- Novelty of new technologies and excitement to use it
- Real-time capabilities and digitalisation
- Support and accessibility
- Training opportunities for employees
- Well set up environment for Industry 4.0

3.2.7 Benefits of Lean 4.0

From the studies reviewed, there were numerous benefits listed in favour of Lean 4.0. These benefits cover a wide range of areas like financial performance, operational performance, human factors, and safety aspects. The following benefits were retrieved from the SLR studies:

- Automated logistics
- Continuous flow monitoring
- Control of planned maintenance activities
- Digital technologies lower the skill level needed for task execution, (leads to more task automation in the future)
- Elimination of waste when starting digitalisation
- Enables greater agility when prioritising, scheduling and tracking inventory
- Fault monitoring
- Financial performance (Resource saving; waste reduction; increased profits)
- Greater flexibility
- Holistic integration and data sharing
- Increase in productivity
- Increase production speed
- Increased transparency
- Integrated system architecture
- Mastering of efficient customisation

- People (Training and development; new knowledge and data driven learning; increase of human-machine integration; job enrichment)
- Predictive maintenance improvements
- Quick detection of problems
- Real-time production data
- Reliability improvements
- Remote integration
- Safety (Increased cybersecurity; manufacturing surveillance; minimised human errors)
- Servitisation increasing
- Simplification of Lean adoption vs complex adoption of Industry 4.0
- Smart Lean automation
- Smart tracking
- Stability improvements and ability to adjust to season fluctuations
- Standardised digital routines
- Supports remote working
- Traceability and Transparency

4 A LEAN 4.0 IMPLEMENTATION FRAMEWORK FOR SOUTH AFRICA

While Lean philosophy is widely known for its benefits, there is a large volume of research available on the implementation of it. Research shows that adopting Lean philosophy a cultural transformation first and foremost, as opposed to a purely technical and manufacturing adjustment [32]. During this cultural change, it is suggested that organisations incoporate their cultural concepts to improve the implementation success rates [32].

South Africa is melting pot of diversity and a developing country. Research done by Mangaroo-Pillay et al. [33] suggest that Ubuntu philosophy could be used to bridge the gaps during Lean cultural changes in South African organisations, as Ubuntu is an indigenous philosophy used in the management sphere. Building on this study, another study introduced the concept of Digital Ubuntu, which “is the idea of people collaborating to solve a problem digitally. It requires thinking in an ecosystem way to resolve issues and, as South Africans, Ubuntu equips people to think and behave in a collaborative and communal” [34]. The authors explain how developed countries have tailored their technological adoptions in roadmaps, unique to their situations, and how African developing countries should follow suit [34]. Moreover, they suggest that African countries support their domestic technological developments and innovation, whilst moving towards sustainability and bridging the digital divide between countries [34].

From the findings presented in section 3, studies suggest that introducing Lean philosophy first, then Industry 4.0 concepts will lead greater buy-in from employees and increase the success rates of Lean 4.0. Considering this, Rossi et al. [7] developed a Lean 4.0 framework (D-LEaMIN), where they suggest introducing Lean thinking first, then the other Lean 4.0 concepts. Another study by Bueno et al. [19] propose a Lean 4.0 framework that follows the PDCA cycle and requires organisations to overcome the barriers, master the enablers and set organisational goals of Lean 4.0 using change management.

Consider the discussion around implementation, the South African Lean 4.0 implementation framework was developed (illustrated in figure 6). The pyramid in the centre builds on the 4P model of the Toyota way, which was introduced by Liker [35] , as framework for Lean implementation.

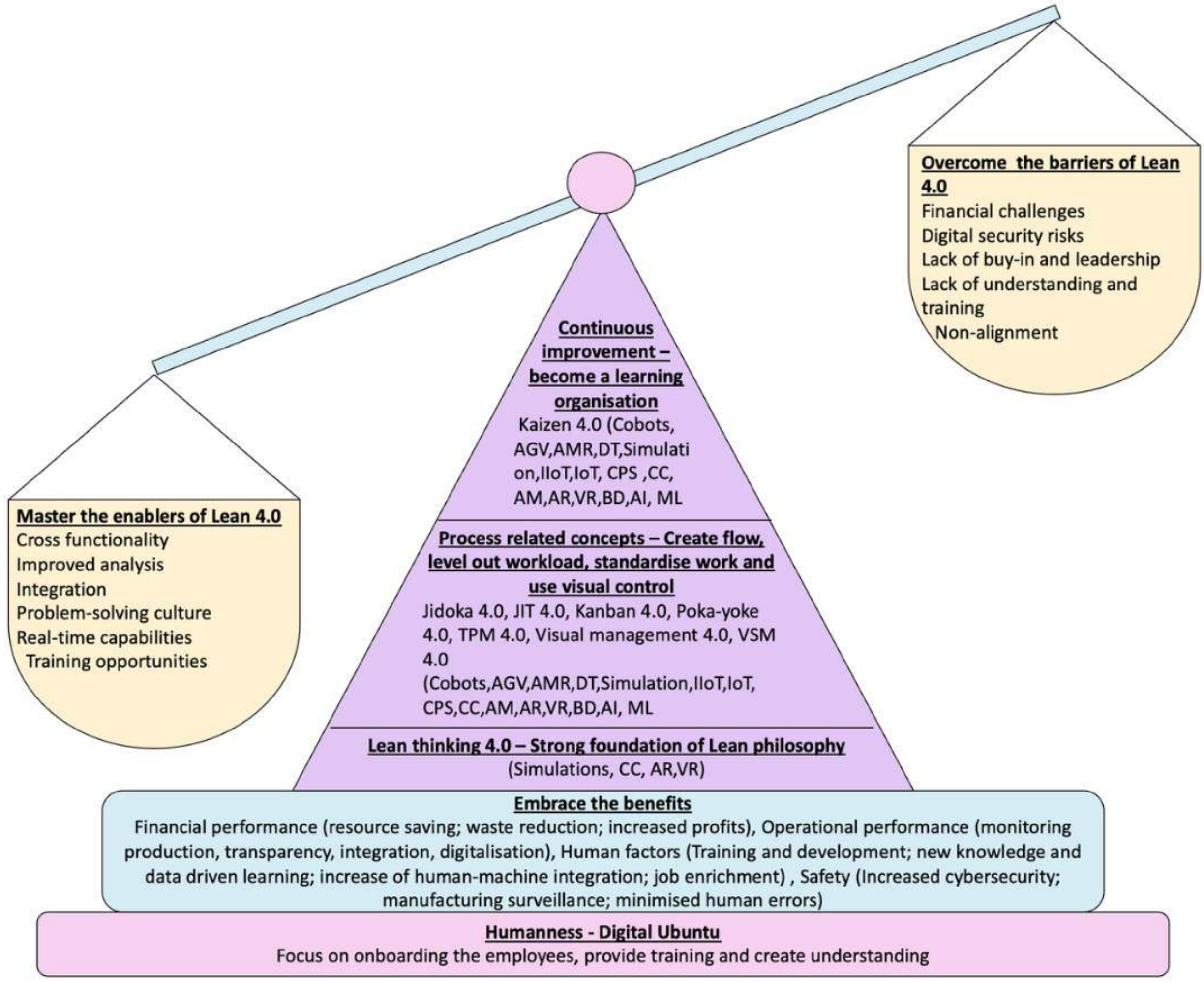

Figure 6: Lean 4.0 implementation framework for South African organisations

In figure 6, the framework illustrates that any Lean 4.0 implementation in South African must start with Humanness, incorporating the concept of digital Ubuntu. Given that the South African national culture is akin to collectivism, it is advisable to onboard employees and create understanding around the Lean 4.0 implementation first. This will allow for the mitigation of misunderstanding and reduce the resistance to change from employees.

Building on this foundation, organisations are encouraged to embrace the benefits of Lean 4.0 and create acceptance using them. This can be used to enhance employee buy-in and increase potential investment in the implementation from stakeholders.

The pyramid in the centre suggests that organisations focus on Lean thinking 4.0 as on the Lean concepts first, as it will allow for a strong foundation in the Lean philosophy (as is required with any type of Lean implementation). Thereafter, organisations are to focus on the process related concepts like Jidoka 4.0, JIT 4.0, Kanban 4.0, Poka-yoke 4.0, TPM 4.0, Visual management 4.0 and VSM 4.0. This will allow for organisations to create flow, level out the workload, standardise work and use visual control for overall process improvement. Afterwards, it is recommended that organisations focus on continuous improvement using Kaizen 4.0 in order to become a learning organisation that is always growing and developing. Additionally, all the Industry 4.0 concepts used for each section are listed in brackets. The detail of the correlation between Lean concepts and industry 4.0 can corresponds with the findings presented in table 2.

Finally, the framework illustrates the balancing act organisations must go through when considering the trade-offs between the enables and barriers of Lean 4.0, which is depicted with a scale at the top of the pyramid. Thereby encouraging organisations to master the enables while the overcome the barriers of Lean 4.0 implementations.

This framework provides a high-level overview of the levels and considerations needed to guide South African organisations during Lean 4.0 implementations.

5 CONCLUSION

As South African stands on the brink of change, with technological advancements reshaping the international manufacturing landscape, Lean 4.0 provides organisations an approach to add value during their digital transformation. This study collected and documented available literature on the scope, benefits, barriers and enables of Lean 4.0, resulting in the design of a guidance framework for implementation in South Africa.

During this study, it was found that there are various benefits, barriers and enables of Lean 4.0. It was also found that organisations need to implement Lean philosophy first, then introduce Industry 4.0 concepts, to improve the chances of successful implementation of Lean 4.0. Moreover, this study incorporated the South African cultural element of humanness (Ubuntu) into the implementation framework to increase buy-in from employees.

While this study provided a fulsome analysis of the studies uncovered during the SLR process, it is worth noting that the findings were limited to the selected databases. Therefore, it is recommended that future studies expand to include other databases. This study explores adding a South African level to the implementation strategies of Lean 4.0; however, it is suggested that other studies explore this in different country contexts.

This study utilised an SLR to find the relevant literature. However, this revealed that the overwhelming majority of the studies were from the manufacturing industry. While this could be attributed to the large footprint that both Lean and Industry 4.0 share in the manufacturing research sphere; it is also indicative of the need for more research and examples of Lean 4.0 in different sectors and industries. Moreover, it would worth investigating how the different Lean 4.0 concepts play out in service industry.

During this study, the overlap between Lean and Industry 4.0 (which is Lean 4.0) was investigate. However, emerging trends in research suggest that the overlap between Lean and Industry 5.0 is an up-and-coming concept. Ergo, it is suggested that future research explore the scope and meaning of Lean 5.0.

In order to advance in this technological era, South African organisations need to improve their competitive advantage in the international manufacturing sphere. The Lean 4.0 implementation framework illuminates the path forward with an opportunity to do this, without leaving their employees behind and with a South African twist.

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7 APPENDIX A

Table 4: Data extracted from applicable literature

#	Title	Authors and year	Barriers	Enablers	Benefits	Lean 4.0 Tools	Industry 4.0 Technology	Country	3rd world Application	Industry	Future Research	Reference
1	Exploring relationships between Lean 4.0 and manufacturing industry	Javaid et al. (2022)	X	X	X	X	X	India	X	Manufacturing	X	[18]
2	Lean 4.0': How can digital technologies support lean practices?	Cifone et al. (2021)	X		X		X	Italy German UK		Manufacturing	X	[8]
3	Lean 4.0 implementation framework: Proposition using a multi-method research approach	Bueno et al. (2023)	X	X	X	X	X	Brazil France Australia Argentina	X	Manufacturing	X	[19]
4	Lean 4.0: A New Holistic Approach for the Integration of Lean Manufacturing Tools and Digital Technologies	Valamede et al. (2020)	X	X	X	X	X	Brazil	X	Manufacturing	X	[20]
5	Implementation of a Lean 4.0 Project to Reduce Non-Value Add Waste in a Medical Device Company	Foley et al. (2022)	X		X		X	Ireland Italy India		MedTech	X	[21]
6	An approach to design a semi-automated assembly line for the automotive industry implementing the Lean 4.0 concept	Markov et al. (2022)	X		X		X	Bulgaria	X	Automotive	X	[22]

7	Implications of Lean 4.0 Methods on Relevant Target Dimensions: Time, Cost, Quality, Employee Involvement, and Flexibility	Dillinger et al. (2022)			X	X	X	Germany		Manufacturing	X	[23]
8	Lean 4.0-A conceptual conjunction of lean management and Industry 4.0	Mayr et al. (2018)	X			X	X	Germany		Manufacturing	X	[24]
9	Competence Requirements in Manufacturing Companies in the Context of Lean 4.0	Dillinger et al. (2022)	X	X	X	x	X	Germany		Manufacturing	X	[25]
10	Lean 4.0: A Digital Twin approach for automated cycle time collection and Yamazumi analysis	Pinheiro et al (2023)			X	X	X	Portugal		Manufacturing	X	[26]
11	Lean and industry 4.0: A leading harmony	Naciri et al. (2022)	X	X	X	X	X	Morocco	X	Automotive Aerospace	X	[27]
12	Lean 4.0: Synergies between Lean Management tools and Industry 4.0 technologies	Elafri et al (2022)	X	X	X	X	X	Morocco	X	Manufacturing	X	[28]
13	Industry 4.0 and Lean Manufacturing - a systematic review of the state-of-the-art literature and key recommendations for future research	Saad et al. (2023)	X	X	X		X	UK		Manufacturing	X	[3]
14	Adoption of Industry 4.0 and lean concepts in hospitals for healthcare operational	Ilangakoon et al. (2022)			X	X	X	Sri Lanka Australia	X	Healthcare	X	[29]

	performance improvement											
15	Integration of Lean manufacturing and Industry 4.0: a bibliometric analysis	Kumar et al. (2024)			**X**	**X**	**X**	India	**X**	Manufacturing	**X**	[30]
16	Industry 4.0 technologies integration with lean production tools: a review	Singh et al. (2023)	**X**	**X**	**X**	**X**	**X**	India	**X**	Manufacturing	**X**	[31]

Appendix B

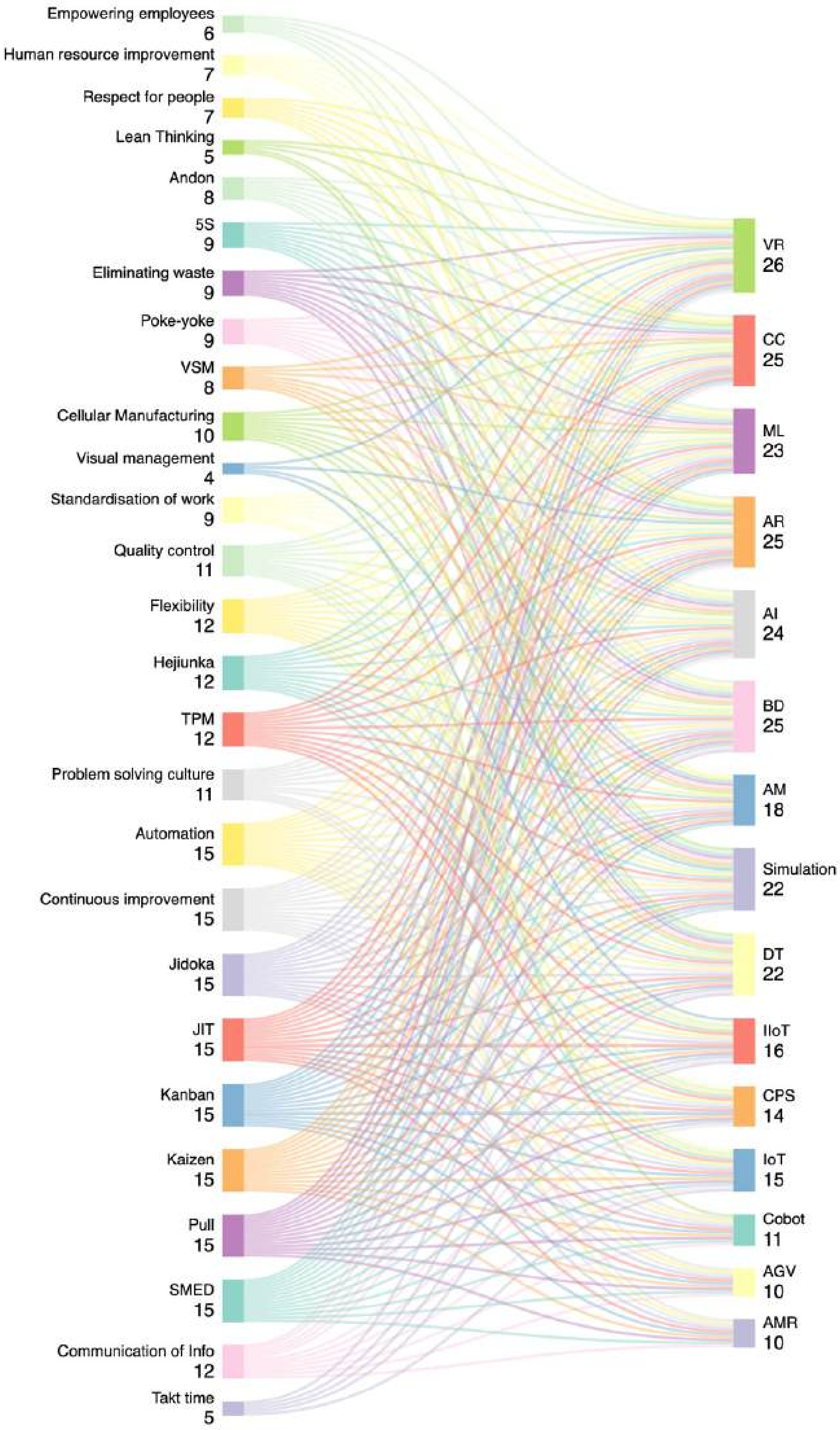

Figure 7: Sankey chart of the relationship between Lean concepts and Industry 4.0 concepts

COMPARISON OF ARCHIMEDES AND MICROSCOPIC IMAGING METHODS FOR THE MEASUREMENT OF RELATIVE DENSITY OF 304SS ADDITIVELY MANUFACTURED PARTS

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ABSTRACT

This paper examines the precision of density measurements for samples produced through Selective Laser Melting (SLM). To achieve this, the study employs the accessible and cost-effective Archimedes method and microscopic imaging techniques. The research follows a well-structured methodical approach, carefully describing the methods employed to facilitate the reader’s understanding. Relative density measurements are obtained for 304SS SLM printed samples using the two mentioned methods, followed by a t-Test analysis to validate a stated hypothesis. The findings demonstrate that both methods produce similar relative density measurements, as evidenced by the non-significant p-value derived from the t-Test. However, the study proposes that the Archimedes method be prioritized for density measurements due to its high repeatability and lower resource requirements. This study gives researchers confidence in the two stated methods which they can use for quickly and economically determining the relative density of SLM printed samples.

Keywords: selective laser melting, relative density, microscopic imaging, t-Test

1 INTRODUCTION

In the modern day highly competitive business environment, companies are constantly facing the challenges of mass customization and globalization, which in turn are pushing the traditional industries towards new business models and Industry 4.0 (I4.0) [1]. These technologies can greatly help businesses achieve sustainability in their operations by enabling maximum efficiency and output while minimizing resource utilization. Additive manufacturing (AM) is one of the elements of I4.0, and it has emerged as a promising technology for producing complex and customized components with reduced material waste and production time [2], [3], [4]. AM has been explored in aeronautics, automotive industries, dentistry, medical implants, robotics, and toy-making [5]. It aids designers and manufacturers in creating physical models in a significantly shorter time frame and at a reduced cost compared to conventional methods. This is accomplished by the melting, fusing, or bonding of the feedstock material layer by layer. The building process is done directly from a 3-dimensional CAD file, rather than the conventional subtractive or forming approach [6].

Different publications have categorised AM processes in different ways [5], [6], [7]. However, the common classification is based on the ASTM-F42committee guidelines according to which AM can be classified into seven categories [7]. These categories are powder bed fusion (PBF), vat photopolymerization (VP), binder jetting (BJ), material jetting (MJ), material extrusion (ME), sheet lamination (SL), and directed energy deposition (DED). Selective laser melting which falls under the PBF category is one of the most popular AM processes [8]. This is mainly because the parts produced by this process usually offer enhanced mechanical properties compared to the properties of conventionally produced parts from bulk materials [9]. In SLM, the layer height is the thinnest which offers a relatively improved forming precision [10].

Relative density is a significant response variable in SLM-AM investigations which is used to determine the quality of parts produced by this technology hence it needs to be measured as accurately as possible [11]. The process-based parameters are seldomly varied to get the desired results of relative density, typically the highest relative density, together with other response variables that may be of interest. The most common of these parameters are laser power, scan speed, hatch spacing and layer thickness [12], [13], [14]. There are three main techniques for density measurement of a part: porosity measurement through analysis of optical microscopic images of a cross-section of the part, Archimedes method and X-ray or neutron imaging [9]. In this paper, the authors used only the Archimedes and microscopic imaging because these two methods are easy to carry out and the equipment required is cheaper to acquire as compared to the X-ray scanning equipment. Archimedes is a widely adopted method [15] and it is a non-destructive test (NDT) that considers the as printed sample for density measurements. Microscopic imaging on the other hand requires the sectioning of the printed sample and optical microscopic images of parts of the cross-section are then analysed and used to estimate the porosity of the whole sample assuming that whatever characterisation is observed on the analysed part is uniform throughout the sample.

304SS is a widely used stainless steel due to its excellent corrosion resistance, mechanical properties, and cost-effectiveness [16], [17]. The excellent corrosion resistance exhibited by this material is because of its high Chromium content [18]. These properties make SS304 a desirable material for implementation in a wide range of industries including automobile, chemical and nuclear industries [16], [17], [18], [19]. In this study, SLM technology was used to fabricate the 304SS samples that were used to carry out the necessary experimental work. The advantages of the chosen technology and material have been highlighted above. The aim of this paper is to compare the relative density measurements of the samples fabricated by SLM technology and test the statistical significance of the above-mentioned methods. This work should help researchers decide the method they choose to use depending on the scope of their own research work and help give them confidence in their results. The methods can also be adopted in the industry as cheaper alternatives for calibrating different AM procedures.

2 METHODOLOGY

A comprehensive overview of both methods under investigation is presented in Figure 1. This aims to showcase the complexities of the two methods explored in this research. This visual representation acts as a guide, providing a broad perspective of the methodologies under investigation. The next subsections provide a more in-depth description of each step depicted in the figure.

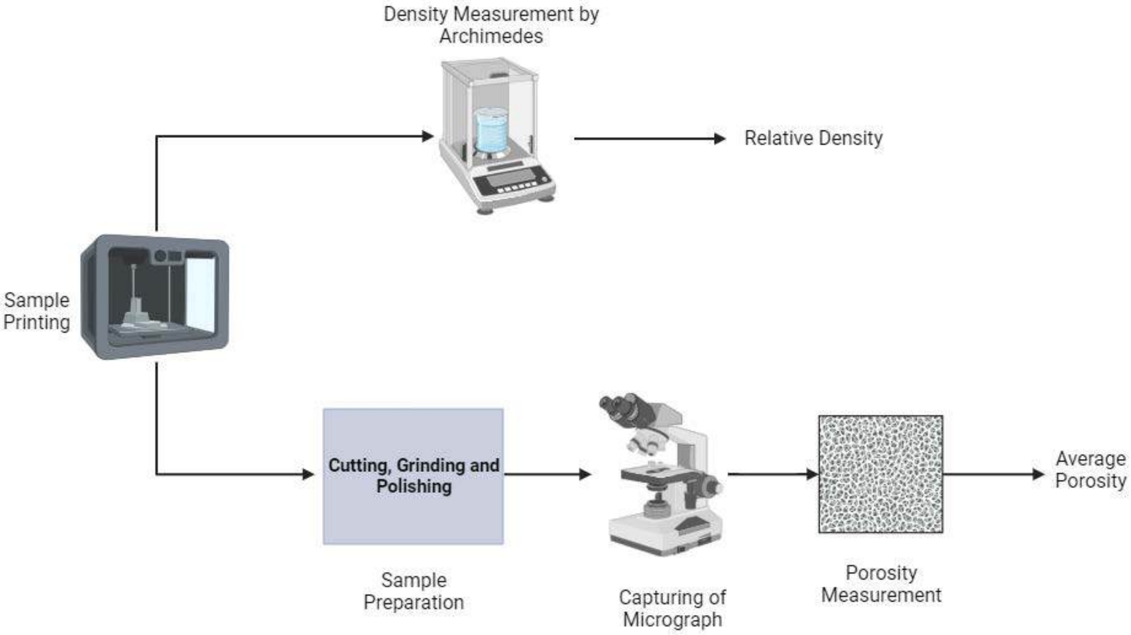

Figure 1: Methodology Flow Diagram.

2.1 Powder Feedstock

The 304SS powder used in this study was supplied by AVIMETAL AM. The chemical composition as well as the volume fraction of this powder are given in Table 1 and Table 2, respectively. The volume fraction values of this feedstock are within the typical range recommended for SLM powders [20]. The major elements in this composition are similar to what other researchers have used in their work [21], [22].

Table 1: Chemical composition of 304SS powder feedstock.

Element	Fe	Cr	Ni	Mn	Si	P	C	S	O	N
Composition (wt %)	Bal	18.62	10.50	1.12	0.20	0.01	0.01	0.005	0.077	0.105

Table 2: Particle sizes volume fraction.

Volume Fraction (%)	Particle Size (µm)
D_{10}	17.4
D_{50}	30.2
D_{90}	50.9

Figure 2 shows the spherical particulate morphology of the powder used in the study; most of the particles had smooth surfaces; however, it can be observed that some of the particles are stuck together, and most of the particles are not perfect spheres. This arises from the manufacturing processes which are used to produce the laser powder bed fusion powders [23]. The particles which made up the feedstock powder had a positively skewed particle size distribution. Such powders with a high content of fine particles are reported to be good for high part densities and good scan surface [24], [25]. The cumulative particle size distributions (PSD) and volume frequency percentage of the feedstock powder are shown in Figure 3. The apparent density was 4.48 g/cm^3, while the Hall flow rate was 17.20s/50g.

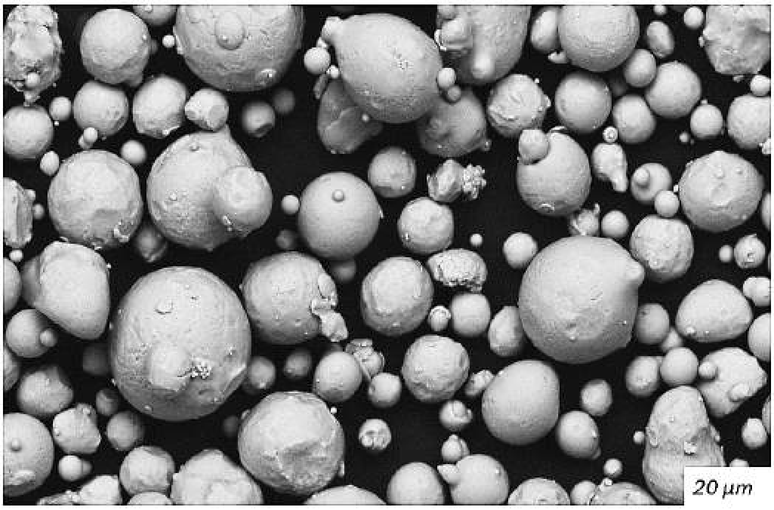

Figure 2: SEM Image Showing the Morphology of 304SS Powder Particles.

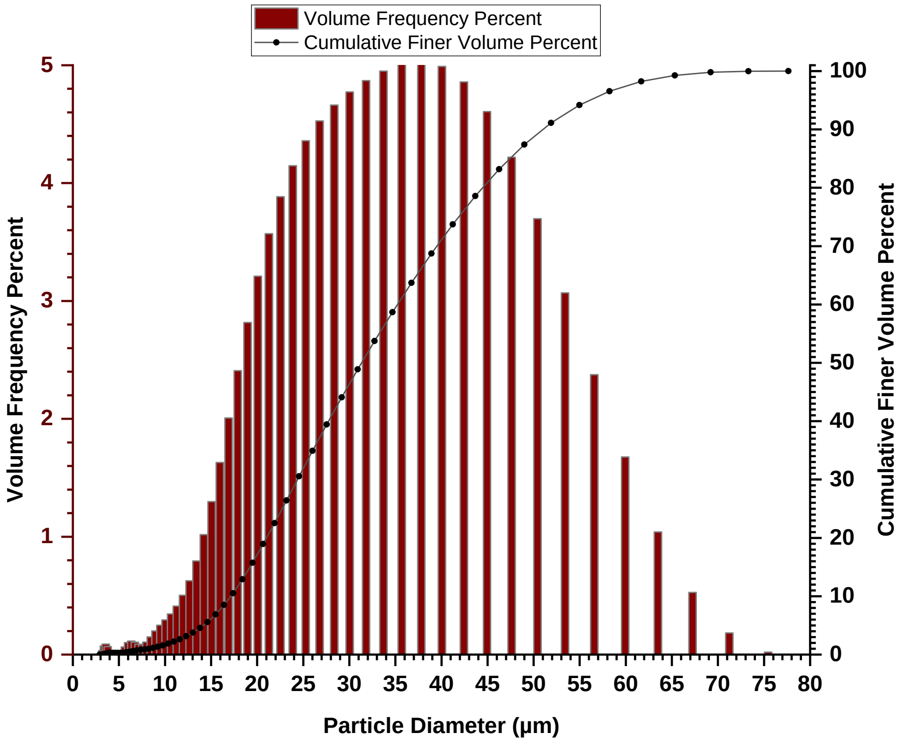

Figure 3: Cumulative Particle Size Distribution and Volume Frequency Percentage.

2.2 SLM Process

The SLM printing was done using the GE Additive Concept Laser Mlab 200R SLM machine. This machine is suited for good surface finishes and for creating intricate designs. Its specifications are presented in Table 3.

Table 3: Concept Laser Mlab 200R specifications.

Parameter	Machine Specs
Build Volume	100 x 100 x 100 mm
Scanning Speed	Up to 7000 mm/s
Focus Diameter	75
Laser Power	Up to 200 W
Coater Blade Material	Rubber

The process parameters from literature [18], [22], [26], [27] were used to get the sets of parameters for printing. Central composite design (CCD) in Stat-Ease Design Expert was used to predict these parameters and get the experimental runs. It is important to note that past research that used parameters with laser power greater than 200W was not considered since the SLM machine used in this work has a maximum laser power capacity of 200W. This study varied three factors to run the design of experiments in the Design-Expert software; simulations: laser power which determines the amount of energy delivered to the powder bed, influencing the melting and bonding of the powder particles, scanning speed which affects the interaction time between the laser and the powder bed, thus influencing the heat input, melting behaviour, and solidification rate in the SLM process and hatch distance which affects the overlap of melted tracks and the uniformity of energy distribution across the layer in SLM. In this study, the layer thickness was kept constant at 30 µm. The investigation used a wider range of values for the factors to get a true representation of how the relative density would change according to the varying process parameters. Table 4 shows the selected lower (L) and higher (H) values for the three parameters which were initially used for the CCD design of experiment (DOE) in the Design-Expert software.

Table 4: Parameters processing window.

Process Parameter	Lower Values (L)	Higher Values (H)
Laser Power (W)	90	200
Scanning Speed (mm/s)	700	1500
Hatch Spacing (mm)	0.05	0.1

The parameters given above were run in Design-Expert. Table 5 shows the different sets of processing parameters which were obtained and used to print the test sample runs. To eliminate any potential bias that could arise from assigning a particular order, the experiments were randomized according to the standard order [28].

Table 5: Processing parameters of the samples.

Run	Laser Power (W)	Scanning Speed (mm/s)	Hatch Distance (mm)
1*	90	1500	0.05
2	200	1500	0.05
3	145	1100	0.05
4	90	1100	0.075
5	200	700	0.1
6	145	1500	0.075
7	90	700	0.05
8	200	1100	0.075
9*	90	1500	0.1
10	200	700	0.05
11	145	700	0.075
12	145	1100	0.1
13	200	1500	0.1
14	90	700	0.1

Run 1 and run 9 failed to print and had to be omitted from the building process. The failure of these two runs can be alluded to their low laser power and high scanning speed combinations. This might have resulted in the laser not having sufficient dwell time on the powder interface to sufficiently melt and fuse it.

2.3 Density Measurements

a) Archimedes Method

This method is non-destructive in the sense that the printed sample does not need to be cut/sectioned in any way in preparation carry take the measurement. These experiments were carried out following the ASTM B311 standard. To carry out the measurement, first the test specimen is weighed in air (mass A) using a KERN ABT 120-5DM analytical balance. Next, a container of water is set up over the balance pan, the test specimen support is suspended in distilled water, and the immersed test specimen and support are weighed (mass B). The support is weighed in distilled water at the same depth without the specimen (mass C). The temperature of the water is recorded to the nearest 0.5 °C and its density (E) at that temperature is determined from a provided table. These measurements enable the calculation of the density of the test specimen using the principles of buoyancy as shown in Equation 1 [29].

$$\boldsymbol{Density} = \frac{(\boldsymbol{A} \times \boldsymbol{E})}{(\boldsymbol{A} - \boldsymbol{F})} \tag{1}$$

Where F = (Mass B - Mass C)

b) Sample Preparation and Porosity Measurement

For porosity measurements, the samples were cut into transverse and longitudinal cross-sections, as shown in Figure 4, using a precision cutter. The cut samples were mounted into cylinders using resin. These mounted samples underwent mechanical polishing following the Struers steps for the metallographic preparation of stainless steel [30]. After polishing, optical microscopic images were captured using a known magnification on the Olympus GX51 inverted metallurgical microscope. For this exercise, five images per cross section were captured at different locations from each specimen at both cross sections to approximate porosity over the selected surface, and hence that of the whole sample. Porosity was measured using ImageJ, a license-free software, as described in literature [31]. After capturing the microscopic images using a known magnification, the software is calibrated using the scale on the image this is to ensure accurate measurements. After the software has been calibrated, a thresholding technique is applied to the image. This distinguishes between material and the pores. This thresholding step heavily relies on the user's input. Lastly, use the "analyse particles" function to obtain the porosity percentage across the analysed area. Generally, the porosity values obtained using this approach depend on the authors’ choice of lens magnification as well as the number of photos taken at a specified magnification level [32]. To account for this five different photos taken at the same magnification level were used to analyse the SLM printed samples. This approach aimed to reduce the influence of using just a single photo on the overall analysis.

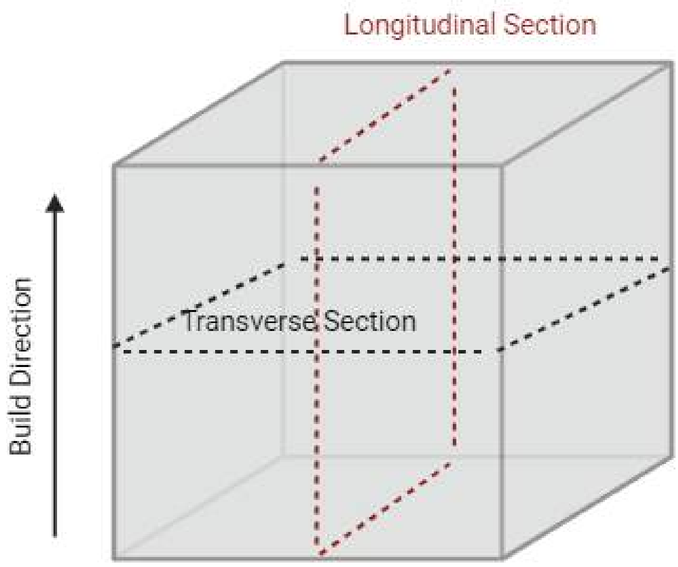

Figure 4: Representation of the Longitudinal and Transverse Sections.

2.4 Statistical Test

The independent sample statistical t-Test analysis was used to test if the difference between the measurements which were obtained by the two different methods was statistically significant. The significance threshold is typically p=0.05. The two hypotheses for this investigation were defined as follows:

- **Null hypothesis (H_0):** Two methods means are equal ($\mu_A = \mu_I$).
- **Alternative hypothesis (H_A):** Two methods means are not equal ($\mu_A \neq \mu_I$).

The analysis was run in Excel. If the p-value reported from the t-Test is less than or equal to the significance level, reject the null hypothesis, as this would mean that the difference between the two means is statistically significant; otherwise, accept the alternative hypothesis.

3 RESULTS AND DISCUSSIONS

a) Archimedes Method

Three measurements of masses A, B and C were taken for each sample, and these were used to calculate three density values for the sample. These density values were then averaged and divided by the theoretical density value of 304SS (7.93 g/cm^3 [33]) and multiplied by 100 to get the relative density of the sample. Figure 5 shows the recorded average density and relative density for each of the twelve measured samples.

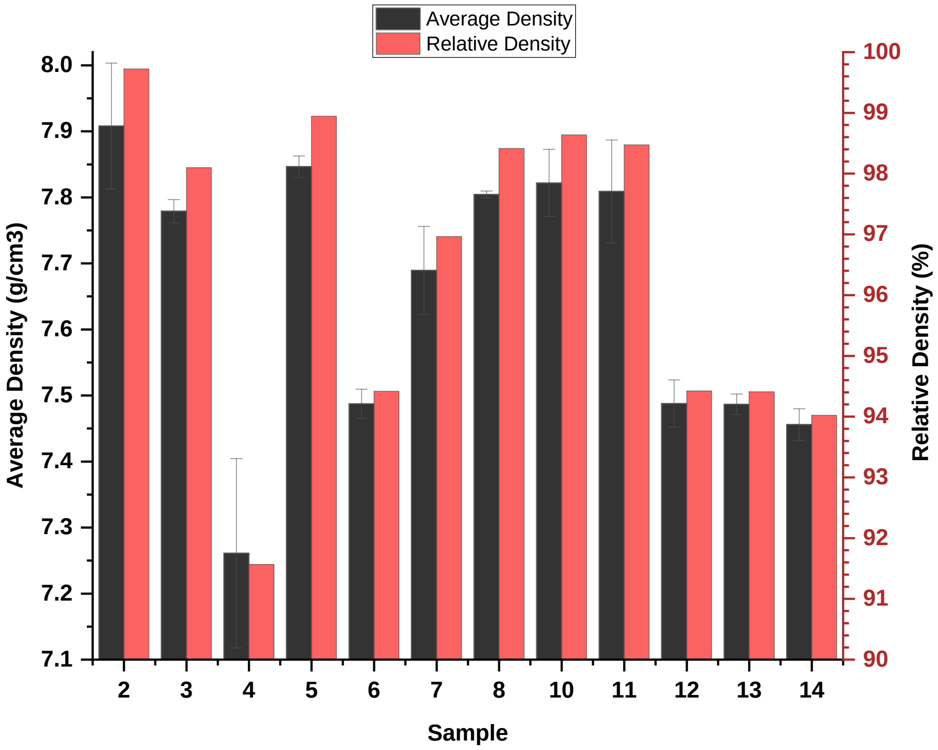

Figure 5: Archimedes Density Measurement Results.

b) Microscopic Imaging

Ten random microscope images were analysed in ImageJ to measure the porosity of the sample over the exposed area. The average of the longitudinal and transverse sections of the sample were then combined to give the combined average porosity of the sample. Figure 6a and 6b shows these summarised sample measurements results. The porosity values obtained using the microscopic imaging were then used to calculate the relative densities of the samples using the equation below [34].

$$Relative\ Density = 100 - Combined\ Average\ Porosity\ Percentage \qquad (2)$$

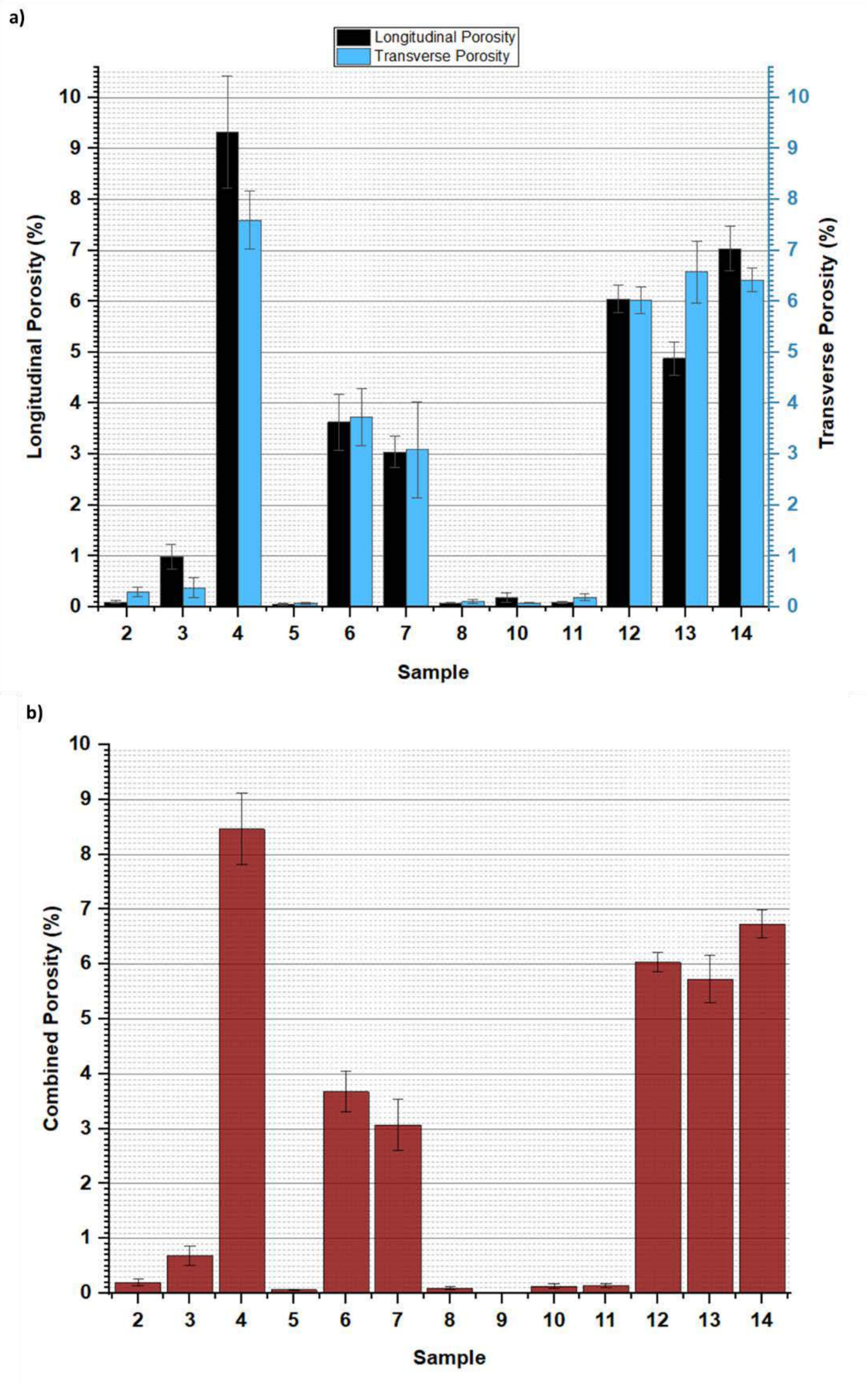

Figure 6: a) Longitudinal vs Transverse Porosity b) Combined Sample Porosity.

The t-Test output table, Table 6, shows that the reported p-value, 0.63, is greater than the significance value, p = 0.05, therefore the null hypothesis was accepted for this work. This means that both the methods discussed can be used for the measurement of relative density of SLM printed parts.

Table 6: t-Test output.

Observations	12
Df	21
t Stat	0.490929
P(T<=t) one-tail	0.314284
t Critical one-tail	1.720743
P(T<=t) two-tail	0.628568
t Critical two-tail	2.079614

It is also important to look at the complexities and considerations for both methods in detail. Figure 7 shows a comparison of the relative density measurements obtained by both the Archimedes and microscopic imaging methods. It can be noted that the results recorded using these two methods are not consistent with each other. The Archimedes method on its own had very low standard deviation values for the three measurements which were taken whereas the microscopic imaging method had relatively high standard deviation values, a comparison of the standard deviation values obtained by these two methods is presented in Figure 8. This observation gives confidence that the Archimedes method gives more accurate and reproducible results [35]. Additionally, Archimedes approach considers the whole geometry of the sample under investigation whereas microscopic imaging only focuses on as small section on the surface and assumes that whatever trend is observed on that surface is consistent throughout the whole body of the sample which may not always be true in most cases. It is worth pointing out that there is room for improvement with the imaging approach and high repeatability and accuracy may be achieved if a more standardised and advanced approach is used.

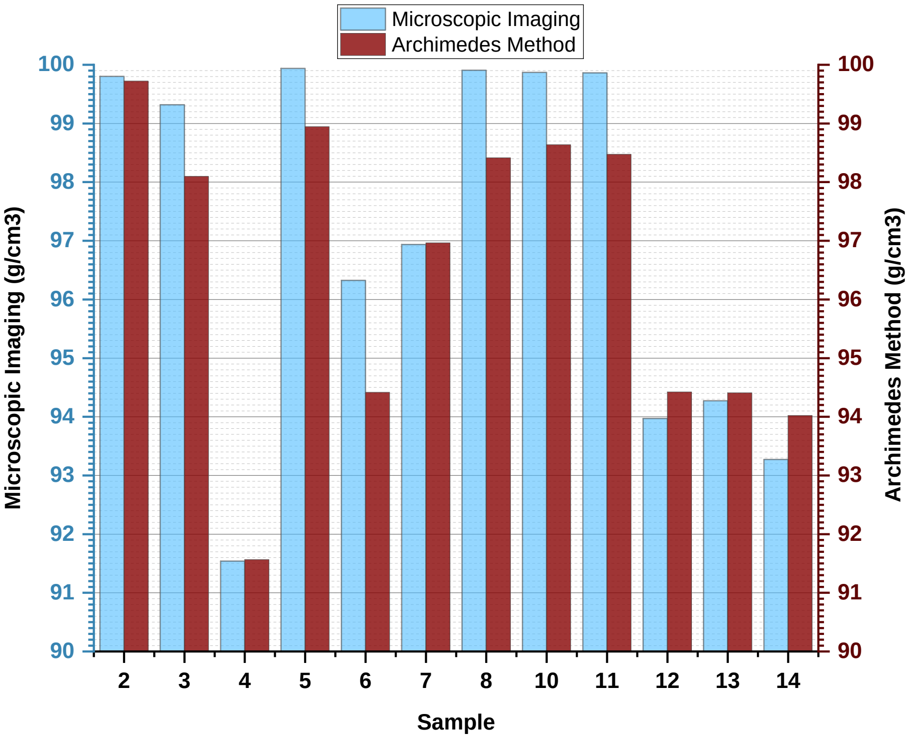

Figure 7: Archimedes Method and Microscopic Imaging Relative Densities.

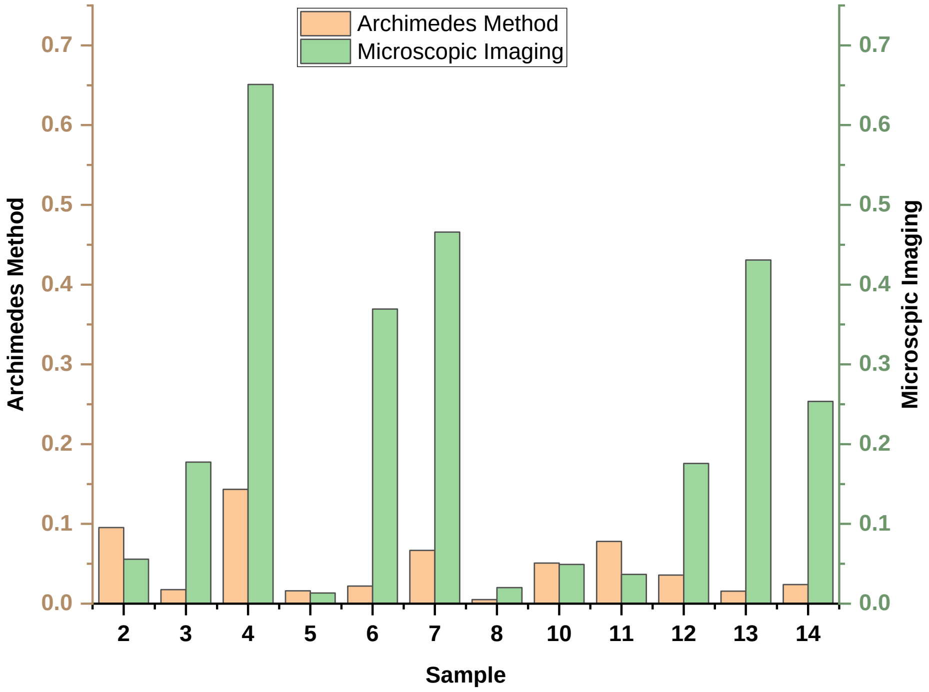

Figure 8: Comparison of Standard Deviation in Porosity Measurements Obtained by the Two Discussed Methods.

The authors identified various possible sources of error in measurements using both methods. In order to address potential errors in the Archimedes method, three measurements were conducted, and their average was used as the measurement value. Similarly, for microscopic imaging, five photos were consistently taken at the same magnification level to obtain five measurements, and their average was considered as the sample measurement. The multiple measurements allowed for the calculation of standard deviation for the porosity values, indicating the reliability of the results.

In general, it is important to understand that Archimedes is a non-destructive testing approach, relatively cheap and quick approach whereas the microscopic imaging is a destructive meaning that it requires relatively more preparatory work before the actual results can be obtained [36]. The preparatory work involved includes sample preparation and the capturing of the microscopic images. This process can be quite complex and time consuming compared to the Archimedes approach. Microscopic imaging also requires a lot of resources and consumables. These consumables include cutting disk and cutting oil for the precision cutter, mounting resin for the automatic mounting machine as well as grit papers and polishing lubricants for the final grinding and polishing.

4 CONCLUSION

This study has statistically proven that both methods investigated can be used for relative density measurement of 304SS SLM printed parts. This is indicated by the insignificant p-value of 0.63 for the stated null hypothesis. However, when prioritizing the measurement of relative density with a focus on precision and reliability, the Archimedes method emerges as the superior choice. This is due to its ability to produce consistent results, as demonstrated by the low standard deviation values. Also, the Archimedes method requires fewer resources and less labour, which facilitates faster acquisition of results compared to the more complex microscopic imaging approach. Overall, the selection between these methods depends on the specific objectives at hand. If the goal is to explore the finer characterization of a material's pores, the microscopic imaging approach proves to provide a detailed and comprehensive characterization that goes beyond relative density alone. Future studies should focus on using multiple photos taken at different heights along the build direction or at different longitudinal sections. The current study used photos taken at the same height as well as the same longitudinal section.

Declaration of competing interest

Both authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The author[1] was enrolled for an M Eng. (Research) Industrial Engineering degree in the Department of Industrial Engineering, Stellenbosch University.

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A SIMULATION-BASED APPROACH TO ILLUMINATE INVENTORY CONTROL DECISIONS: POLICY IDENTIFICATION AND OPTIMISATION FOR STAKEHOLDER INFORMED STRATEGIES

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ABSTRACT

This paper utilises a simulation-based approach to address challenges in identifying inventory control strategies for modern manufacturing companies. It follows a systematic framework, beginning with a critical analysis of traditional inventory control methods and their inherent complexities. By drawing from diverse research sources, it investigates the root causes of shortcomings in current inventory management practices. The study presents a dynamic simulation model designed to capture the intricate dynamics of inventory control policies. Leveraging stakeholder engagements and input data, the simulation model functions as a virtual laboratory for testing and refining strategies. Evaluation of these strategies identifies strengths, weaknesses, and opportunities for optimisation. By integrating rigorous analysis with stakeholder insights, the resulting strategies are theoretically robust, practically feasible, and aligned with organisational goals. The paper offers a comprehensive framework for developing informed and adaptive inventory control strategies, combining empirical research with simulation-based insights. The findings aim to advance the field of inventory management, offering actionable recommendations for optimising inventory control practices in manufacturing contexts.

Keywords: Inventory Control Policies, Policy Identification, Simulation-Based Methodology, Stakeholder-Informed

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1 INTRODUCTION

From Axsäter [1], it can be learned that inventory control is the conductor of a stock orchestra. It orchestrates the seamless flow of goods within an organisation. Axsäter further expresses how crucial it is to manage the flow of materials from suppliers to customers. A lot of money is invested in inventory, including raw materials, work-in-progress, and finished goods. Controlling inventory better can save costs and give manufacturing companies an edge by reducing costs, improving customer satisfaction, and enabling quicker responses to market changes [2]. Chaouch [3] explains that inventory control does not happen in isolation. It involves handling purchasing, production, and marketing. Often, there are conflicting goals. Ideally, it is necessary to keep inventory levels low to save money, but the purchasing department might want to buy in bulk to get discounts.

2 PROBLEM, AIM, OBJECTIVES AND STUDY CONTRIBUTIONS

This paper will explore the various aspects of enhancing inventory management practices in the upcoming sections. Beginning with a root cause analysis (RCA), the focus will be on uncovering the underlying factors contributing to inventory inefficiencies. The discussion will then progress to existing inventory control policies, providing an overview of current methodologies to lay the foundation for developing more effective strategies. Following this, the conceptual design of the simulation model will be outlined, and its theoretical framework will be explained. Practical implementation of the simulation model will be discussed in detail, alongside verification and validation techniques, to ensure its accuracy and reliability. Subsequently, simulation evaluation will analyse the outcomes of simulation experiments to inform the policy implementation plan, facilitating the translation of findings into actionable strategies. Finally, the paper will provide conclusions, recommendations, key insights, and topics for future research and application in inventory control optimisation.

2.1 Industry Gap

The absence of inventory control can result in a multitude of adverse consequences, including heightened costs, compromised inventory tracking, imbalanced stock levels, prolonged time consumption, strained vendor-customer relations, diminished employee productivity, impaired decision-making processes, decreased warehouse organisation, extended lead times, stockouts, and delays in shipping and delivery [4].

2.2 Research Gap

The literature does not have thorough studies on the creation and use of dynamic simulation models to identify inventory control strategies in modern manufacturing. This paper addresses the gap by combining empirical research and simulation-based insights to provide practical recommendations for improving or implementing inventory management practices. By testing and validating strategies in a simulated environment that reflects real-world complexities, this research contributes to advancing both theory and practical applications in inventory management within manufacturing contexts.

2.3 Aim

This paper aims to develop a simulation-based approach to improve inventory control decisions, identify policies, and optimise strategies to address the complexities of implementing inventory control within a manufacturing company.

2.4 Objectives

This paper sets out to achieve the following objectives:

- To outline what RCA tools can be used to identify the underlying factors contributing to inventory inefficiencies.
- To explore existing inventory control policies, providing an overview of current methodologies.
- To outline the design and execution of a dynamic simulation model to capture the intricate interplay between inventory control policies.
- To evaluate and compare inventory control policies to identify strengths, weaknesses, and opportunities for optimisation.
- To develop a policy implementation plan based on simulation outcomes, facilitating the translation of findings into actionable strategies.

2.5 Contribution to Industry

The paper aims to equip manufacturing companies with the following tools and insights:

- Enhanced Decision-Making: By providing a comprehensive framework for developing informed inventory control strategies, companies can make better decisions regarding inventory management, leading to improved operational efficiency and cost savings.
- Risk Mitigation: The simulation-based approach allows companies to assess the potential risks associated with different inventory control policies, enabling them to mitigate risks such as stockouts or excess inventory proactively.
- Adaptability: Companies can use the insights gained from the simulation model to adapt their inventory control strategies in response to changing market dynamics, ensuring they remain agile and competitive.
- Optimised Resource Allocation: By identifying optimised inventory control policies, companies can allocate resources more effectively, minimising waste and maximising productivity.
- Stakeholder Involvement: The stakeholder-informed approach ensures inventory control strategies align with organisational objectives and stakeholder preferences, fostering buy-in and collaboration across departments.

2.6 Industry Case Studies

Case studies are powerful tools for illustrating the practical advantages of inventory control within manufacturing contexts. Three such case studies arise, each offering insights into the transformative impact of implementing effective inventory control strategies.

a) Company X (Animal Feed Manufacturer) [5]:

The initial case study examines an animal feed manufacturing plant that struggled to meet its monthly production target of 15,000 tonnes. Using a simulation-based approach, the study developed tailored inventory control policies to address this challenge. The evaluation of these policies meticulously tackles the production capacity shortfall faced by Company X's feed plant. The (s, S) min/max inventory policy emerged as a standout performer, showcasing its ability to boost production capacity, reduce average inventory levels, and shorten waiting times for products awaiting production. This comprehensive evaluation provided valuable insights into the effectiveness of inventory control policies in addressing Company X's production shortfalls.

b) Company Y (Manufacturer of consumer products for big boxes) [6]:

This case study examines a manufacturing plant's struggles with inventory control and accounts receivable management following a significant ownership change. The company faced challenges maintaining accurate inventory counts, leading to a substantial financial hit and increased stakeholder scrutiny. The study identified key recommendations to improve inventory control through meticulous analysis, such as implementing cycle counting and providing incentives for warehouse workers. Additionally, the study addressed accounts receivable chargebacks by creating a logbook to track reasons and ensure prompt follow-up on discrepancies. These measures led to significant improvements, including reduced chargebacks and enhanced profitability. The study emphasises the importance of individual accountability and engagement in driving organisational success, highlighting the cumulative impact of small procedural changes on overall profitability.

c) Company Z (Start-up company that commercialises gift items) [7]:

The study found that implementing an inventory control policy outperformed focusing solely on container sizes, offering variable order sizes. A manual method was also devised to integrate minimum order quantities into Joint Replenishment Problems (JRPs), even with complex transportation costs. By exploring the use of intermediate stocks to mitigate minimum order constraints, the study achieved improved supply chain control, resulting in shorter lead times and enhanced inventory strategies. Implementing the inventory control policies led to substantial cost savings of up to 44%.

3 ROOT CAUSE ANALYSIS TOOLS

Andersen [8] expresses that RCA comprises a systematic method for problem-solving within various disciplines. In contrast to traditional approaches that focus on the problem's outward signs, RCA looks deeper to find the root cause of a problem. By preventing recurrence, this proactive strategy seeks to maximise resource allocation and performance [8]. The four steps of the RCA process are usually problem formulation, data gathering, data analysis, and solution execution.

By examining the underlying causes of inventory-related difficulties, RCA can be utilised in inventory control to verify whether a manufacturer is experiencing problems with inventory control policies. Confirming the presence of inventory control problems within a company through RCA is a crucial prerequisite before determining relevant inventory control policies.

From a study done by Percarpio [9], it can be learnt that finding the source of complex inventory problems requires a diversified RCA strategy. This calls for using several instruments, each of which has a unique benefit in revealing the underlying causes of disparities. Andersen [8], and Percarpio [9] have identified various inventory control RCA tools that can be employed to ascertain inventory control as a root cause of the challenges encountered by a manufacturer.

These RCA tools consist of the following [8], [9]:

- Pareto Charts: Identify significant contributors to inventory issues (e.g., stockouts, overstock) for focused solutions.
- FMEA: Analyse potential failures and their consequences on inventory.
- 5 Whys: Ask "why" repeatedly to peel back layers and reach the root cause of inventory problems.
- Fishbone Diagram: Organise potential causes (People, Methods, Machines, Materials, Measurement, Environment) visually.
- Fault Tree Analysis: Map how numerous factors lead to specific inventory control failures.
- 8D Report: A structured framework to document the entire RCA process for inventory control issues.
- DMAIC: A problem-solving methodology (Define, Measure, Analyse, Improve, Control) applied to inventory control.
- Scatter Diagram: Reveal relationships between factors like inventory discrepancies and sales forecasts.

4 EXISTING INVENTORY CONTROL POLICIES

After selecting RCA tools, looking at relevant inventory control policies that can be presented within a simulation environment is essential. Hopp's [10] study explores various inventory control policies, offering valuable options for easy implementation. Relevant control policies are followed in the proceeding sections.

4.1 Reorder Point/Order Quantity (R, Q)

An order for a fixed quantity (Q) is placed per the reorder point/order quantity inventory control policy when the inventory level reaches a reorder point (R). By simulating alternative values of R and Q, the user can assess how well this technique performs under different demand patterns, lead times, and safety stock levels. The simulation's insights into the trade-offs between holding costs, stockouts, and the frequency of replenishment orders will make it possible to identify the optimal (R, Q) combination.

4.2 Min/Max (s, S)

The min/max inventory control policy maintains an inventory level (s) and a maximum level (S). When inventory drops below the minimum level (s), a replenishment order is sent to return the inventory to the maximum level (S). The simulation will examine several (s, S) variables to determine how they impact inventory costs, service levels, and order frequency. The goal is to find the best (s, S) values that strike a compromise between holding costs and stockouts.

4.3 Periodic Order Up To (T, S)

Orders are placed regularly (T) per the periodic order up-to-inventory control policy to increase the inventory level to a maximum level (S). In the simulation, one can experiment with different time intervals (T) and maximum inventory levels (S) to observe how they impact stockouts, order frequency, and inventory costs. The simulation will assist in determining the best combination of (T, S) to minimise holding costs and ensure sufficient stock to meet demand.

By giving a manufacturer, a platform to assess and contrast various inventory control policies, the deliverable of an inventory control Discrete Event Simulation can help determine the best-suited inventory control policy. Such a simulation will enable the analysis of the three inventory control policies.

5 SIMULATION MODEL CONCEPTUAL DESIGN

To quote Robinson [11] from a journal published on conceptual modelling: "The conceptual model is a non-software specific description of the computer simulation model (that will be, is or has been developed), describing the objectives, inputs, outputs, content, assumptions and simplifications of the model".

5.1 Data

To guarantee that the inventory control simulation model is accurate and dependable, it should be correctly implemented [11]. To make sure the model can recreate the observed behaviour of the real system, it should be evaluated using a range of input and output data. The following sections stipulate the data that is to be collected for the building of the model.

5.1.1 Quantitative Input Data

Law [12] defines quantitative input data as data comprising numerical information that is observable and quantifiable and is crucial for inventory control at a manufacturing facility:

- Sales Volume: Helps understand demand and optimise production/stocking.

- Cost of Goods Sold: Determines profitability and aids in pricing and cost reduction.
- Lead Time Variability: Helps expect supply chain issues and manage stock levels.
- Production Cycle Time: Monitored to identify inefficiencies and improve customer service.
- Return Rate: Shows product quality issues and impacts profitability. Analysed to improve quality.
- Stock Levels: Maintains a balance between fulfilling demand and keeping carrying costs low.
- Reorder Point: Set to avoid stockouts based on lead times, demand, and safety stock needs.
- Lead Time: Impacts order fulfilment and inventory restocking. Crucial for supply chain management.

5.1.2 Qualitative Input Data

As defined by Law [12], qualitative input data provides descriptive information that aids in placing the quantitative data in its proper perspective~~:~~

- Product Categories: Analyses product impact on sales and inventory.
- Supplier Names: Track supplier performance, identify bottlenecks and negotiate better terms.
- Inventory Locations: Optimise warehouse layout for efficient product allocation and faster order fulfilment.
- Manufacturing Process Steps: Identify inefficiencies and areas for improvement to streamline production and reduce costs.

5.1.3 Quantitative Output Data

The quantitative output data category shows the numerical outcomes and performance indicators from the inventory control simulation at a manufacturing facility [13].

- Stock Levels: Monitor inventory performance, adjust the reorder point, and optimise stock levels.
- Sales Volume: Track business performance, identify seasonal trends, and plan production/inventory effectively.
- Production Cycle Time: Evaluate process efficiency, identify bottlenecks, and shorten lead times for improved customer service.
- Cost of Goods Sold: Monitor production costs, detect cost overruns, and improve cost efficiency.
- Reorder Point: Maintain ideal inventory levels, prompt timely reorders, and prevent stockouts.

5.1.4 Qualitative Output Data

The simulation's qualitative output data provides detailed feedback and assessments. It includes details about seasonal demand trends, supplier reliability ratings, customer comments, and the risk of stockouts or shortages [13].

- Supplier Reliability: Assesses supplier performance, identifies risks, and facilitates backup strategies.
- Seasonal Demand: Tracks demand fluctuations to adjust production, marketing, and inventory.
- Stockout Likelihood: Predicts potential shortages and enables proactive inventory planning.

5.2 Design Requirements

Law [14] asserts that to develop a proficient inventory simulation, it is imperative to fulfil several design requirements:

- Inventory Control: Model the manufacturer's inventory system accurately if one exists.
- Demand Forecasting: Implement forecasting mechanisms based on market trends, historical data, and relevant variables.
- Production Capacity: Ensure the simulation respects manufacturer capacity, including workforce and equipment limitations.
- Raw Material Acquisition: Include systems to procure necessary raw materials for manufacturing.
- Wait Times: Account for delays in the supply chain, including raw material procurement and manufacturing.
- Quality Control: Incorporate techniques to maintain product quality during manufacturing.
- Storage Restrictions: Prevent overstocking or under-stocking based on available storage space.
- Cost Analysis: Enable examination of costs related to raw materials, production, storage, and other relevant fees.

5.3 Simulation Model Selection

Barrett [15] described discrete event simulation (DES) as analysing real-world systems by breaking them into discrete events. Weizhuo [16] demonstrates DES's effectiveness in inventory control, enabling manufacturers to optimise outcomes and minimise stockouts. Paid options like FlexSim and Simio offer user-friendly interfaces and support but lack the cost-free and community-driven development of open-source alternatives. FlexSim facilitates inventory control optimisation, allowing for policy evaluation and efficiency gains.

6 SIMULATION MODEL DESIGN AND EXECUTION

The approach to the design and execution of an inventory control Discrete Event Simulation model consists of two models: a current state model and an inventory control model. A Current State Model will accurately represent the existing inventory control system. This initial model establishes a baseline for comparison and clarifies current limitations. An Inventory Control Model can be built using Discrete Event Simulation principles. This enhanced model will incorporate potential solutions and simulate their impact on the system, identifying the most effective strategies to optimise inventory control for a manufacturer.

6.1 Current State Model

The Current State Model is the benchmark against which proposed inventory control solutions will be evaluated. By meticulously analysing current procedures, limitations, and challenges that restrict a manufacturer from achieving its full inventory capability, this model establishes a foundation for understanding the complexities of the existing system. This analysis forms the starting point for developing a revised inventory control strategy to address the identified problems [14].

6.1.1 System Components

Establishing a robust foundation for the company’s inventory control simulation model begins with identifying key system components such as:

- Inventory Levels: Analyse stock levels, including raw materials, work-in-progress, and finished items.

- Ordering Processes: Understand order steps and quantities, as detailed in Table 15, and estimate arrival intervals through statistical analysis.
- Demand Forecasting: Examine forecasting techniques and sources, utilising all recipes and ingredients to replicate production.
- Inventory Control Policies: Review existing procedures, including replenishment plans and safety stock levels, to simulate inventory replenishment accurately.

Maintaining flexibility in system modelling is vital to ensure accuracy and responsiveness to changes [17]. The following factors are therefore applicable [17]:

- Adaptation to Changes: Consider changes in supplier relationships, demand patterns, and operational limitations.
- Scenario Testing: Test various inventory control policies and techniques under different circumstances.
- Parameters: Use adjustable parameters for easy testing in different settings.
- Sensitivity Analysis: Assess how changes in factors affect inventory control performance.
- Continuous Improvement: Continuously refine the model based on added information and evolving operational environments.

6.1.2 Model Formulation

A successful model is built upon a foundation of clearly defined needs, which stems from thoroughly investigating the system itself [18]. To ensure the simulation accurately reflects a company’s inventory control system, clear boundaries are established:

- Included Components: The model focuses on critical elements like inventory storage, material flow (incoming deliveries, production, outgoing shipments), ordering and replenishment processes, and supplier lead times.
- Excluded Components: Processes unrelated to inventory control, such as employee management, financial accounting, marketing, and sales, are excluded.

A one-month timeframe creates a practical model aligned with production planning, enabling in-depth analysis, streamlined cost tracking, effective scenario testing, and maximising inventory control effectiveness.

6.1.3 Modelling Assumptions

As Monroe shows [19], a simulation model's assumptions are crucial. They form the model's bedrock and significantly impact its results' validity. Unrealistic assumptions can lead the model astray, providing an inaccurate system picture.

The following are assumptions that may become applicable to the current state model:

- Demand: Demand for products/services is assumed to be constant or follow a known probability distribution (independent or dependent).
- Lead Times: Lead times for material deliveries or processing times are assumed to be constant or follow a known probability distribution.
- Resource Availability: Resources (machines, workers) are assumed to be always available and have a constant processing rate.
- Capacity: Production or service capacity is assumed to be constant and not a limiting factor.
- Quality Control: Perfect quality control is assumed, with no defective products or rework.
- Handling and Storage: Standard handling and storage requirements are assumed for all materials/products.

6.1.4 Model Translation

Once all conceptual steps have been completed, the translation of models becomes workable. Illustrated in **Figure 1** is the current state of a company's inventory system transformed into a discrete event simulation model using the FlexSim process flow environment. This model was developed by the main author and was used to successfully identify a best suited inventory control policy for a manufacturing company.

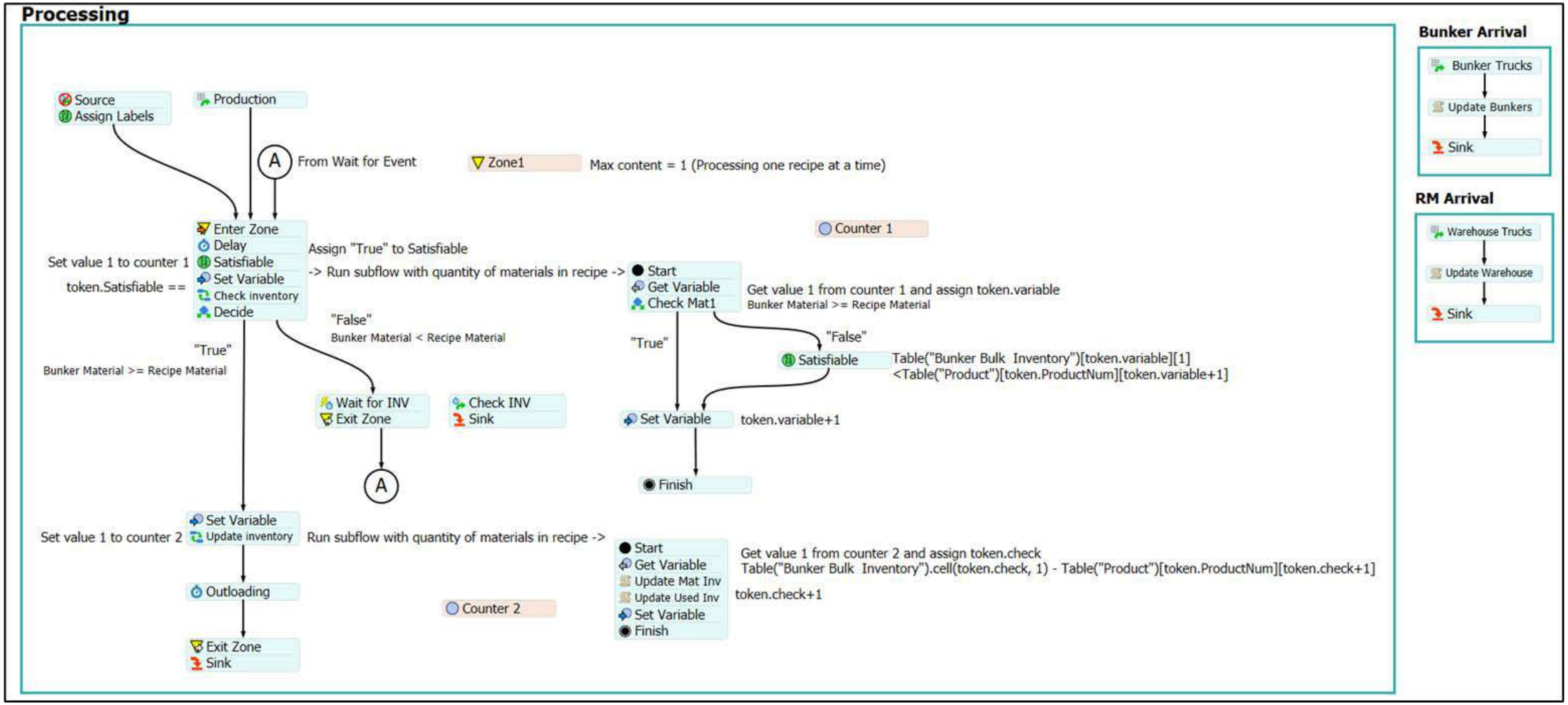


Figure 1: Example of a Current State Discrete Event Simulation Model

a) Discrete Event Simulation Definitions:

The following list aims to improve the understanding of the current state model in **Figure 1** by providing brief definitions of each process flow activity type used in the model [20]:

- **ASSIGN LABELS:** Create or change labels on various objects. Labels are used to store essential data about different objects.
- **COUNTER:** This shared asset allows the modeller to store any data and then read or change that data.
- **CUSTOM CODE:** The Custom Code activity can create custom behaviour in the Process Flow module. Pre-defined picklist options can be selected, or customised code can be written in FlexScript.
- **DECIDE:** Based on defined conditions; the Decide activity sends a token to one or more activities.
- **DELAY:** During the Delay activity, the token will be held for a specified period. The delay time can be fixed or created dynamically using a token value from a statistical distribution.
- **ENTER ZONE:** Tokens can enter the zone through this activity.
- **EXIT ZONE:** Tokens can exit this activity if they are part of a Zone shared asset.
- **GET VARIABLE:** This activity gets the value of a variable shared asset.
- **RUN SUB-FLOW:** The Run Sub Flow activity starts a subprocess flow. Until all its child tokens have finished their sub-flows, the entering token will stay in the Run Sub Flow activity.
- **SCHEDULE SOURCE:** The Schedule Source activity creates tokens according to the Arrivals table's instructions.
- **SET VARIABLE:** This activity determines a variable shared asset's value.
- **SINK:** Tokens are destroyed during the Sink activity, erasing all data.
- **ZONE:** The Zone keeps statistics for activities within a process flow. Optionally, it can restrict access to those activities based on the tokens within those activities.

b) Modelling data sources:

The following data sources in a manufacturing environment are used for the model translation:

- **Formulations:** Detailed formulas for product recipes.
- **Priority:** Rules for sequencing production runs.
- **Inventory Levels:** Real-time availability of raw materials.
- **Properties:** Costs, storage needs, and restocking lead times.
- **Constraints:** Limits on inventory levels and safety stocks.
- **Control Policies:** Replenishment rules like reorder points.
- **Capacity:** Production capabilities and scheduling details.
- **Scheduling:** Plans for production runs and resource allocation.
- **Demand Profiles:** Historical and forecasted customer demand.
- **Customer Orders:** Specific order details influencing production priorities.
- **Time Parameters:** Duration and event triggers for simulations.
- **Stochastic Variables:** Random variations in demand and lead times.
- **Production Records:** Past production details for validation.
- **Inventory Metrics:** Performance data on stock levels and costs.

c) Raw Material Arrival and Processing:

The simulation model initiates with the arrival of raw materials, a crucial precursor to a complete model run. These materials originate from two distinct sources: bunker materials

(Bulk materials) delivered via trucks and warehouse materials (Smaller Materials) brought in various quantities by delivery trucks.

Arrivals from both sources are processed similarly. Each arrival from the bunker or warehouse is tagged with a material type and quantity, ensuring accurate inventory updates. In the case of bunker arrivals, each truck is assumed to carry a whole load of its corresponding material type, maintaining a consistent supply. Conversely, warehouse arrivals, arriving in trucks of varied sizes and frequencies, are allocated specific delivery quantities sourced from a global table.

Upon arrival, each batch undergoes inventory update procedures. Inventory values are directly incremented in a "Bunker Bulk Inventory" global table for bunker arrivals, which holds all these values. Similarly, warehouse inventory updates follow suit, incrementing corresponding material types using pre-defined delivery quantities.

d) Production Arrival and Pre-Production:

In parallel with raw material arrivals, customer orders trigger production activities; each assigned a unique production number corresponding to one of the possible producible products. These production numbers are cross-referenced with a "Product" global table outlining the required materials for each product.

Pre-production processes involve translating conceptual activities into concrete implementations within FlexSim. Entities representing product numbers, each comprising various materials, enter the pre-production zone. These entities are initially labelled as "True" and undergo inventory checks for each material, ensuring availability. Entities progress through decision activities based on material availability. If inventory meets requirements, entities proceed; otherwise, they wait for updates. This iterative process continues until all materials are confirmed satisfiable.

e) Product Production:

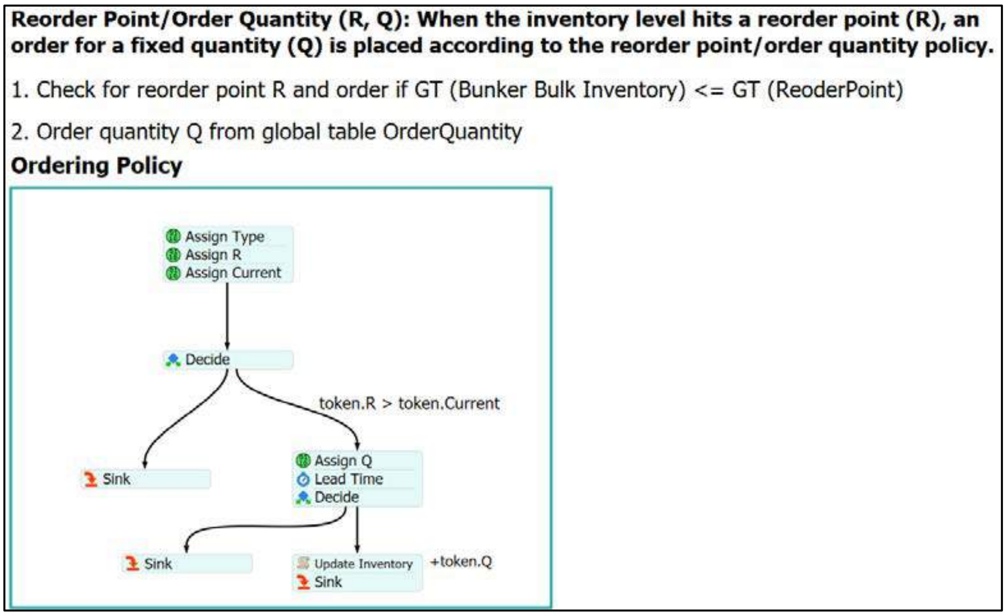
Upon confirming material availability, entities progress to the production phase. Here, variables are set, and inventory updates are executed via custom code activities. The first code subtracts used inventory from the company's inventory table, updating stocks. The second code records these subtracted values in a "Produced Inventory" global table for efficiency analysis. Entities undergo production activities and exit the zone upon completion, allowing the cycle to repeat for subsequent orders. Subsequent models build upon this framework, assessing different inventory control policies' impacts on operations.

6.2 Discrete Event Inventory Control Model

Expanding on Hopp's [10] inventory control policies, subsequent models build upon the current state model, representing a company’s existing inventory practices. These policies are seamlessly integrated into the FlexSim simulation model, interacting with pre-production, production, and demand processes. The figures presented in the following sections represent distinct control policy models created by the primary author of this paper and have been used in practice. Assessing how the inventory control policy impacts inventory levels, costs, and operational efficiency is crucial and will be evaluated alongside other policies in the upcoming sections.

6.2.1 (R, Q) Inventory Control Model

The (R, Q) Inventory Control Model is a cornerstone strategy for enhancing inventory management practices. It focuses on continuously adjusting the reorder point (R) and order quantities (Q) to optimise inventory replenishment while balancing stock levels and holding costs [21]. **Figure 2** depicts an example of how an (R, Q) inventory control policy can be implemented within the current state model.



Reorder Point/Order Quantity (R, Q): When the inventory level hits a reorder point (R), an order for a fixed quantity (Q) is placed according to the reorder point/order quantity policy.

1. Check for reorder point R and order if GT (Bunker Bulk Inventory) <= GT (ReoderPoint)

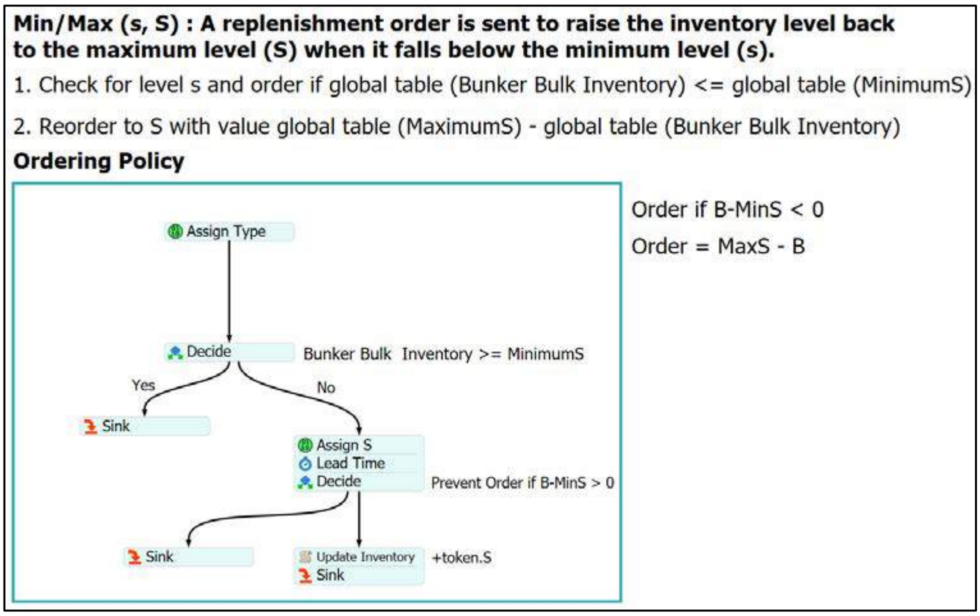
2. Order quantity Q from global table OrderQuantity

Figure 2: (R, Q) Ordering Policy Implementation

6.2.2 (s, S) Inventory Control Model

The (s, S) Inventory Control Model adopts a just-in-time strategy by setting minimum (s) and maximum (S) stock levels. This approach minimises holding costs while ensuring sufficient inventory to meet demand fluctuations [21].

Figure 3 depicts an example of how an (s, S) inventory control policy can be implemented within the current state model.



Min/Max (s, S) : A replenishment order is sent to raise the inventory level back to the maximum level (S) when it falls below the minimum level (s).

1. Check for level s and order if global table (Bunker Bulk Inventory) <= global table (MinimumS)

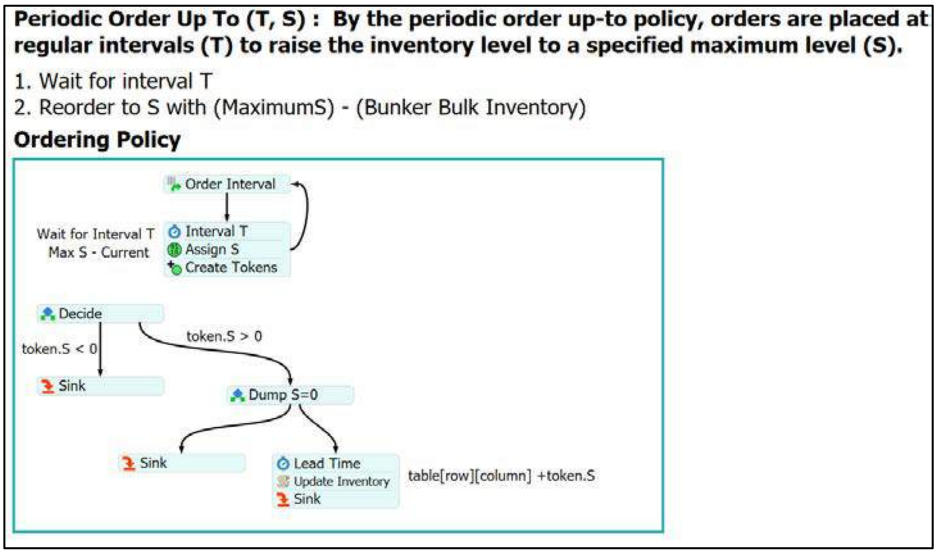
2. Reorder to S with value global table (MaximumS) - global table (Bunker Bulk Inventory)

Figure 3: (s, S) Ordering Policy Implementation

6.2.3 (T, S) Inventory Control Model

A (T, S) Inventory Control Model implemented at a manufacturer emphasises maintaining target inventory levels (T) and order-up-to-levels (S) to balance stock availability and cost control [21].

Figure 4 depicts the completed (T, S) inventory control policy implemented in the current state model.



Periodic Order Up To (T, S) : By the periodic order up-to policy, orders are placed at regular intervals (T) to raise the inventory level to a specified maximum level (S).

1. Wait for interval T
2. Reorder to S with (MaximumS) - (Bunker Bulk Inventory)

Ordering Policy

Figure 4: (T, S) Inventory Control Policy Implementation

Figure 4 shows that the (T, S) inventory control policy starts at the scheduled source, which assigns pre-defined interval labels for each material type. These entities are sent to a delay activity before looping back to the scheduled source, ensuring the creation of entities after each delay.

7 VERIFICATION TECHNIQUES

Verification is essential in constructing a reliable and effective inventory control simulation model. This verification ensures the reliability and accuracy of the intricate algorithms and procedures governing the model, ensuring its validity to the real-world inventory system it aims to emulate. Law [14] has shown that there are various foundational techniques and strategies within the simulation verification process.

- Incremental Development: Rather than attempting to construct an entire simulation model simultaneously, incremental development advocates for building and debugging it in smaller, iterative steps. This method begins with core components and verifies each one thoroughly before moving on, resulting in a more robust and reliable model.
- Collaborative Review: Involving multiple individuals in a code review through structured walkthroughs ensures comprehensive scrutiny, preventing developer tunnel vision and ensuring thorough validation of each logical path.
- Parameter Exploration: Testing the simulation with input parameter values helps assess its responsiveness and output sensitivity, ensuring accurate representation of real-world scenarios and identifying anomalies.
- The Power of Trace: Using a "trace" to record the simulation's state after each event allows for thorough analysis, comparing the data with manual computations to confirm the program's performance and uncover any faults.
- Assumption Verification: Evaluating the model under simplified assumptions helps validate its correctness, ensuring accurate results even with streamlined components.
- Visualisation through Animation: Dynamic animation provides a visual representation of the system's behaviour, aiding in detecting anomalies or unexpected behaviours that may be difficult to identify through static analysis.

- Leveraging Simulation Packages: While commercial simulation software can streamline programming efforts, caution is advised because of potential inaccuracies. Interactive debugging features allow for pause, evaluation, and adjustments during simulation.

8 VALIDATION TECHNIQUES

As referenced by Kleijnen [22], validation involves assessing whether the created model accurately mirrors the simulated underlying real system. The following techniques that were outlined by Sargent [23] can be used for validating the inventory control simulation models:

- Animation: The operational behaviour of the model is visually represented as it progresses through time. Balci [24] depicts that graphical depictions illustrate the movement of parts within a factory throughout a simulation run.
- Comparison to Other Models: The validation process involves comparing the results, such as outputs, of the simulation model under scrutiny to those of other validated models as per Sargent's [23] definition.
- Event Validity: The events generated by the simulation model are those observed in the actual system to discover their similarity.
- Face Validity: Sargent [23] explains that experts familiar with the system should be consulted to provide insights on the model and its behaviour, assessing whether they are reasonable.
- Historical Data Validation: Sargent [23] expressed that should historical data be available, a portion of this data, typically collected for constructing and testing a model, is utilised in building the model itself. Subsequently, the remaining dataset is employed to validate or test whether the model accurately replicates the system's behaviour.
- Sensitivity Analysis: Sargent [23] explained that this method involves altering the values of input and internal parameters within a model to assess their impact on the model's behaviour or output. The aim is to ensure that the relationships observed in the model mirror those in the system. This technique can be applied qualitatively, focusing solely on the directions of outputs, or quantitatively, considering both the directions and precise magnitudes of outputs.
- Predictive Validation: The model is employed to forecast the system's behaviour, and subsequently, comparisons are drawn between the predicted behaviour of the system and the forecasts generated by the model. Balci [24] shows that this comparative analysis aims to discover the similarity between the actual behaviour observed in the system and the forecasted behaviour predicted by the model.

9 SIMULATION EVALUATION

In assessing the effectiveness of inventory control policies in addressing a company's challenges, a set of key performance indicators (KPIs) needs to be identified. As highlighted by Luther [25], these indicators play a crucial role in comparing and assessing inventory control policies. They serve as vital metrics to gauge the outcomes and success of the inventory control policies in addressing the study's aim and problem statement.

- Production Capacity per Month: This KPI evaluates the company's ability to meet the desired monthly production capacity, directly assessing whether inventory control policies have improved production capacity.
- Average Inventory: The average inventory level is a vital metric to assess inventory management effectiveness, with a reduction indicating improved control and potential cost savings.
- Average Recipes Awaiting Production: This KPI evaluates production process efficiency by assessing the average number of recipes awaiting production, indicating smoother operations and reduced waiting times.

- Sell-Through Rate: The sell-through rate measures inventory turnover efficiency, showcasing how quickly products are sold and replaced, with a higher rate implying better inventory control.

While one inventory control policy may appear optimal for the company under evaluation, it is crucial to acknowledge that different companies may find varying policies more suitable based on their unique contexts and goals. Therefore, the evaluation process outlined here offers a comprehensive framework for assessing and selecting the most appropriate inventory control policy for the company under evaluation. By analysing KPIs across different policies, companies can gain valuable insights into their operations, enabling informed decisions to improve efficiency and performance.

10 POLICY IMPLEMENTATION PLAN

The policy implementation plan systematically introduces a novel inventory control system and integrates it seamlessly within the company's operational framework.

The following implementation plan phases detail the steps to be taken over 12 months to successfully adopt an inventory control system within the company.

- **Week 1-2:** Familiarise stakeholders with the inventory control policy, emphasising benefits such as cost reduction and stockout prevention.
- **Week 3-4:** Select a pilot area based on lead time and demand variability, demonstrating the balance between ordering frequency and inventory levels.
- **Month 2:** Test the policy in the pilot area, training staff on adaptability to demand uncertainty.
- **Months 3-4:** Implement and evaluate the policy in the pilot area, adjusting inventory levels as needed.
- **Month 5:** Prepare for company-wide rollout, allocating resources and planning communication.
- **Month 6:** Implement the policy company-wide, conducting comprehensive staff training on technology usage.
- **Months 7-12:** Monitor and optimise the policy, conducting performance reviews and automating data collection to enhance decision-making.

11 CONCLUSIONS

In conclusion, if research endeavours were undertaken to enhance inventory control at a company, they would yield promising results. The paper has laid a solid foundation for improving operational efficiency and meeting production goals by meticulously crafting a tailored inventory control policy and outlining a comprehensive implementation plan. The adoption of an inventory control policy, with its focus on data-driven decision-making and balancing inventory levels, promises to bring about significant gains in efficiency while mitigating risks of stockouts. A company can become well-positioned to navigate dynamic market dynamics, optimise inventory levels, and seize opportunities for sustained success.

12 RECOMMENDATIONS

While this paper yields valuable insights and recommendations for enhancing inventory control within a company and adopting an inventory control policy, there remain avenues for future research and exploration in inventory control. These areas of inquiry present opportunities for further refinement and innovation in pursuing operational excellence.

- Advanced Analytics and Machine Learning: Integrating advanced analytics and machine learning can offer more precise insights into inventory control, enabling proactive responses to changing market conditions [26].

- Ethical and Responsible Sourcing: Future research can explore how inventory control can align with ethical and responsible sourcing principles, mitigating reputational risks and meeting consumer demand for ethically sourced products [27].
- Cross-Industry Benchmarking: Comparing inventory control strategies with leading companies in different industries can provide valuable insights and innovative approaches for optimising inventory control practices [28].

These areas of future research guide the company toward continued excellence and innovation in inventory control, contributing to broader discourse and strengthening competitive positioning in the business landscape.

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OPTIMISING UNDERGROUND MINE TRAIN SCHEDULING: A MIXED-INTEGER LINEAR PROGRAMMING APPROACH

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ABSTRACT

Underground mines utilise a single-lane, bidirectional transportation network during ore extraction. Once the underground train has reached the elevator shaft, the ore is dumped into a skip and lifted to ground level for further handling. Congestion on the single-lane network is a significant problem for underground mines. Several studies have addressed the congestion problem on a double-lane network, but the proposed models do not apply to the single-lane, bidirectional network. First, a brief background is provided regarding the related studies. Second, a mathematical programming model is proposed to schedule trains on a single-lane, bidirectional transportation network. The model aims to improve the network's transportation throughput. The formulation of the mathematical programming model is verified and validated using historical data. The main contribution of this study is the formulation of a mathematical programming model for scheduling underground mine trains on a single-lane, bidirectional network.

Keywords: Flow conservation, Optimisation, Single-lane bidirectional network

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1 INTRODUCTION

Operations research is essential for planning and scheduling in mines' transportation and production departments [1]. A detailed schedule should consider short-term and long-term requirements and daily operations. Block models commonly represent orebodies and are utilised in mathematical modelling to maximise the net present value of mine operations [1].

Underground mines extract ore from mineral deposits through drilling, blasting and crushing to transport the ore on a network of tunnels and shafts. The transportation network of the ore consists of various transportation methods, namely trackless vehicles, conveyor belt systems and rail bounded vehicles. The networks have very primitive communication and vehicle tracking systems leading to poor scheduling, causing inefficient and low transportation of ore across the network. The model proposed in this study aims to improve the transportation throughput to increase the mine's output capacity. The physical limitations and resource availability are crucial for understanding the transportation network and during the development of the mathematical model.

This study focuses on scheduling rail-bound vehicles on a single-lane, bidirectional transportation network to maximise the transportation throughput in tonnes. To simplify the mathematical model, only one level of an underground mine network is examined and scheduled. The personnel on the network is not part of the scheduling. The assumption is that the personnel's working hours are within the prescribed hours according to the labour and health and safety acts. The mine operates in shifts, and the change-overs between shifts are made seamlessly so that no disruption in the schedules occurs.

The rail-bound vehicles travel at 10km/h when loaded and have a top speed of 20km/h when empty. The locomotives have a load capacity of 35 tonnes for transporting ore. The transportation network's topology is reminiscent of an acyclic graph with a central line and branches connecting the extraction sites to the central line. The network is extended as the exploration expands and additional extraction sites are constructed. The mine supplies a list of coordinates regarding the nodes and edges of their network. Figure 1 visualises the network for a better understanding of the layout.

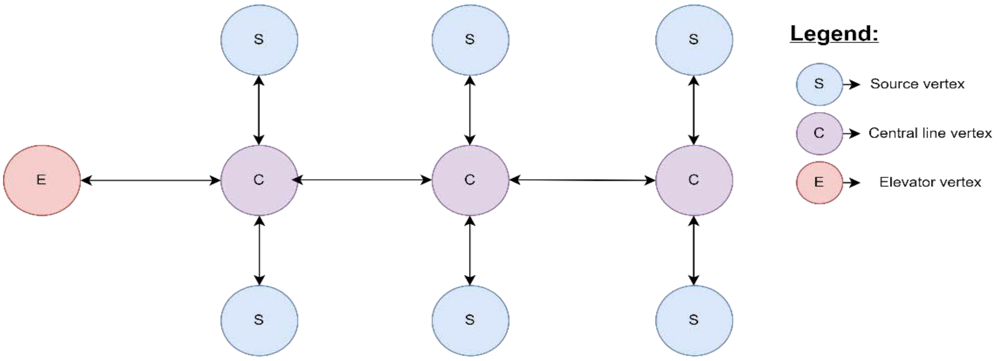

Figure 1: Visualisation of an underground mine network

The transportation network is constructed in table format from the coordinates supplied by the mine. The distance calculations of each arc are included within the input data, and the model calculates the travel durations per arc for loaded and empty trains.

Shift hours differ between mines. Generally, workers are present in a mine for the whole 24 hours. Mines operate approximately between 341 and 351 production days annually. Blasting and drilling operations are included in the shift operations, with two planned blasts per day, as in some mines [2]. The case mine utilised for the mathematical model's verification and validation had 263 production days and 102 days with production downtime. The daily ore transportation throughput is averaged at 66.12015 tonnes for the first 22 days, after which a 21-day downtime started. This study focuses solely on the transportation network of the underground mine. The supply capacity of the extraction site is assumed to be unlimited, ensuring that the transportation throughput is the limiting factor on the network. The profit or net present value (NPV) is not considered during the model formulation and calculations.

To address this problem experienced in the mining industry, this study proposes a mixed integer linear programming (MILP) model to determine the optimal train schedule on the single-lane, bidirectional network. The proposed model aims to maximise the transportation throughput of the network while considering the prevention of collisions on the network.

Scheduling the flow of trains in a single direction is computationally easier as combinations of trains are selected. For scheduling the overlapping flows of empty and loaded trains, the permutations of the different trains at different sections of the network are considered a feasible solution.

Following the introduction, the article briefly discusses related studies to the identified problem in Section 2. The mixed integer linear programming model is formulated in Section 3. Section 4 is the verification and validation of the model. In Section 5, the scalability of the model is examined, and the results are listed. The conclusion is given in Section 6, followed by a recommendation for future work in Section 7.

2 RELATED STUDIES

Numerous problems exist in transportation networks, and congestion and energy consumption are some of the most popular issues addressed in various research papers [3]. Congestion is a complex problem with numerous aspects influencing schedules. Varying demand is one of the leading causes of congestion in train stations; Blanco et al. [4], Ying et al. [5], and Shahabi et al. [6] proposed three different solutions to improve the effectiveness of the model’s solution against the variation in the demand.

A mixed integer linear programming (MILP) model was implemented with a constraint programming model to address periodic and non-periodic problems on a network [7]. A MILP model was developed and implemented with a stochastic programming model to prevent the Coronavirus disease at train stations [8].

Amaya and Uribe [9] proposed two models for improving train crew scheduling. The first model determines the train routes and schedules according to a network provided and loaded into the model. The second model focuses on scheduling the crew members according to the given law requirements, balancing the weekly load between drivers, and minimising the salary differences between drivers.

Marli’ere et al. [10] focused on a railway network's real-time traffic management problem. They proposed a constraint-based scheduling approach and compared its performance to the Recherche sur la Capacité d’Infrastructures Ferroviaires mixed integer linear programming algorithm. The study aimed to improve schedule changes caused by disruption to reduce passengers' dwell time. Giorgio et al. [10] proposed a mixed integer linear programming model with a dynamic graph for addressing the problem of period and non-periodic disturbances on the network.

Authors of [11], [12] and [13] attempted to reduce the disruptions in schedules caused by maintenance on the network. Zang et al. [11] combined a binary integer model and a dynamic programming model to schedule trains and planned maintenance on the network. Rokhforoz and Fink [12] focused on scheduling preventative maintenance on a network with multiple routes between stations, and a mixed integer linear programming model was proposed. Buriuly et al. [13] focused on dynamic programming and scheduling the downtime in the network.

3 MODEL FORMULATION

First, the model notation is given, and all the relevant sets, variables, and constants are defined. The model formulation follows in Section 3.2, where the objective function and all the required model constraints are given.

3.1 Model notation

The sets utilised in the mathematical model to formulate the scheduling problem are listed in Table 1.

Table 1: Sets implemented in the mathematical model

Symbol	Description
A	the set for all the arcs in the network
A_l	A subset of $A,$ defining all the arcs; $A_l \subset A$
A_e	A subset of $A,$ defining all the arcs; $A_e \subset A$
V	the set for all the vertices in the network
T	the set for all the trains in the network
E	Elevator vertices in the set of all vertices; $E \subset V$
C	Central line vertices in the set of all vertices; $C \subset V$
S	Supply vertices in the set of all vertices; $S \subset V$
B	Non-supply vertices in the set of all vertices; $B \subset V$

Set A is a superset of sets A_e and A_l, Which is utilised in the model for two graphs seen in Figures 2 and 3, respectively. The bidirectional graph is divided into two single-directional graphs representing the forward and backward flow across the network.

The graphs visualised in Figures 2 and 3 are relevant to the set functions in Table 2. The transportation network is a multi-layer graph consisting of $\mathrm{G_o}$ and $\mathrm{G_1}$. Graph $\mathrm{G_o}$Consist of all the arcs required for the forward flow. Graph $\mathrm{G_1}$consist of all the arcs required for the backward flow.

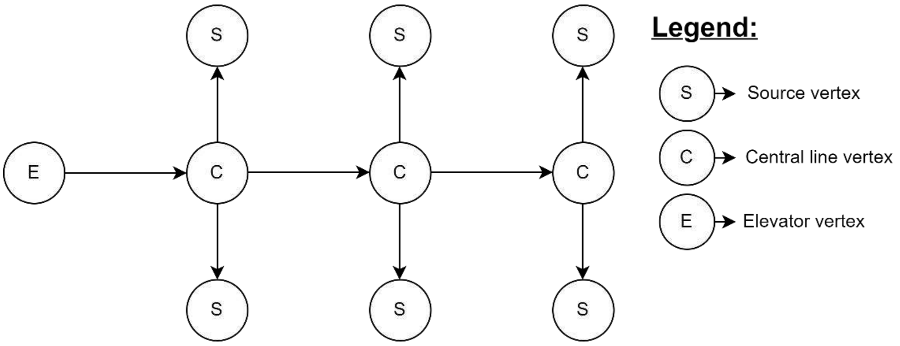

Figure 2: Visualisation of graph $\mathrm{G_o}$ with the forward flow

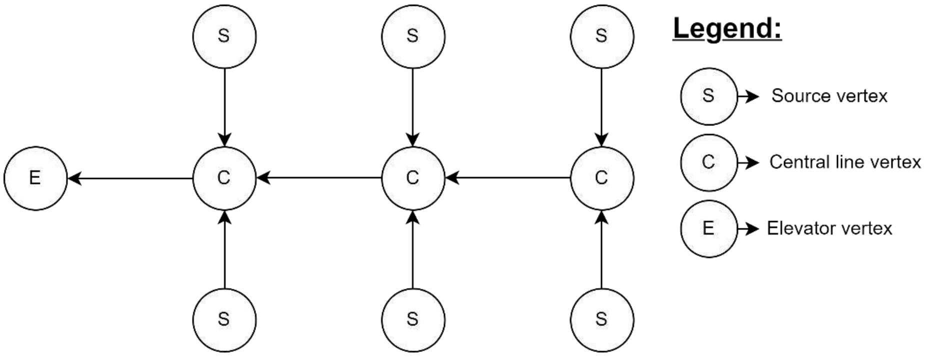

Figure 3: Visualisation of graph G_1 with the backward flow

Set functions are utilised in the model for specific constraints requiring a subset of particular vertex and arc sets. Table 2 lists all the set functions used within the model.

Table 2: Set functions utilised in the mathematical model

Symbol	Description
$IE(v)$	A set function that returns all incident arcs for vertex v in graph $\mathrm{G_o} = (\mathrm{V}, \mathrm{A_e})$
$OE(v)$	A set function that returns all emanating arcs for vertex v in graph $\mathrm{G_o} = (\mathrm{V}, \mathrm{A_e})$
$I(v)$	A set function that returns all incident arcs for vertex v in graph $G_1 = (V, A_l)$
$O(v)$	A set function that returns all emanating arcs for vertex v in graph $G_1 = (V, A_l)$
$\sigma(a)$	A set function returning source vertex of an arc a in graph $G_1 = (V, A_l)$
$\beta(a)$	A set function returning source vertex of an arc a in graph $G_o = (V, A_e)$

Table 3 lists the relevant variables utilised in the model, along with the domain, indices, and description. The first four variables are the time variables allocated in the model to capture the time of each train at each interval. The rest are decision variables utilised in the model.

Table 3: Notation of variables utilised in the mathematical model

Symbol	Domain	Index sets	Description
γ_{vt}	$\mathbb{R}_+$	$v \in V, t \in T$	Time variable for backward flow entering vertex
δ_{vt}	$\mathbb{R}_+$	$v \in V, t \in T$	Time variable for backward flow exiting vertex
ζ_{vt}	$\mathbb{R}_+$	$v \in V, t \in T$	Time variable for forward flow entering vertex
ϵ_{vt}	$\mathbb{R}_+$	$v \in V, t \in T$	Time variable for forward flow exiting vertex
x_{at}	{0,1}	$a \in A, t \in T$	Backward flow decision variable
y_{vtk}	{0,1}	$v \in V, t \in T, k \in T$	Sequence of the flow decision variable
w_{vtk}	{0,1}	$v \in V, t \in T, k \in T$	Second sequence of flow decision variable

z_{vt}	{0,1}	$v \in V, t \in T$	Decision variable of vertices used in the model
b_{at}	{0,1}	$a \in A, t \in T$	Forward flow decision variable
d_t	{0,1}	$t \in T$	Train usage decision variable

Table 4 lists all the relevant constants utilised in the mathematical model within the objective function and constraints.

Table 4: Notation of constant utilised in the mathematical model

Symbol	**Index sets**	**Description**
ρ_a	$a \in A$	Travel duration for loaded trains in minutes
κ_a	$a \in A$	Travel duration for empty trains in minutes
M	Scalar	Large value for Big-M constraints
μ	Scalar	Arc load capacity in tonnes
P	Scalar	Time duration of a train passing a vertex
ω	Scalar	Schedule interval duration

The travel duration per arc for the loaded and empty trains is represented by ρ_a and κ_a respectively. The value of the Big-M constant, M, was determined as 1440. The arc capacities, μ, is utilised in the objective function for the throughput calculations. The constant P is utilised in the model to implement a time duration between the start and end of a train passing a vertex. The time variables are constrained to an upper bound, ω, which is predetermined as the schedule duration.

3.2 The model is formulated as follows:

Maximise

$$\boldsymbol{\sum_{t\in T}\sum_{e\in E}\mu z_{et}} \qquad \textbf{(3.1)}$$

The objective function aims to maximise the product of the binary flow across the elevator vertex, $\boldsymbol{z_{et}}$, and the train capacity, $\boldsymbol{\mu}$.

subject to

{*Forward Flow Constraints*}

$$\boldsymbol{\sum_{s\in S}\sum_{a\in O(s)} x_{at} = \sum_{e\in E}\sum_{k\in I(e)} x_{kt}}, \qquad \boldsymbol{\forall t \in T} \qquad \textbf{(3.2)}$$

$$\boldsymbol{\sum_{a\in O(c)} x_{at} = \sum_{k\in I(c)} x_{kt}}, \qquad \boldsymbol{\forall c \in C, t \in T} \qquad \textbf{(3.3)}$$

Constraint (3.2) ensures that the sum of the loaded trains exiting the elevator vertices equals the sum of the loaded trains entering the supply vertices. Constraint (3.3) implements the conservation of the flow of the loaded trains across the vertices in the central line of the network.

$$\boldsymbol{\sum_{a\in I(v)} x_{at} = z_{vt}}, \qquad \boldsymbol{\forall v \in V, t \in T} \qquad \textbf{(3.4)}$$

Constraint (3.4) links the decision variables of the flow of loaded trains to the decision variable of vertices utilised in the model. The $\boldsymbol{z_{vt}}$ decision variable is utilised in the objective function and other constraints.

{*Backward Flow Constraints*}

$$\boldsymbol{\sum_{e\in E}\sum_{a\in OE(e)} b_{at} = \sum_{s\in S}\sum_{k\in IE(s)} b_{kt}}, \qquad \boldsymbol{\forall t \in T} \qquad \textbf{(3.5)}$$

$$\boldsymbol{\sum_{a\in OE(c)} b_{at} = \sum_{k\in IE(c)} b_{kt}}, \qquad \boldsymbol{\forall c \in C, t \in T} \qquad \textbf{(3.6)}$$

Constraint (3.5) ensures that the sum of the empty trains exiting the elevator vertices equals the sum of the empty trains entering the supply vertices. Constraint (3.6) implements the conservation of the flow of the empty trains across the vertices in the central line of the network.

$$x_{at} = b_{at}, \qquad \forall s \in S, a \in IE(s), t \in T \tag{3.7}$$

$$\sum_{e \in E} \sum_{a \in OE(e)} b_{at} = \sum_{e \in E} \sum_{k \in I(e)} x_{kt}, \qquad \forall t \in T \tag{3.8}$$

Constraint (3.7) ensures that the flow of empty trains at the supply vertices has a corresponding flow of loaded trains at these vertices. Constraint (3.8) provides that the sum of the empty trains exiting the elevator vertices equals the sum of the loaded trains entering the elevator vertices.

{*Time Constraints*}

$$\gamma_{vt} \le \omega, \qquad \forall v \in V, t \in T \tag{3.9}$$

$$\delta_{vt} \le \omega, \qquad \forall v \in V, t \in T \tag{3.10}$$

$$\zeta_{vt} \le \omega, \qquad \forall v \in V, t \in T \tag{3.11}$$

$$\epsilon_{vt} \le \omega, \qquad \forall v \in V, t \in T \tag{3.12}$$

Constraints (3.9-3.12) are included to set the upper bound of the time variables.

$$\gamma_{st} \ge \rho_a x_{at} + \gamma_{\sigma(a)t} + M[x_{at} - 1], \qquad \forall s \in B, a \in I(s), t \in T \tag{3.13}$$

$$\gamma_{st} \le \rho_a x_{at} + \gamma_{\sigma(a)t} + M[1 - x_{at}], \qquad \forall s \in B, a \in I(s), t \in T \tag{3.14}$$

Constraints (3.13) and (3.14) are conditional equalities; the condition is determined by the value of x_{at}. If x_{at} is equal to one the time variable, γ_{st}, The loaded train's time value at the preceding vertex should equal the sum of the travel duration between the two vertices.

$$\gamma_{vt} = \delta_{vt} - P, \qquad \forall v \in V, t \in T \tag{3.15}$$

$$\gamma_{st} = \zeta_{st} + \lambda, \qquad \forall s \in S, a \in IE(s), t \in T \tag{3.16}$$

Constraint (3.15) links each loaded train's entering and existing times. Constraint (3.16) links the time variable of the empty trains with the loaded trains at the supply vertices.

$$\zeta_{vt} \ge \kappa_a b_{at} + \zeta_{\beta(a)t} + M[b_{at} - 1], \qquad \forall v \in V \setminus \{e\}, e \in E, a \in IE(v), t \in T \tag{3.17}$$

$$\zeta_{vt} \le \kappa_a b_{at} + \zeta_{\beta(a)t} + M[1 - b_{at}], \qquad \forall v \in V \setminus \{e\}, e \in E, a \in IE(v), t \in T \tag{3.18}$$

Constraints (3.17) and (3.18) are conditional equalities, with the condition determined by the value of b_{at}. If b_{at} is equal to one the time variable, ζ_{vt}, should be equal to the sum of the time value of the empty train at the preceding vertex and the travel duration between the two said vertices.

$$\zeta_{vt} = \epsilon_{vt} - P, \qquad \forall v \in V, t \in T \tag{3.19}$$

Constraint (3.19) links each loaded train's entering and existing times.

$$\zeta_{vt} \le \zeta_{vk} - \tau + M[1 - w_{vkt}], \qquad \forall v \in V, t \in T, k \in T \setminus \{t\} \tag{3.20}$$

$$\zeta_{vt} \ge \zeta_{vk} + \tau + P - M w_{vkt}, \qquad \forall v \in V, t \in T, k \in T \setminus \{t\} \tag{3.21}$$

$$w_{vtk} + w_{vkt} = 1, \qquad \forall v \in V, t \in T, k \in T \setminus \{t\} \tag{3.22}$$

Constraints (3.20-3.22) are conditional equalities; the conditions are dependent on the value of w_{vtk} determining the sequence of the empty trains passing each vertex in the network.

{*Constraint Propagation*}

The set T is defined as follows

$$T = \{1, 2, \cdots, |T|\}$$

$$\sum_{e\in E}\sum_{a\in I(e)} x_{at} \leq 1, \qquad \forall t \in T \tag{3.23}$$

$$\sum_{e\in E}\sum_{a\in I(e)} x_{at} \leq \sum_{e\in E}\sum_{a\in I(e)} x_{at-1}, \qquad \forall t \in T \setminus \{1\} \tag{3.24}$$

$$\sum_{e\in E}\sum_{a\in OE(e)} b_{at} \leq 1, \qquad \forall t \in T \tag{3.25}$$

$$\sum_{e\in E}\sum_{a\in OE(e)} b_{at} \leq \sum_{e\in E}\sum_{a\in OE(e)} b_{at-1}, \qquad \forall t \in T \setminus \{1\} \tag{3.26}$$

$$\sum_{s\in S}\sum_{a\in O(s)} x_{at} \leq 1, \qquad \forall t \in T \tag{3.27}$$

$$\sum_{s\in S}\sum_{a\in O(s)} x_{at} \leq \sum_{s\in S}\sum_{a\in O(s)} x_{at-1}, \qquad \forall t \in T \setminus \{1\} \tag{3.28}$$

$$\sum_{s\in S}\sum_{a\in IE(s)} b_{at} \leq 1, \qquad \forall t \in T \tag{3.29}$$

$$\sum_{s\in S}\sum_{a\in IE(s)} b_{at} \leq \sum_{s\in S}\sum_{a\in IE(s)} b_{at-1}, \qquad \forall t \in T \setminus \{1\} \tag{3.30}$$

Constraints (3.23) and (3.25) and constraints (3.27) and (3.29) ensure that a train can only enter one elevator and supply vertex for the loaded and empty trains, respectively. Constraints (3.24) and (3.28) and constraints (3.26) and (3.30) ensure the schedule utilises the trains in chronological order, therefore reducing the combinations of feasible solutions with different trains and with the same throughput.

$$\gamma_{st} + M[1 - x_{at}] \geq \gamma_{kt-1}, \qquad \forall s \in S, a \in O(s), k \in S, c \in O(k), t \in T \setminus \{1\} \tag{3.31}$$

$$\zeta_{st} + M[1 - b_{at}] \geq \zeta_{kt-1}, \qquad \forall s \in S, a \in IE(s), k \in S, c \in IE(k), t \in T \setminus \{1\} \tag{3.32}$$

$$\zeta_{et} + M[1 - b_{at}] \geq \zeta_{kt-1}, \qquad \forall e \in E, a \in IE(e), k \in E, c \in IE(k), t \in T \setminus \{1\} \tag{3.33}$$

Constraint (3.31) ensures the loaded trains are scheduled chronologically at the supply vertices. The big M constraint ensures that loaded trains can flow from different supply vertices and are not constrained to one supply vertex. If trains flow to different supply vertices, the constraint is unbounded. Constraints (3.32) and (3.33) ensure that the empty trains are scheduled chronologically at the supply and elevator vertices, respectively. The big M constraints ensure that empty trains can flow to different supply or elevator vertices and are not constrained to one supply or elevator vertex.

{*Collision Prevention Constraints*}

$$\sum_{a\in A} x_{at} \geq d_t, \qquad \forall t \in T \tag{3.34}$$

$$x_{at} \leq d_t, \qquad \forall a \in A, t \in T \tag{3.35}$$

$$y_{vtk} + y_{vkt} = 1, \qquad \forall v \in V, t \in T, k \in T \setminus \{t\} \tag{3.36}$$

$$\gamma_{vt} \leq \zeta_{vk} - Pd_t - \rho_a x_{at} - \kappa_c b_{ck} - \tau + M[1 - y_{vkt}] + M[1 - b_{ck}], \qquad \forall v \in C, t \in T, k \in T \setminus \{t\}, a \in IE(v), c \in I(v) \tag{3.37}$$

$$\gamma_{v,t} \geq \epsilon_{vk} + Pd_t + \rho_a x_{at} + \kappa_c b_{ck} + \tau - My_{vkt} + M[b_{ck} - 1], \qquad \forall v \in C, t \in T, k \in T \setminus \{t\}, a \in IE(v), c \in I(v) \tag{3.38}$$

Constraints (3.34) and (3.35) ensure that the required decision variables are linked to implementation in constraints (3.37) and (3.38). In constraint (3.36), the decision variables are constrained to one, ensuring that a loaded train can pass a vertex before or after the empty trains, but not both conditions can be true. Collisions on the network are prevented by constraints (3.37) and (3.38), which determine the time of the loaded and empty trains as well the sequence of flow of the load and empty trains across the network. The constraints ensure the loaded and empty trains are not simultaneously located at the same vertex or arc. The big M constraints are useful for conditional equality, which is crucial to scheduling with the flow conservation approach. The big M constraints extend the model bounds and reduce the model tightness. This causes the model to take longer to solve for optimality than a tight model.

4 VERIFICATION AND VALIDATION

In this section, the formulation of the mathematical model is verified. The results obtained from the model are validated to ensure the effectiveness of the model's schedule.

4.1 Verification

A critical evaluation of the constraints (3.2) to (3.38) is conducted using the Elytica platform and HiGHS 1.6.0 solver to verify the model. During verification, each constraint's impact on the model's results is evaluated to determine if the model is correctly formulated and implemented. A small-scale data set is used in the verification phase. The trains are scheduled for a 24-hour duration.

4.1.1 Objective function

The model verification starts with the objective function without including any constraints. A baseline is created to assess the impact of each constraint on the model.

Table 5: Verification result of the objective function

Description	**Value**
Objective value	210
Binary decision variables: $x_{at}, \forall a \in A, t \in T$	Either 1 or 0, have no influence and is randomly allocated
Binary decision variables: $b_{at}, \forall a \in A, t \in T$	Either 1 or 0, have no influence and is randomly allocated
Binary decision variables: $d_t, \forall t \in T$	Either 1 or 0, have no influence and is randomly allocated

Table 5 provides the decision variables, and the model yields 210 tonnes. This is expected as the model is limited to 6 trains with a capacity of 35 tonnes each; therefore, the solution found is the maximum throughput of the model. The flow parameter $z_{et}, \forall e \in E, \forall t \in T$ is maximised in the objective function, which is defined between 0 and 1. With six available trains in the model, the maximum possible objective value is 210 tonnes.

4.1.2 Flow constraints

Constraints (3.2) to (3.8) are included in the model to verify its flow. The flow constraints do not limit the model's results, as flows are created without any time duration or constraining factor except for the train's load capacity.

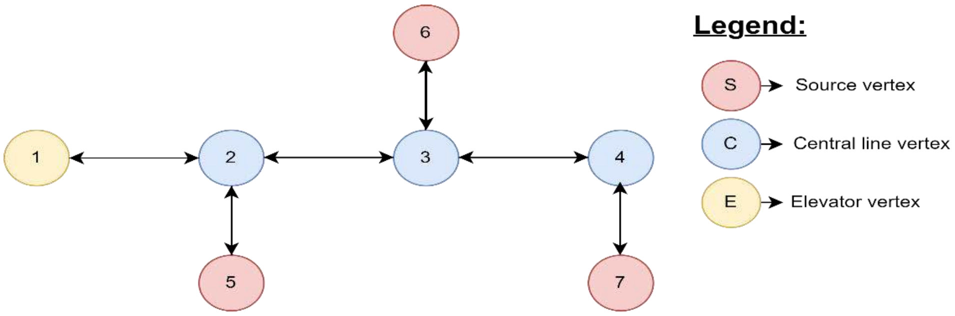

Figure 4: The small-scale dataset network topology

Figure 4 visualises the network utilised in the verification of the model.

Table 6: Verification results of the model with constraints (3.2 - 3.8)

Description	Value
Objective value	210
Binary decision variables: x_{1t} and $x_{6t}, \forall t \in T$	1
Binary decision variables: $x_{at}, \forall a \in A\backslash\{1,6\} t \in T$	0
Binary decision variables: b_{1t} and $b_{6t}, \forall t \in T$	1
Binary decision variables: $b_{at}, \forall a \in A\backslash\{1,6\} t \in T$	0
Binary decision variables: $d_t, \forall t \in T$	Either 1 or 0 has no influence and is randomly allocated

Table 6 provides the model results; all the trains are scheduled to and from mine site 1 at vertex 7. Results obtained from the model are as expected, with the maximum possible flow of 210 tonnes obtained. The distance and time duration of the trains do not influence the model results. Therefore, one of five possible routes, along with its relevant combination of decision variables.

Table 7: Combination of decision variables according to mine sites

Flow to the mine site	Decision variables set to 1 $\forall t \in T$
Mine site 1: Vertex 7	x_{1t} and x_{6t}
Mine site 2: Vertex 8	x_{1t} , x_{2t} and x_{7t}
Mine site 3: Vertex 9	x_{1t} , x_{2t} , x_{3t} and x_{8t}
Mine site 4: Vertex 10	x_{1t} , x_{2t} , x_{3t} , x_{4t} and x_{9t}
Mine site 5: Vertex 11	x_{1t} , x_{2t} , x_{3t} , x_{4t} , x_{5t} and x_{10t}

These combinations of the binary decision variable x_{at} will be selected randomly as the model determines a specific mine site to retrieve the ore. The decision variable b_{at} will be selected for the same arcs and trains as the model should send an empty train for a loaded train to be able to return.

4.1.3 Time constraints

The time constraints (3.9 - 3.22) are added to the model for the following stage of the verification phase. All the time constraints are included in the model as constraints interlink.

Table 8: Verification results of the model with constraints (3.2 - 3.22)

Description	Value
Objective value	210
Binary decision variables: x_{1t}, x_{2t} and x_{7t}, $\forall t \in T$	1
Binary decision variables: $x_{at}, \forall a \in A\backslash\{1,2,7\} t \in T$	0

Binary decision variables: b_{1t}, b_{2t} and b_{7t}, $\forall t \in T$	1
Binary decision variables: $b_{at}, \forall a \in A \backslash \{1,2,7\} t \in T$	0
Binary decision variables: $d_t, \forall t \in T$	Either 1 or 0 has no influence and is randomly allocated

The time constraints link the time variables to the flow variables, respectively. Intersecting flows of loaded and empty trains are not prevented by time constraints. Therefore, the results obtained in Table 8 are similar to what is expected. The decision variable d_t is selected randomly as the variable is still unbounded by the included constraints.

4.1.4 Constraint Propagation

Constraints (3.23 - 3.32) are included in the model to implement constraint propagation and improve its calculation time. The train passes are scheduled chronologically to reduce the combinations in the feasible solution region.

Table 9: Verification results of the model with constraints (3.2 - 3.32)

Description	**Value**
Objective value	210
Binary decision variables: x_{1t}, x_{2t} and x_{7t}, $\forall t \in T$	1
Binary decision variables: $x_{at}, \forall a \in A \backslash \{1,2,7\} t \in T$	0
Binary decision variables: b_{1t}, b_{2t} and b_{7t}, $\forall t \in T$	1
Binary decision variables: $b_{at}, \forall a \in A \backslash \{1,2,7\} t \in T$	0
Binary decision variables: $d_t, \forall t \in T$	Either 1 or 0 has no influence and is randomly allocated

The results obtained from the model in Table 9 correlate with the expected results. The maximum possible trains are scheduled chronologically, with empty and loaded trains still colliding.

4.1.5 Collision Prevention Constraints

The last seven constraints (3.32 - 3.38) are included in the model to ensure that collisions are prevented on the network. The binary decision variable d_t is linked with the flow of the loaded trains in constraints (3.34) and (3.35). The purpose of the binary decision variable d_t is to remove the influence of the passing duration constant, P, and relaxing the constraint. A test case was constructed to compare the model results. Table 10 below provides the times of each vertex visited per train.

Table 10: Results of calculations in Microsoft Excel

Description		Train 1	Train 2	Train 3	Train 4	Train 5	Train 6
Empty Train	Vertex 1	0	277	554	831	1108	1385
Empty Train	Vertex 2	5	282	559	836	1113	1390
Empty Train	Vertex 7	14	291	568	845	1122	1399

Loaded train	Vertex 7	214	491	768	1045	1322	1599
Loaded train	Vertex 2	226	503	780	1057	1334	1611
Loaded train	Vertex 1	276	553	830	1107	1384	1661

As seen in Table 10, only five trains can be scheduled to retrieve ore from a mine site and return to the elevator node within the 1440-minute time frame. These results will be compared with the model results, including all the constraints.

Table 11: Verification results of the model with constraints (3.32 - 3.38)

Description	**Value**
Objective value	175
Binary decision variables: x_{1t} and $x_{6\,t}$, $\forall t \in T/\{6\}$	1
Binary decision variables: $x_{at}, \forall a \in A\backslash\{1,6\}t \in T$	0
Binary decision variables: b_{1t} and b_{6t}, $\forall t \in T$	1
Binary decision variables: $b_{at}, \forall a \in A\backslash\{1,6\}t \in T$	0
Binary decision variables: $d_t, \forall t \in T/\{6\}$	1
Binary decision variables: d_6	0

Table 11 provides results from the model that are as expected, with constraints (3.2) to (3.38) included; the correctness of this model is verified in this section.

4.2 Validation

Section 4.1 verified a model for scheduling trains on a single-lane, bidirectional network with small-scale data; ensuring that the formulation of the model is correct. The validation of the model ensures that the result from the model is an improvement on the current state of the scenario. The model was run with a historical data set to compare the results with the historical data results.

The model schedules the trains within a 1440-minute, similar to the verification model. The historical data consists of averaged data used for comparison, which is the daily supply of the mine network. The data is averaged, meaning the daily supply was 66.12015 tonnes on operating days and zero tonnes produced on shutdown days. The model aims to schedule trains on the days the mine operates and have a supply greater than zero tonnes per day. The optimal objective value found by the mixed integer linear programming model was 175 tonnes per day. The model results are listed in Table 13.

Table 12: Model results with historical input data

Description	**Value**
Objective value	175
Binary decision variables: x_{6t} and x_{8t}, $\forall t \in T/\{7\}$	1
Binary decision variables: $x_{at}, \forall a \in A\backslash\{6,8\}t \in T$	0
Binary decision variables: b_{6t} and b_{8t}, $\forall t \in T$	1

Binary decision variables: $b_{at}, \forall a \in A\backslash\{6,8\} t \in T$	0
Binary decision variables: $d_t, \forall t \in T/\{7\}$	1
Binary decision variables: d_7	0

The results obtained for the mathematical model improve the daily supply by 66.120 tonnes. The model also supplies the schedule's time parameters listed below.

Table 13: Empty trains scheduled time [Minutes]

Vertex	Train 1	Train 2	Train 3	Train 4	Train 5
1	0	285.04	570.08	855.12	1140.16
2	1.51	286.55	571.59	856.63	1141.67
3	33.02	318.06	603.10	888.14	1173.18
4	34.53	319.57	604.61	889.65	1174.69
8	36.04	321.08	606.12	891.16	1176.20
5	36.17	321.21	606.25	891.29	1176.33
7	36.33	321.37	606.41	891.45	1176.49

The times for the loaded trains returning from the supply vertices.

Table 14: Loaded trains scheduled time [Minutes]

Vertex	Train 1	Train 2	Train 3	Train 4	Train 5
7	236.33	521.37	806.41	1091.45	1421.29
5	236.65	521.69	806.73	1091.77	1421.61
8	236.92	521.96	807.00	1092.04	1421.88
4	239.95	524.99	810.03	1095.07	1421.29
3	242.98	528.02	813.06	1098.10	1427.94
2	246.01	531.05	816.09	1101.13	1430.97
1	249.03	534.07	819.11	1104.15	1433.99

The model scheduled two trains to operate in a relay or handover manner. Here's an explanation of the order of operations for the trains: Train A will leave the elevator vertex as soon as the loaded train B enters it. Train B will start to unload, and as soon as train A enters the elevator vertex, train B will leave to retrieve the ore. In this manner, the trains can transport 175 tonnes of ore daily.

The model is an ideal solution, but it did not consider breakdowns or unscheduled maintenance on the network, varying supply capacities, or downtime at supply. These disruptions to the network will influence the schedule and will be deemed to happen sometime during the mine's operations. Therefore, the case study considered uses empirical data. To prove optimality and validate the model Figure 5 is included in the validation to visualise the bottleneck forming at Vertex 1, the elevator vertex.

If the trains can retrieve ore from different source vertices, no congestion will occur at the source vertices. However, the elevator vertex will experience congestion once more than one train is sent to retrieve ore from various source vertices. Two trains will enter the elevator vertex to unload, and additional trains will have to wait on the network until these trains finish unloading at elevator vertices and travel across the network to load ore at a source vertex. Thus, the same amount of ore will be transported across the network as the model schedules. The only difference between the schedules is that more trains will be utilised, and loaded trains will have to wait on the network.

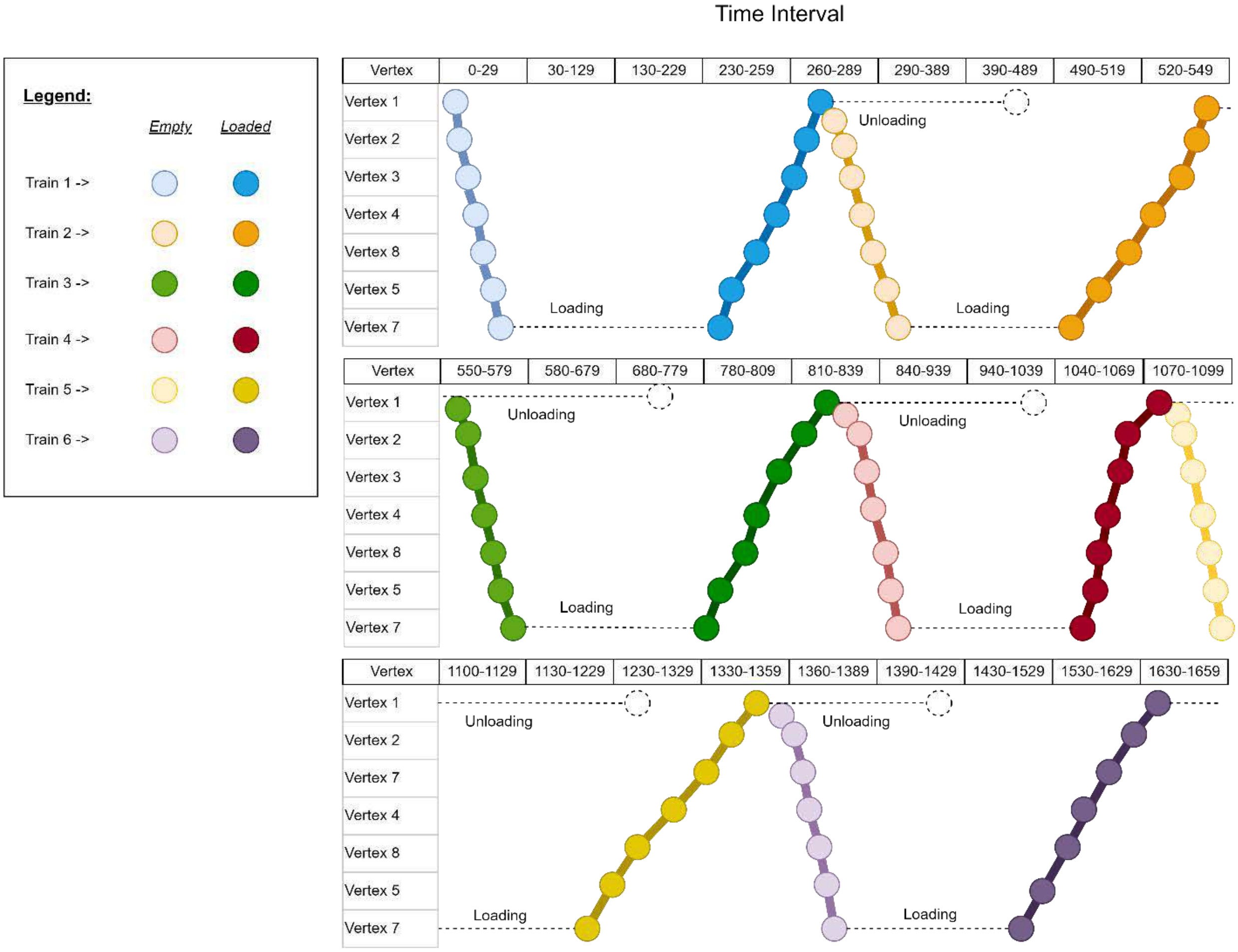

Figure 5: Visualisation of train position over time

5 RESULTS

The mathematical model was developed and implemented on the Elytica platform using a HiGHS solver algorithm, version 1.6.0. The model calculations were conducted on 60 vCPUs. The mathematical model is scoped to schedule trains on the transportation network for only 24 hours, reducing the computational power required and calculation time.

Table 16 lists the relevant information regarding the scalability testing of the model.

Table 15: Scalability results of the mathematical model

Iteration	Total number of arcs	Total number of nodes	Number of supply nodes	Number of available trains	Optimal solution found (in tonnes)	Average solving time (in seconds)	Standard deviation (in seconds)
1	7	8	1	7	175	0.390	0.066
2	9	10	2	7	175	5.130	0.905
3	11	12	3	7	175	60.619	19.531
4	13	14	4	7	175	582.889	169.380
5	15	16	5	7	175	3987.632	617.336

6	17	18	6	7	175	20221.405	3985.580
7	21	20	7	7	175	>43200	-

The HiGHS solver algorithm utilises random seeding of solutions within the feasible region as part of its exploration and solving process. The average and standard deviation of the solving time for ten iterations were calculated and included in Table 16.

As seen with the iterations of different network sizes and linear increase in supply nodes, the computational time of solving the model grew exponentially. The cutoff for the dataset size is a time limit of 43 200 seconds or 12 hours, as it is the general shift duration. The model should be flexible enough to adjust after the first shift and recalculate the schedule for the following day. The ideal is a shorter computational duration so that the model is more responsive towards disruptions on the network. The model reached the time limit with the 7th iteration; therefore no standard deviation is included for the 7th iteration.

The optimal solution obtained by the mathematical model was included in the results. The optimal solution was consistent between the iterations as the given case study used in the scaling has one path towards the single elevator on the network and the simultaneous movement of trains clash.

6 CONCLUSION

The demand for operations research is exceptionally high in business, as mathematical optimisation is highly diverse and valuable. The mining sector has various opportunities for optimization. This study found that scheduling trains more efficiently can significantly improve the transportation network.

The mine network consists of various transportation systems for different mine sections. This study focuses on the rail-bounded transportation section in the transportation network of underground mines. Trackless vehicles load the train wagons at the supply vertices from which the trains transport the ore to elevator shafts. The elevator raises the ore to the surface for further processing or stockpiling.

Given the constraints and requirements, this study proposes a mixed integer linear programming model that maximises the transportation throughput of the rail-bounded vehicle network. The model quantifies the time duration for traversing the network in a loaded and empty train and uses the values to schedule the trains. The mathematical formulation of the mixed integer linear programming model is verified to ensure that it is correctly formulated and coded in Elytica. Historical data is used to validate the results obtained from the model. The model was solved using an open-source solver, but commercial solvers will perform better.

7 FUTURE RECOMMENDATIONS

Future research should further investigate the model's response by comparing the simulated results to those obtained for the practical case study.

This study schedules trains without uncertainty in any parameter, making the schedule ideal but impractical. For future research, uncertainty within the schedule will be recommended to determine a more practical and applicable day-to-day schedule. The unscheduled maintenance and breakdowns will increase the complexity of the model; a stochastic model will incorporate the probability of unscheduled breakdowns on the network and downtime in the supply.

As seen in Table 16, the model’s scalability is poor and impractical for large data sets. An exact or heuristic model with greater bounds is recommended for solving in a shorter time, which will improve the model’s practicality for real-time solutions.

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ASSESSING MAINTENANCE 4.0 MATURITY: A CASE STUDY OF A SOUTH AFRICAN MINING COMPANY

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ABSTRACT

The study designed a Maintenance 4.0 maturity model to guide organizational leadership in the South African mining industry in assessing readiness and improving their maturity in maintenance practices. The model was developed using a top-down approach within a Design Science Research paradigm. The model consists of ten dimensions structured along five maturity levels derived from the capability maturity model. The model's effectiveness was validated using a close-ended questionnaire at a South African mining company, revealing that adoption rates of success criteria were mostly in the nascent stages of maturity. The maturity assessment of the South African mining company revealed that the overall maturity level was in the early stages of implementing Maintenance 4.0.

Keywords: maintenance 4.0, readiness model, mining, South Africa

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1 INTRODUCTION

The South African mining industry has long been a cornerstone of the nation's economy, contributing significantly to employment, export earnings, and overall economic stability. The South African mining industry has faced increasing challenges, such as an increase in labour costs, a decline in productivity, increased safety concerns related to equipment degradation and the targeting of ever-deeper mine reserves [1]. This has a bearing on the industry's future, given that there is a reluctance to continue investing in the sector [2]. Furthermore, mining companies worldwide are expected to continue to be under increasing pressure to operate at costs that are in line with international competitors [3]. This is primarily shaped by the prices of metals and minerals, which are determined by the market [2, 4].

It is proposed that to ensure long-term business sustainability, the improvements to the mining industry can be implemented in those lifecycle phases that contribute the most to cost: operations and maintenance [5, 6]. Organisations must operate with minimal disruptions to their operations, and it is the maintenance function that is important in reducing the cost due to downtime owing to the probability of failure [7], impaired quality, and reduced efficiency [8]. Over time, several maintenance philosophies have been proposed to minimise failure and reduce cost. These philosophies have developed from rudimentary models that only implement maintenance action when an item fails (corrective maintenance or run-to-failure) to more innovative techniques that detect and predict the onset of failure [9].

At the Hanover Messe in 2011, "Industrie 4.0" was officially invented [10]. The term "Industrie 4.0" was coined to present the step-change evolution away from the past three industrial revolutions and to name the strategy pursued by the German government formally [11]. This new revolution, also known as the fourth industrial revolution [12], promises to bring enhancements to a wide range of industries [13], sub-sectors [14] and even individual, organisational functions such as maintenance.

Several authors have reported that the adoption of Industry 4.0 technologies has the potential to lead to the improvement of the operational performance of companies through the indirect improvement of existing production and maintenance practices [15-17]. However, the intersection of Industry 4.0 and maintenance needs further clarification [18]. There is a drive to ground the constructs of maintenance in the Industry 4.0 frame on empirical grounds [19] since the lack of concept clarity can lead to a multitude of problems [20], with a rapid increase in the development of a multitude of concepts that are related but which are termed differently being but one of the main problems [21]). This is evidenced by related definitions, such as e-Maintenance [22], Maintenance 4.0 [23], Smart Maintenance [15], Intelligent Maintenance [24] and Maintenance Digital Transformation [25]. Furthermore, the concept of proliferation, which is defined by [20] as "a development of concepts with different names but overlapping domains" is potentially detrimental to the adoption, further explanation of theory, and conducting empirically grounded research [19] and it can lead to reduced creation of new knowledge [26] as it manifests in confusion among researchers and practitioners [21].

Within the new paradigm of maintenance conducted where digitalisation is prevalent, the emphasis is placed on increased intelligence, improving efficiency and automaton through automated data collection, employing more advanced data analytics visualisation and improving decision-making through structured means [25]. At the bedrock of this new paradigm of conducting maintenance are the key enabling technologies that define Industry 4.0 - Internet of Things (IoT), Big Data and Analytics, Cloud Computing, Artificial intelligence, Cyber-Physical Systems (CPS), Augmented Reality (AR) and Simulation [27]. However, implementing Industry 4.0 technologies is only one of the determiners of success. A combination of managerial, organisational and people factors [28], amongst others, is expected to improve performance positively. Furthermore, the combined effect of people, technology, and organisational factors on the successful implementation of digital transformation of maintenance is a topic that requires further explanation [15].

Given that the rates of digitalisation in the mining industry are relatively low [29] compared to manufacturing, financial services and retail, this identifies that the industry's orientation towards realising the benefits offered by the Industry 4.0 paradigm could be better directed [15]. Therefore, to effectively pursue Industry 4.0 adoption, organisations must comprehensively understand their maturity level. The organisation's strategic framework must guide the comprehension of the present condition and the direction towards an improved state [27].

As a mechanism to facilitate this identification of capabilities required for transformation, assessment frameworks, especially those of the maturity models, have become indispensable [30-35]. Furthermore, several authors have proposed that applying maturity models and readiness assessments as the initial step in the implementation of Industry 4.0 [33, 36-38]. Maturity models and assessments provide an organised method for institutions to evaluate their current proficiencies, systematically promoting the application of enhancements and modifications. A maturity model is an orderly aggregation of components which describe specific dimensions of an organisation's capability maturity [35]. Maturity models have been utilised extensively to assess the current state of maturity or readiness and to prepare a roadmap for maturation to allow the gap between the current state and the target state to be closed. Thus, to properly orient organisations towards transformation, assessing the current readiness levels across the different concepts is essential to identifying gaps and prioritizing strategic initiatives to advance Maintenance 4.0 maturity.

1.1 Research Objectives

The primary objective of this research was:

1. To develop a Maintenance 4.0 maturity model specifically tailored for the South African mining industry.
2. Assess and guide the maturity progression of maintenance practices within the specific South African mining company.

1.2 Research Questions

The research questions focus on defining Maintenance 4.0 concepts, identifying influential factors, evaluating maturity, and assessing readiness. This was done through the following research questions:

1. What main concepts define Maintenance in the Industry 4.0 paradigm from a technology, organisational, people and management perspective in other industries, and how do they compare to the South African Mining Industry?
2. What are the most influential factors in successfully implementing Maintenance 4.0?
3. How can the maturity and maintenance readiness state in the Industry 4.0 era be understood and evaluated?
4. What is the current state of maturity for Maintenance 4.0 implementation in a specific South African mining company?

The outline research methodology consisted of a review of scientific literature on concepts of maintenance within the paradigm of Industry 4.0. This was done to locate, analyse, and synthesise existing academic literature, with the focus being the identification of models, frameworks, or concepts with academically verified constructs for evaluating the maturity or readiness of organisations in implementing a successful transition to Maintenance 4.0.

2 THEORETICAL FRAMEWORK

This section discusses the concept of maturity models, their importance in assessing organisational capabilities, and how they provide a structured approach for guiding organisations through progressive stages of development and improvement in the context of Maintenance 4.0.

2.1 Maturity Models

Several authors have proposed maturity models and readiness assessment as the initial step in implementing Industry 4.0 [33, 36, 38]. Furthermore, several authors have recommended developing maturity models incorporating people, technology, and organisational factors [15, 25]. In the context of a globally competitive business environment, it is paramount that entities ascertain their unique advantageous positions, leveraging these for optimal performance [31]. Assessment frameworks, especially those of the maturity models, have become indispensable to facilitate this [31]. They provide an organised method for organisations to evaluate their current proficiencies, capabilities, or level of sophistication, systematically promoting the application of enhancements and modification [31]. Such a maturity model can be delineated as an orderly aggregation of components which outline specific dimensions of an organisation's proficiency maturity [35].

A typical maturity model presents levels of maturity based on a description of the main dimensions that define the framework under study. Several characteristics for each maturity level describe each of the dimensions with features approaching those of the desired state with each step forward along the continuum [31]. These descriptions build on one another as the maturity of the desired state is approached, and it is common practice to assign the low maturity state with a low number descriptor and the high maturity state with a high number descriptor. The typical components of a maturity model (where all may not be present) are the following [39]:

- several maturity levels (typically 3-6),
- a description of each maturity level,
- a general description or summary of the characteristics of each maturity level,
- several dimensions or process areas (that can be further segmented into subdimensions or categories),
- several elements/attributes or activities for each dimension or process area, and
- a description of each element or activity as it could present itself at each maturity level.

A five-level maturity ranking was chosen for this study. The premisses for each maturity level were based on the descriptions of a generalised level shown in Table 1.

Table 1: Description of each maturity level

Maturity Level	**Descriptors of maturity level**
Level 1: Initial	ad hoc, not recognized, informal, uncertainty, occasionally even chaotic, no formal approach, few activities are defined, success depends on individual effort and heroics, performance not predictable, value not realized, no learning from experience, everything is new or unique; problems are mostly managerial and organisational; temporary processes; defined by failure to reach Level 2
Level 2: Repeatable	basic, initial efforts, regression, repeatable activities, tracking of costs, schedule, and functionality; operational activities are planned and tracked; process discipline is established to repeat earlier successes; focus shifts to operational activities (not described in detail, but planned and tracked)

Level 3: Defined	documented, standardized, and integrated into a set of standard competencies for the organisation; new projects and programs make use of an approved and tailored version of the organisation’s set of standard approaches, methods, and processes; operational processes are first explicitly addressed (organisational learning)
Level 4: Managed	wisdom, enlightenment, excellence, improvement integrated, managed, competencies and activities quantitatively understood, and controlled; evidence-based management; statistical thinking
Level 5: Optimising	certain, collaborative, enterprise-wide integration, continuous improvement, culturally embedded, best in class, mastered, institutionalized, optimised; competencies, processes and activities are understood; difference in performance can be explained

Source: Von Scheel *et al.* [35]

A systematic literature review conducted on May 10, 2023, revealed ten dimensions with a summary of the validated attributes required to implement Maintenance 4.0 as illustrated in Figure 1. The attributes identified through the review were found to have been tested in multiple countries and industries and through the application of different research designs. This demonstrated their validity, generalisability, and applicability.

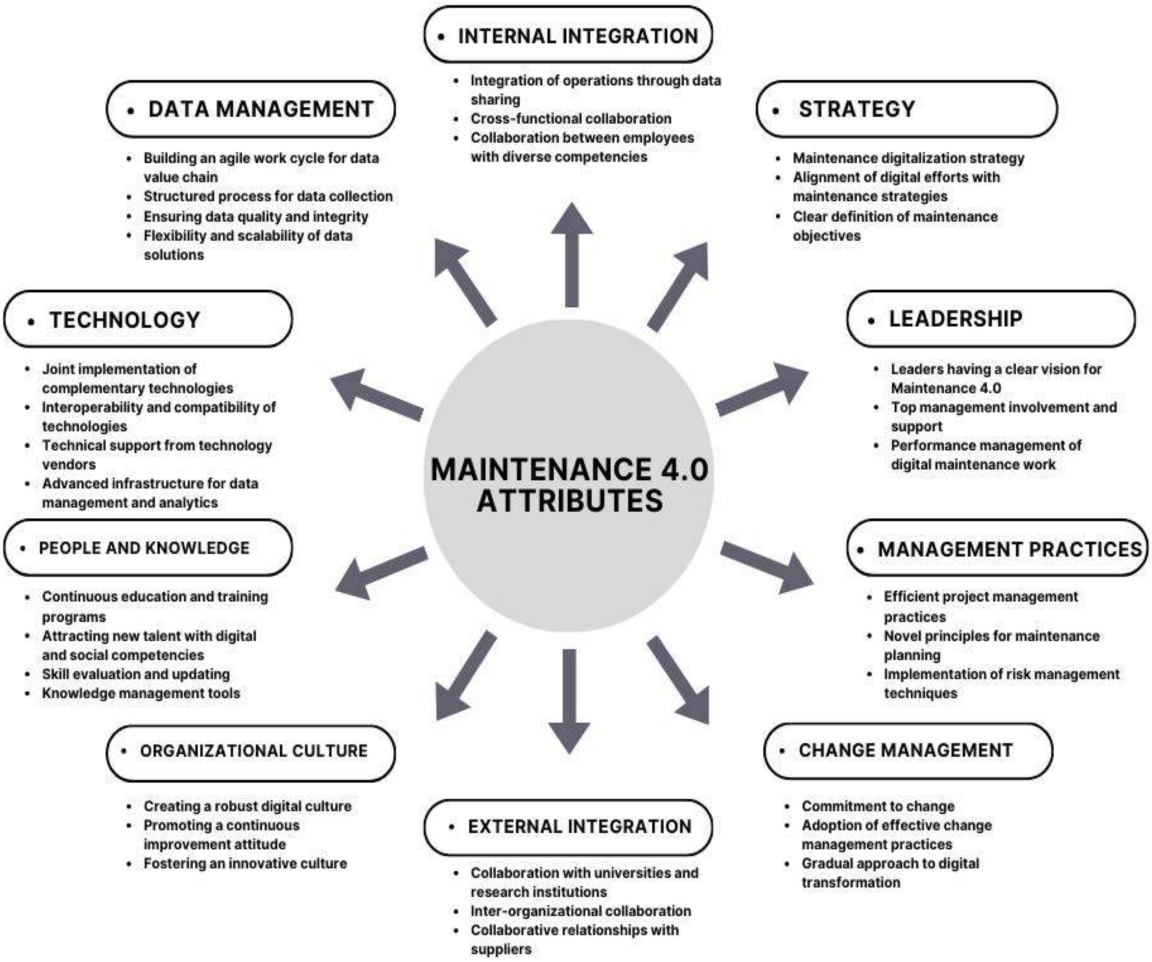

Figure 1: Identified Maintenance 4.0 dimensions with attributes.

When developing maturity and readiness models, researchers are tasked with identifying gaps or inefficiencies in current states, designing models to chart optimal evolutionary paths, and rigorously evaluating their efficacy [31]. The development of maturity models can follow several paths: conceptualising a new model, improving on an existing model, combining several existing models to form a new whole, or transferring concepts from one domain to another [30]. According to [40], the development of a maturity model must overcome the following main challenges:

1. The methodology for quantifying the distance between maturity levels.
2. The scale that is utilised for measurement.
3. Approaches to tackle the additivity challenge and determine the overall maturity.
4. The origin of the dimensions being considered.
5. Defining the maturity levels and operationalising the relationship between dimensions and maturity levels.

Several authors have developed frameworks for formulating maturity models, as summarised in Table 2. These frameworks provided a theoretical foundation to operationalise and contextualise the maturity model to the specific domain of Maintenance 4.0.

Table 2: Maturity model development frameworks

De Bruin, et al. [31]	Becker, et al. [30]	Maier et al. [41]
1. Scope 2. Design 3. Populate 4. Test 5. Deploy Maintain	1. Problem definition 2. Comparison of existing models 3. Development strategy 4. Iterative MM development 5. Concept of transfer and evaluation 6. Implementation of transfer media 7. Evaluation Rejection of Maturity Model	1. Phase I: Planning a. Specify audience b. Define aim c. Clarify scope d. Define success criteria 2. Phase II: Development a. Select process areas b. Select maturity levels c. Formulate cell text d. Define administrative mechanism 3. Phase III: Evaluation a. Validate b. Verify 4. Phase IV: Maintenance a. Check benchmark b. Maintain results database c. Document and communicate the development process and results

2.2 Assessment tools

Maturity is assessed first by obtaining quantitative data from a questionnaire graded on an ordinal scale [33, 38, 42, 43]. Whereafter, the data can be transformed using a synthetic indicator based on the P2 distance method [44], factor loadings [43], or mean values coupled with additional statistical measures for data analysis and discussion [33, 38].

2.3 Representing the results of the maturity model

The results of the maturity assessment are typically displayed on a radar chart to provide an overall result briefly and to increase further understanding of the individual attributes that are organised in various dimensions [33, 38, 43].

Furthermore, where multiple organisations are compared, statistical measures and representation using box plots are also common [42].

3 CONCEPTUAL MODEL

In developing a tailored maturity model to measure the extent of Maintenance 4.0 success factor implementation within South African mining companies, an approach drawing from the frameworks of [31], [15], and [25] was employed.

A holistic and multi-faceted conceptualisation of success factors was presented by [25] that, when incorporated into an organisation, could lead to the successful transformation of the maintenance function and success in improved maintenance outcomes and firm performance.

The relative importance of these factors was investigated through a multiple-round Delphi Study.

Consequently, this structure was adopted for this research study as it proposed that a complete overarching model will both educate research participants about the relevant dimensions of Maintenance 4.0 and will allow the executive, senior and middle-level managers in maintenance functions to adequately prepare and implement targeted action plans to reach their targeted states of maturity.

The data extracted through the SLR was coded following the framework developed by [25] as a guide, along with the proposed conceptual model that is presented in Figure 2. The points indicated with "✓'' were part of this current study, whereas the light grey ">'' points were excluded.

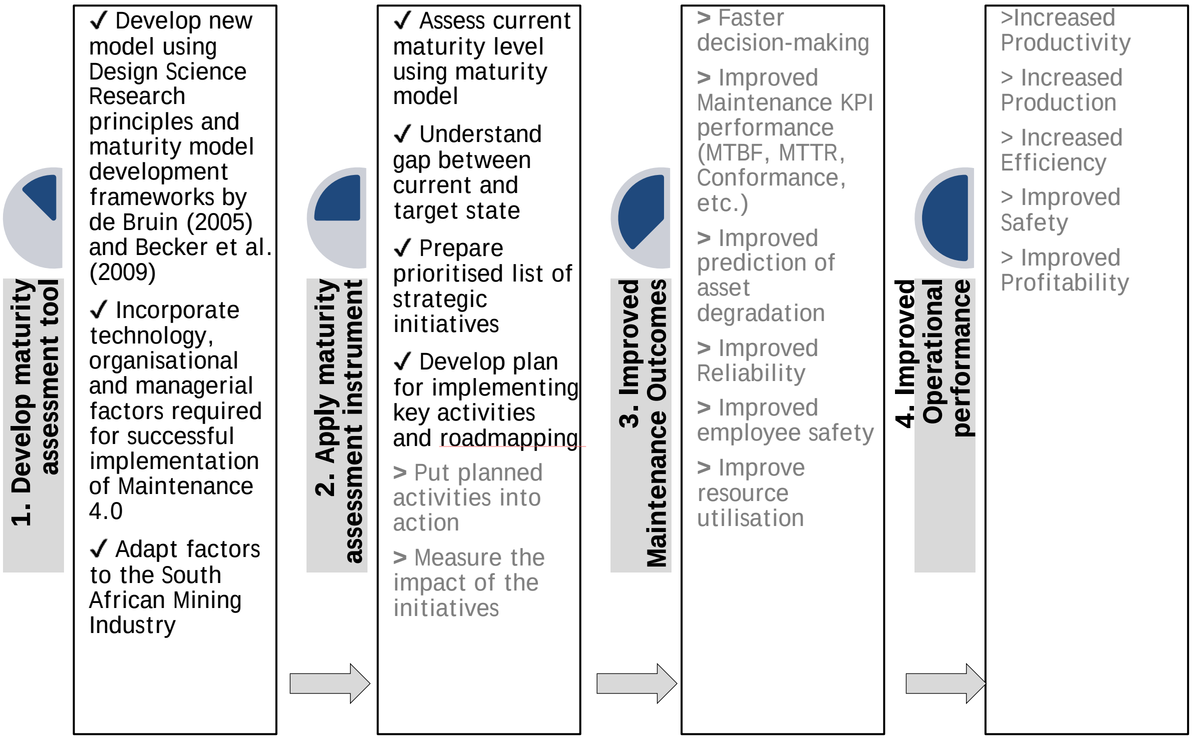

Figure 2: Conceptual framework for the research study.

The following frameworks contributed to the development of the conceptual mode:

1. An increase in capability maturity is positively related to improving organisational performance [31].
2. Maturity models are an effective tool for understanding the current state of capability maturity and providing a starting point for increasing maturity performance [31].
3. Improving Maintenance 4.0 capabilities can improve organisational performance via improved maintenance performance [15, 17].
4. Technology alone is insufficient to ensure the success of digitalisation attempts [25].

4 RESEARCH METHODS

4.1 Questionnaire

A questionnaire was developed to answer the research question: What is the current state of maturity for Maintenance 4.0 implementation in a specific South African mining company?

Each of the attributes of the maturity model was formulated into questions to test the maturity of these attributes using the five levels of maturity. Some attributes had more than one question, resulting in 46 close-ended questions to measure attribute maturity as developed in the maturity model. The closed-ended questions were not organised per dimension but as a complete list. This was to eliminate the risk that the grouping of the questions would influence the responses. The attributes were scored on a five-point Likert scale, where 1 represents the lowest maturity level, and 5 represents the highest maturity.

An example of a question is shown below.

Question 1: “To what extent is the incorporation of digitalization within maintenance considered a fundamental element of a wider digital strategy?”

- Level 1: Maintenance digitalisation is ad hoc and informal. Strategic thinking and top management support are uncertain and unpredictable.
- Level 2: Maintenance digitalisation is part of a basic digital strategy. Initial efforts towards strategic thinking and top management support are noticeable but not fully established.
- Level 3: Maintenance digitalisation is part of a documented digital strategy, standardised and fully supported by top management. Strategic thinking is integrated into the organisation's competencies.
- Level 4: Maintenance digitalisation is managed and controlled under a wisdom-driven digital strategy. Strategic thinking is an evidence-based activity supported by enlightened management.
- Level 5: Maintenance digitalisation is a certainty in the organisation's digital strategy, which is institutionally optimized. Strategic thinking is collaborative and embedded in the culture, leading to continuous improvement.

5 RESULTS

5.1 Maturity Assessment

The organisation's relevant asset management and maintenance professionals were identified and invited to participate in the research following a purposive sampling technique. The questionnaire was distributed on August 08, 2023, and was open for two weeks to allow the respondents sufficient time to complete it. 17 fully completed questionnaires were returned from the 57 questionnaire invitations sent. The profiles of the different participant classifications are shown in Table 3.

Table 3: Response rate of the maturity assessment questionnaire

Participant class	Role	No. of participants
1	Engineering manager	4
2	Maintenance engineer	9
3	Junior engineer	2
4	Telecommunications, instrumentation, and IT practitioners	2
	Total	17

The data was downloaded from the Microsoft Forms platform and analysed using Microsoft Excel. The mean, median, mode, standard deviation and coefficient of variation were then calculated, and conditional formatting was applied to the coefficient of variation values to highlight variation across the attributes of the maturity model.

The results from the questionnaire designed to measure the current state of maturity of a South African mining company are discussed briefly. The mean, median, mode, standard deviation and coefficient of variation are interpreted in terms of central tendency and variation to determine the consensus between research participants and to draw conclusions. Recommendations are made based on an analysis of the systematic literature review's data, conclusions, and findings.

The attribute with the highest maturity score was within Technology: " Implementation of cyber security and data protection solutions”, with a mean of 3.35 and medians and modes of 3 and 4, respectively.

- The mean response of 3.35 suggests that the organisation has moved beyond the initial recognition of the importance of cybersecurity and data protection. It indicates a transition from ad-hoc approaches to a more systematic and defined cybersecurity strategy emphasising robust measures to safeguard digital assets and comply with data protection regulations.
- The median value of 3, however, underscores the overall central tendency among the responses toward the organisation having a defined cybersecurity strategy, with consistent protection of digital assets and adherence to regulations.
- The mode of 4 emphasises that most respondents believe the organisation has advanced cybersecurity measures. They see the organisation as being resilient to cyber threats, systematically ensuring compliance with regulations, and quantitatively managing the effectiveness of protective measures.

In conclusion, the data suggests that the organisation has progressed in its cybersecurity and data protection efforts, moving beyond initial recognition and ad-hoc measures to more structured and advanced strategies. However, there might be room for improvement.

The attribute with the second highest maturity score was under Management Practices: “Adhere to environmental standards during the implementation” with a mean of 3.29 and median and modes of 3, respectively.

- Most respondents perceived that the organisation has a basic strategy to adhere to environmental standards in technology implementation and that there are guidelines for responsible disposal and energy-efficient technology usage. However, the respondents may also perceive that the implementation may not be consistent across all projects.
- This attribute also has the lowest coefficient of variation of 0.17 among all the attributes, which indicates a strong consensus among respondents.
- While there was slight variation amongst all respondents, the Engineering Managers who completed the survey were aligned with a mean response of 4, with no variation in responses. This suggests that this group believes the organisation has a well-defined and consistent strategy to integrate environmental standards into technology implementation and actively considers sustainability criteria when selecting vendors and technologies. Furthermore, there is a perception that efforts are made to optimise energy consumption and minimise environmental impact.
- The differences in the Engineering Manager responses and the whole sample may indicate a disparity in knowledge about the organisation's strategies between higher-level managers and the rest of the organisation.
- The organisation is certified to ISO 14001: 2015, which binds it to the requirements of the comprehensive standard and requires routine audits to maintain the certification. This indicates that adhering to environmental standards, in general, is a component of

the organisation's strategy and that incorporating new technologies is aligned with these requirements.

The attributes with the lowest maturity scores are People and knowledge: “Attract new talents: experts of Industry 4.0 and data scientists” and External Integration: "Establishing inter-company collaboration", with respective means of 1.76 and modes of 1. The respective coefficients of variation for these two attributes are 0.5 and 0.46, which are the third and fourth highest, respectively, after Strategy: "Establish ROI/Cost-benefit analysis," and People and knowledge: "Continuous education and training to develop required workforce competencies," with coefficients of variation of 0.51.

The maturity score for each dimension was calculated as the mean of the individual attribute scores in each dimension. The results are ranked in Table 4. The company's maturity is still at Level 2, where process discipline is established to repeat earlier successes and initial efforts have been made.

6 CONCLUSION

The systematic literature review identified several concepts and constructs similar to Maintenance 4.0. Terms such as Maintenance Digitalisation, Maintenance Digital Transformation, Intelligent Maintenance, e-Maintenance, Smart Maintenance and Digital Maintenance were identified. While these were derived in separate settings, they all consider the impact that Industry 4.0 has on the maintenance function. They provide various maintenance benefits, which were validated by applying different research methods in various industries.

Table 4: Ranking of maturity dimensions by mean scores in descending order.

Dimension	Mean Score	Rank
D2: Leadership	2,65	1
D7: Technology Management	2,53	2
D8: Data Management	2,52	3
D9: Internal Integration	2,41	4
D3: Management Practices	2,41	5
D4: Change Management	2,33	6
D1: Strategy	2,27	7
D5: Organisational Culture	2,24	8
D10: External Integration	1,98	9
D6: People and Knowledge	1,98	10
Overall Maturity Score	2,33	

The findings from the research indicate that the assessment tool developed in this research study was useful for providing an as-is assessment of the organisation's standing concerning Maintenance 4.0 and the way it was defined in the study. The presentation of the tool to decision-makers in a South African mining company was met with positive sentiment and a desire to incorporate the findings into the organisation's asset management strategy. This provides validation that the tool, created following the design science research paradigm, developed knowledge and produced effective and innovative solutions to real-world problems [45].

The overall company Maintenance 4.0 maturity score was 2.33, and at the extreme ends of maturity, i.e. attributes with the lowest and highest maturity scores, it was found that the attributes with the lowest maturity scores had the highest variation in responses:

- Strategy - Establishing ROI
- People and knowledge - Continuous education and training to develop required competencies
- People and knowledge - Attracting new talents and
- External Integration - Establishing collaboration with universities and research institutions

Moreover, the attributes with the highest maturity scores had the lowest variations in responses:

- Management Practices - Adherence to environmental standards

Furthermore, the responses indicated a strong desire to pursue greater Maintenance 4.0 maturity, as evidenced by the selection of Level 5 across the board in response to the question about the organisation's desired state. This insight indicates that the decision-makers at the South African mining company believe that Maintenance 4.0 is worth pursuing, which is also underscored by engineering executives' recommendations to incorporate the learning from the maturity assessment into the organisation's asset management strategy. Thus, the research and the problem it aimed to solve are thus validated.

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DEVELOPING AN ENTERPRISE RISK MANAGEMENT (ERM) MODEL TO INCLUDE PROJECT RISK MANAGEMENT, CASE STUDY: CONSULTING ENGINEERING, WINDHOEK NAMIBIA

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ABSTRACT

Enterprise Risk Management (ERM) moves away from the traditional silo-based risk management and focuses on the combined effect of the risks. The downward economic spiral of the construction industry in Namibia from 2016 to date has led to the investigation of incorporating ERM in the consulting engineering sector. Factors that may contribute to Namibian recessions are severe drought, reduced public investments, lower commodity prices, and reduced growth in neighbouring countries. The risks impact organisations beyond project risks and require a holistic approach to risk management. The study aimed to develop an ERM model for the consulting engineering industry in Windhoek. The first step was identifying the general requirements for an effective ERM model. Semi-structured interviews identified the significant organisational and project risks experienced, including economic, political, cyber security, and infrastructure risks. Adopting proactive measures can contribute to the growth, competitiveness, and resilience to face various challenges within the sector.

Keywords: Enterprise Risk Management (ERM), ERM Framework, Project Risk

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1 INTRODUCTION

The economy in Namibia from 2016 to date has been on a downward spiral, with three of the past years being in recession [1]. The World Bank further states that the probable factors linked to the recession are severe drought, reduced public investments, lower commodity prices, and reduced growth in neighbouring countries. The Namibia Statistics Agency (NSA) published figures indicating an overall positive performance within the third quarter of 2021 for the Namibian economy, but the construction industry declined by 43.7% [2]. The construction industry affects a sizeable portion of Namibia's consulting engineering industry. Effective, holistic, and proactive risk management procedures may reduce the volatility of the construction industry in Namibia.

Organisations all over the world experience various forms of risk on a daily base. With the current economic climate in Namibia, it is essential to develop a working knowledge regarding risk and risk management. The definition for risk provided by the Oxford English Dictionary [3] is as follows: "*a chance or possibility of danger, loss, injury or other adverse consequences.*"

$$Risk = Probability \times Consequence \tag{1}$$

In the stated definition, risk describes only a negative occurrence or outcome. On the other hand, opportunity risk can have positive results for the organisation if the correct decisions are made. Ward & Chapman [4] state that management should move towards project uncertainty management instead of project risk management. Commonly, society links risk to an adverse event, but uncertainty management tries to take the focus away from the preconceived negative connection and more on uncertainty. The Project Management Institute [5] define risk as either positive (opportunities) or negative (threat) risks. Threats should be managed within a project to prevent or limit cost overruns, delays, reputational damage, or inefficient performance [5]. The uncertainty within opportunities still produces a risk but a potentially positive result. The International Organisation for Standardisation (ISO) defines risk as the "*effect of uncertainty on objectives*" [6]. Risk is the uncertainty that can impact the outcome or fulfilment of the organisational objectives or goals [7].

There are multiple risks that an organisation can encounter throughout projects or general operations. Risk management will not eliminate the risks but can reduce them to an acceptable level [7]. Olson and Wu [8] indicate that the risks are operational, strategic, legal, credit, and market risk. It is crucial to evaluate the effect on an organisation due to each mentioned risk type and manage the risks accordingly. Further, Hopkin [7] divides the potential risks encountered by an organisation into four categories. The categories are compliance, hazard, control/uncertainty, and opportunity risks. Compliance risk is related to all the mandatory requirements and regulations a company must comply with to ensure uninterrupted operation. Hazard risk, also called pure risk, is associated with an adverse effect or a source of potential harm that can undermine the organisation's objectives. Hazard risks are often insurable, but this might not always be true. Control risks are associated with project uncertainty. The severity or consequence of the event is difficult to predict and control due to multiple variables and unknowns within projects. Opportunity risk has a positive connection as the risk is for the potential gain within the organisation. The outcome of opportunity risk can still induce an adverse effect due to the uncertainty.

1.1 Enterprise Risk Management

Before the 1970s, risk management focused on hazard risks linked to liability, employee safety and property [9]. Traditional risk management is commonly associated with silo-based risk management. Corporate risk managers focus on hazard risks, and the treasury department manages and mitigates financial risks [10]. The combined effect of individual risks can generate more significant consequences than the sum of the individual risks [7]. It is essential to understand each risk together with the interaction of the risks [11]. The holistic overview of organisational risk influences crucial risk decisions an organisation faces.

Organisations tend to move away from silo-based risk management and towards a holistic view of risk management [12]. Hopkin [7] indicates that the holistic or broader approach to risk management is enterprise risk management (ERM). Gordon et al. [12] state that the comprehensive approach of the ERM is a key factor drawing organisations away from the traditional risk management approach. Organisations implement ERM to increase the ultimate effectiveness of the risk management processes and the stakeholder value [13]. A study conducted by Tillinghast-Towers Perrin [14] argues that ERM has developed past the growing pains, and the benefit of strategic risk management is receiving increasingly more attention.

There are various definitions for ERM, but a widely accepted definition as per the Committee of Sponsoring Organisations of the Treadway Commission (COSO) [15] is:

> *"Enterprise risk management is a process, effected by an entity's board of directors, management and other personnel, applied in strategy setting and across the enterprise, designed to identify potential events that may affect the entity, and manage risk to be within its risk appetite, to provide reasonable assurance regarding the achievement of entity objectives."*

An organisation's strategy, culture and competitive position influence the appetite towards risk [16]. Dionne [17] furthermore includes that management's perception of risk and corporate governance affects the choice and implementation of risk management activities. Risk perception, in simple terms, is the view, feeling or judgement an organisation has towards managing threats and chasing opportunities. Organisations must adapt and change their risk appetite to prevent underperformance, as risk management should be dynamic and continuously adjusted. The participation and culture of the organisation's board, management and employees are essential for a successful ERM.

There are various frameworks and standards focused on the implementation of ERM within organisations. Hopkin [7] highlighted mutual features between the different ERM approaches as follows:

- All-inclusive to organisational risk exposure.
- Prioritise and manage risk holistically, not individually.
- Evaluate risk in all significant internal and external contexts.
- Individual risks can be interrelated and have a cumulative effect more significant than the sum of the individual risk exposures.
- Has a structured procedure to manage risks.
- Integrates risk into all critical decisions regarding the organisation.
- Aid organisations to identify strategic risks that can aid in objective achievement.
- It improves the communication and reporting of risks.
- It provides a structured approach to internal auditing.
- Effective risk management is a competitive advantage to achieve organisational objectives.

Lam [18] states that the critical focus of ERM is integration. Further, Lam [18] indicates the following requirements for an effective ERM integration: integrated risk organisation, integration of risk transfer and the complete integration of risk management within the objectives or processes of the organisation. Integrating an ERM into business operations will increase organisational effectiveness, improve risk reporting, and improve business performance [18]. The implementation of ERM provides a framework for implementing discipline within the organisation to methodologically assess opportunities, deal with uncertainties, and provide the required transparency for the stakeholders [19].

2 LITERATURE REVIEW

2.1 ERM Implementation

The increase in stakeholder value is one proposed benefit that is highly sought after when implementing ERM in an organisation. Assisting the managers in identifying, monitoring, and managing the organisation's overall risk increase in stakeholder value [20]. If management values risk and returns as a measurement of performance, an effective implementation of an ERM without an increase in return can still count as achieving the organisational objectives [21].

ERM implementation enhances the value of larger businesses by reducing market volatility, increasing returns, improving the return on equity, and increasing capital efficiency [22]. Integrating an ERM framework within an organisation combines all the risk management activities to facilitate the holistic evaluation of the organisational risk [23]. Various contractors suffered significant losses due to focusing only on lower-risk projects without consideration of the overall effect on the organisation [24]. Being risk averse lowers the immediate project risk but can reduce the potential gain from opportunities. Identifying all the possible organisational risks but focussing on the holistic, more significant risk can save time and administration towards risk management with an improved outcome.

A study by Oliveira, Méxas, Meiriño & Drumond [25] provided various factors contributing to effective ERM implementation. Some factors include high management commitment, awareness and risk culture, risk communication, risk indicators, monitoring, review, and improvement, establishing the organisational risk tolerance and appetite, and providing sufficient resources availability.

Successfully implementing an ERM model requires multiple steps to be incorporated. Some of the steps, but not limited to, include obtaining leadership, involvement, and oversight from the board and senior management. Selecting a strong ERM champion or leader to drive the initiative is imperative. Establish a designated risk management committee with an initial risk assessment conducted at the enterprise level to develop an action plan. Establish the current risk management processes. Establish the risk reporting procedures. Revise action plans and continuously provide training and communication [26].

2.2 ERM Framework

Various frameworks exist to assist organisations with the implementation of ERM models. The implementation approach and requirements depend on the industry and will differ from organisation to organisation. Governance structure and policies, risk assessment and management, and monitoring and reporting form the main structure of three highly adopted risk management and ERM frameworks.

All three frameworks, namely COSO, AS/NZS 4360, and ISO 31000 stress the importance of organisational governance for implementing ERM. Important governance aspects noted from the frameworks are establishing clear roles, responsibilities, and accountability. The integration of ERM should form part of the organisational objective setting and strategic planning. Management should determine the risk culture and communicate the risk culture to the entire organisation.

Once the organisation and its internal and external context are understood [6], the risk assessment and treatment of the frameworks start with identifying and evaluating the potential risks. The process headings are broken down differently between the frameworks but include similar activities. After the identification and evaluation, the risk-appropriate treatment options are developed and implemented. Monitoring and reviewing the organisational risk and applied treatment options is essential to track any changes within the organisational risk profile and adapt the risk management strategy accordingly. The frameworks share common elements but with different terminology, structure, and specific guidance provided. The chosen framework for implementation will depend on the organisational requirements, regulations, and industry standards.

Implementing an ERM framework within an engineering project-based organisation will present some challenges. Each project is subject to unique and project-specific risks not addressed within the generic risk frameworks. The frameworks provide an integrated approach for the organisational risk but with minimal guidance on project-specific risks. Projects are temporary and time-bound, with a clear start and end date. The threats between the various project phases are dynamic and will change throughout the life cycle. ERM frameworks focus on long-term organisational objectives and high-level goals [27], [28] but not on time-bound project risks.

3 METHOD

The research was a qualitative case study, utilising a literature review in the form of a scoping review as the primary data collection form. The scoping review provides extensively researched information regarding ERM frameworks, requirements, benefits, and organisational structures. The information from the scoping study was sufficient to determine the general requirements of an ERM model and provide guidance for compiling the semi-structured survey.

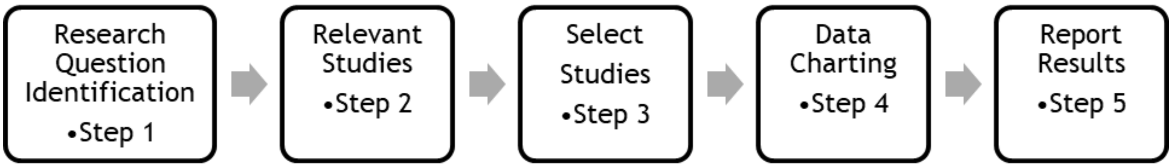

Figure 1: Scoping Review Protocol. Source: [29]

The established method to conduct a scoping review was by [29] and then further refined by The Joanna Briggs Institute [30]. Figure 1 illustrates the steps followed during the scoping review. Moher, Stewart, and Shekelle [31] explain that a scoping study is done to obtain an overview of a broad field, not if specific answers are required. The intent is to provide a visual presentation or map of the data obtained for the extensive area. Anderson, Allen, Peckham, and Goodwin [31] further indicate that a scoping review aids in the process of identifying gaps or questions within the study parameters.

3.1 Information Source and Search Strategy

The selected databases for sourcing relevant material included Scopus and Web of Science (WoS). Each database yielded different volumes of results. Evaluating the eligibility of the results was done before using the source within the study. Google Scholar was incorporated into the search process to obtain papers relevant to Namibia. During the preliminary literature survey, Scopus and WoS provided minimal results linked to the Namibian context of the study.

The following are keywords used during the search process:

- ‘Enterprise risk management’ AND ‘Implementation’
- ‘Enterprise risk management’ AND ‘Framework’
- ‘Enterprise risk management’ AND ‘Challenges’
- ‘Enterprise risk management’ AND ‘Benefits’
- ‘Enterprise risk management’ AND ‘Governance’
- ‘Enterprise risk management’ AND ‘Namibia’
- ‘Enterprise risk management’ AND ‘Project risk management’
- ‘Enterprise risk management’ AND ‘Engineering projects’
- ‘Enterprise risk management’ AND ‘Construction’

Snowballing was the second component during the search for relevant sources. The snowballing approach examines the source's reference list obtained during the database searches. After establishing critical scholars within the field, citation tracking will aid in getting additional information within the study area [32]

Published papers formed the bulk of the sources obtained during the scoping review. The sourced documents were not limited to published articles; grey literature forms part of the study. During the initial literature survey, it became evident that more published literature is needed to establish the operational and project risks encountered by the engineering sector in Windhoek. The sources provide general requirements of an ERM, and Windhoek-specific data was obtained through semi-structured interviews.

3.2 Eligibility Criteria

Only some sources obtained during the search process were relevant to the study. Screening identified documents or studies was to establish potentially relevant studies for sourcing. The screening process flow diagram illustrated in Figure 2 It is an adaptation of the process proposed by PRISMA 2020 [33].

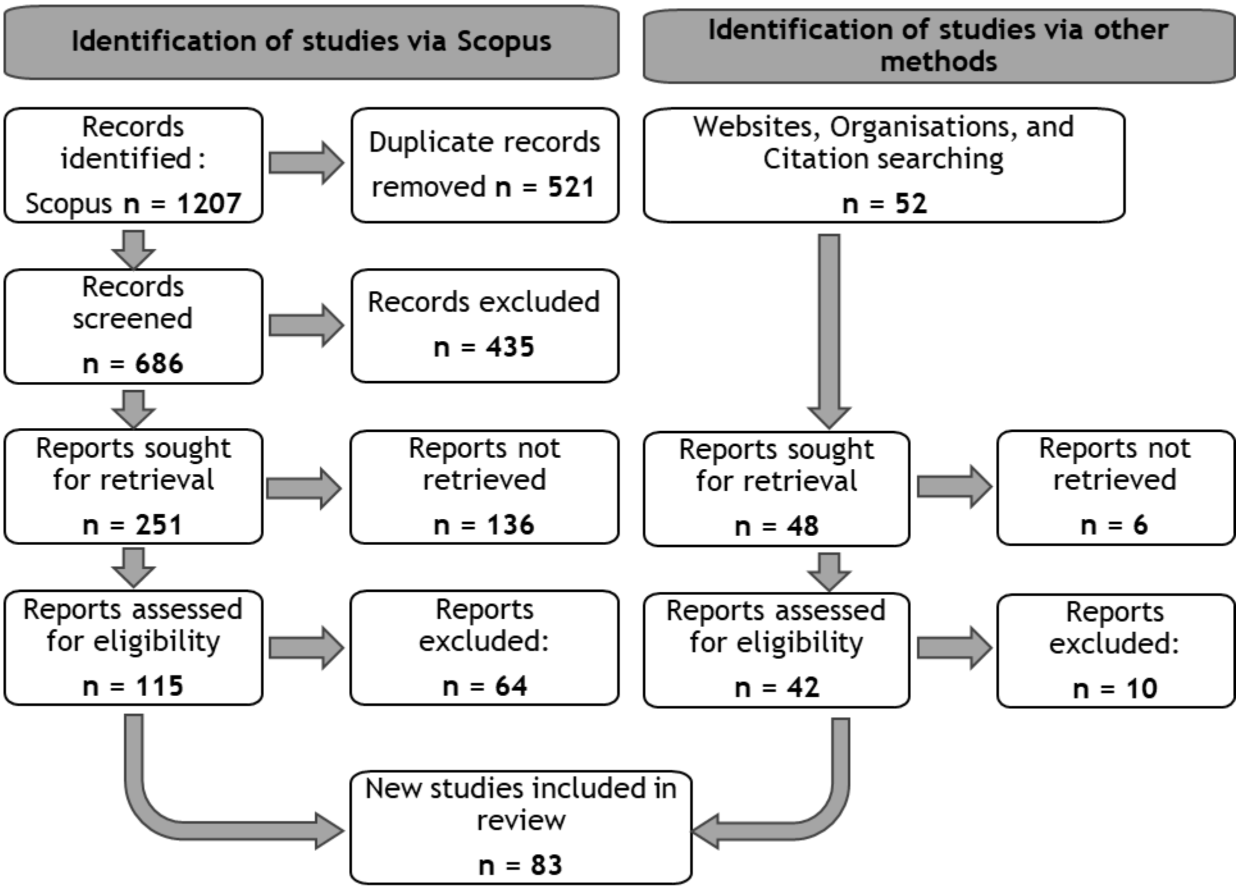

Figure 2: PRISMA 2020 Flow of Information Source: [33]

The removal of duplicate studies commenced after the identification of potentially relevant studies. The leading search on Scopus used the keywords produced 1207 potentially relevant studies. With the n = 1207 results obtained from the Scopus search, the identified duplicated studies (n= 521). With the elimination of duplicate documents, the studies were screened. Citation tracking, snowballing, and grey literature search formed the second component of the search process, and an additional 52 potential documents were identified, but only 48 were part of the retrieval process.

The following is a list of inclusion criteria used during the screening:

- All papers on the efficient implementation of ERM in organisations.
- All documents on COSO and ISO 31000 framework implementation.
- All articles on factors influencing ERM effectiveness.
- Frameworks and guidelines for ERM implementation.
- All papers on Engineering Risk management.

Criteria used that exclude sources from the study:

- Language barrier.
- Literature that requires payment to access the content.
- Full-text articles.
- Risk management is not relatable to ERM.

The use of inclusion and exclusion criteria narrowed the sought sources. The retrieval process further reduced the number of studies due to relevance, the payment barrier, and the documents needing to be full-text articles. After the retrieval, the inclusion and exclusion criteria pinpoint studies for the coding and data extraction.

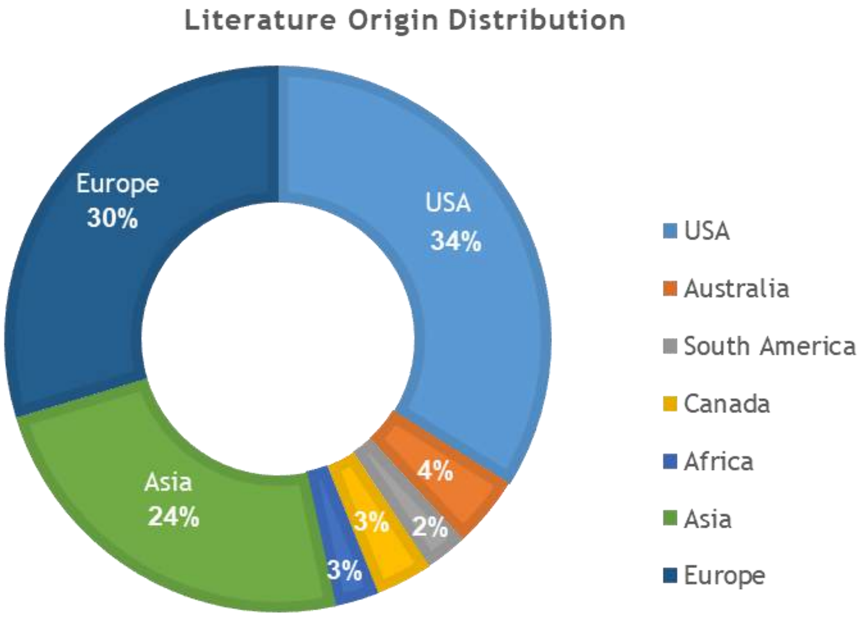

Figure 3: Literature Geographic Distribution

Figure 3 illustrates the geographical distribution of the documents and studies retrieved for the scoping review. Within the search parameters designed for this study, the highest volume of applicable literature retrieved was from studies conducted in the United States of America (USA), with 34%. Europe (30%) and Asia (24%) were the other leading continents with relevant information. The search process did not obtain any studies directly focused on the engineering sector, but the construction sector is closely related.

3.3 Data Mapping and Charting

The identified list of information and data required as part of the charting process is as follows:

- Title
- Author
- Year published.
- Geographical location
- ERM specific
  - Governance and Structure
  - Risk management
  - Reporting and Review
  - Implementation
  - Benefits

The starting point was to identify key concepts related to ERM from the selected sources. Atlas.ti Word Cloud generator aided in the concept identification. The software can analyse documents and determine the words with the highest frequency of occurrence. Figure 4 Illustrates Word Cloud extracted by the software.

Figure 4: Word Cloud ERM

Risk, management, and enterprise have the highest frequency within the various documents; it is understandable as the focus of the study was ERM. The top three recurring words did not assist with the concept identification, but the other word proved valuable. The key concepts extracted from the Word Cloud related to the general ERM requirements were strategic, objectives, board, control, information, analysis, assessment, aptitude, and reporting. The concepts created a solid foundation to start the sub-coding for the mapping and coding process.

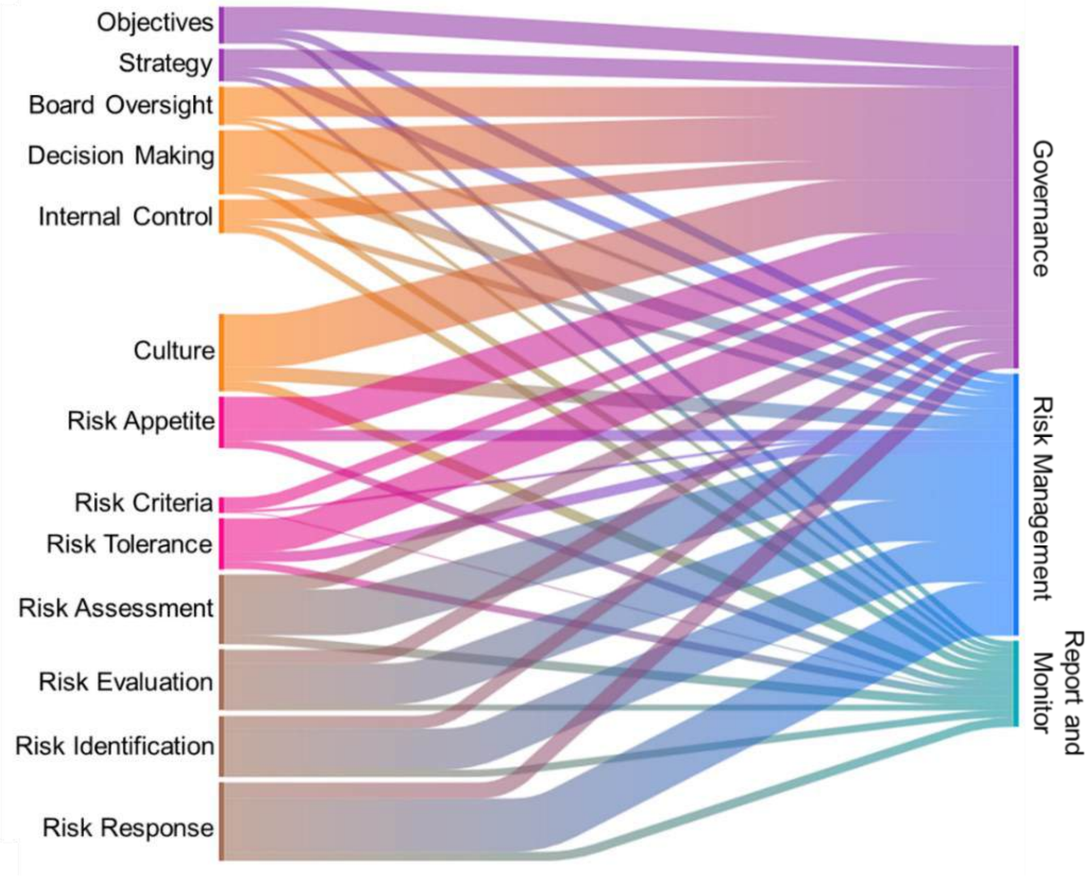

Figure 5: ERM Requirements Sankey Diagram

The extraction of a Sankey diagram was possible with the use of Atlas.ti software, as shown in Figure 5. The Sankey diagram was the result of the coding of the documents. The graph illustrates the various ERM activities on the left, connecting with bands to the ERM components. ERM components are Governance, Risk Management, and Reporting and Monitoring. The thickness of the bands leading from the activity to the ERM components illustrates the number of representative codes applied within the documentation. The identified studies had a solid connection to all the required ERM components. The bands show the interconnectedness of all the activities needed to implement and maintain an ERM.

4 RESULTS

4.1 General requirements of an effective ERM model.

Lam [18] indicates that the minimum building blocks for an effective ERM are governance structure and policies, risk assessment and quantification, risk management, and reporting and monitoring. These building blocks strongly correlate to the compared frameworks COSO, AS/NZS 4360, and ISO 31000. The result of coding the documents produced in Figure 6 illustrates the identified core requirements of an ERM.

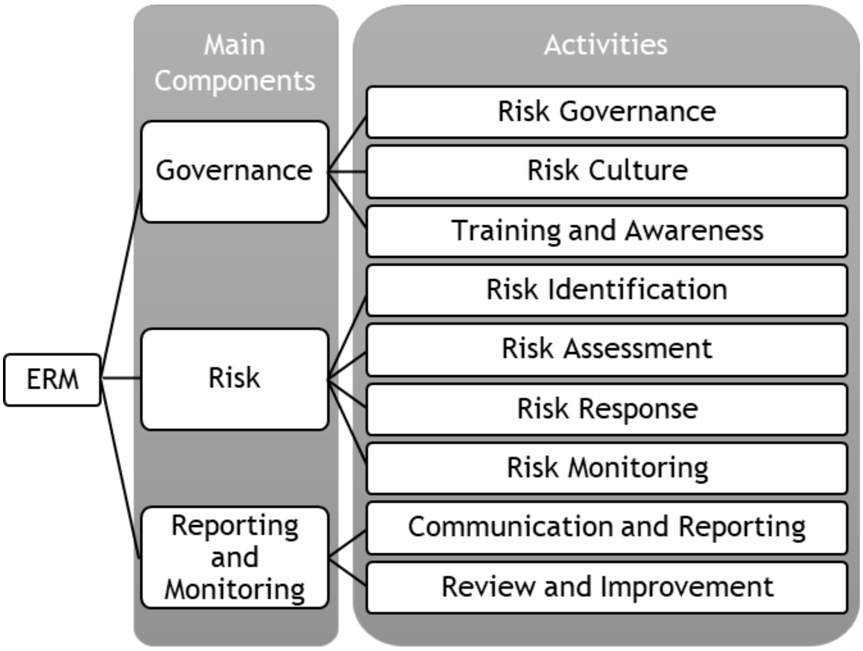

Figure 6: ERM Activities

4.1.1 Primary Data Gathering

After establishing the general requirements of an ERM model, the study progressed to the semi-structured interview to determine the risks consulting engineering organisations in Windhoek faced. The semi-structured interview had three focal areas. The first focal area was establishing the organisational risk with the highest impact within the consulting firm. The second series of questions aimed to gain insight into the current organisational structure. It focused on the organisational size, risk management style, and practices incorporated. The final focal point was to establish the highest influence on project risks. Briefing each participant regarding the nature and objective of the study commenced before the data collection. A sample of five willing participants responded positively to the interview. The interview invitation went to fifty-two Consulting Engineering Organisations that are members of Windhoek's Association of Consulting Engineers of Namibia (ACEN).

4.1.2 Organisational Risk

Each interviewee rated the organisational risk as perceived from experience. Figure 7 Figure 7 illustrates the results obtained from the interviews. The y-axis depicts the mean values obtained with a standard deviation shown for the various organisational risks.

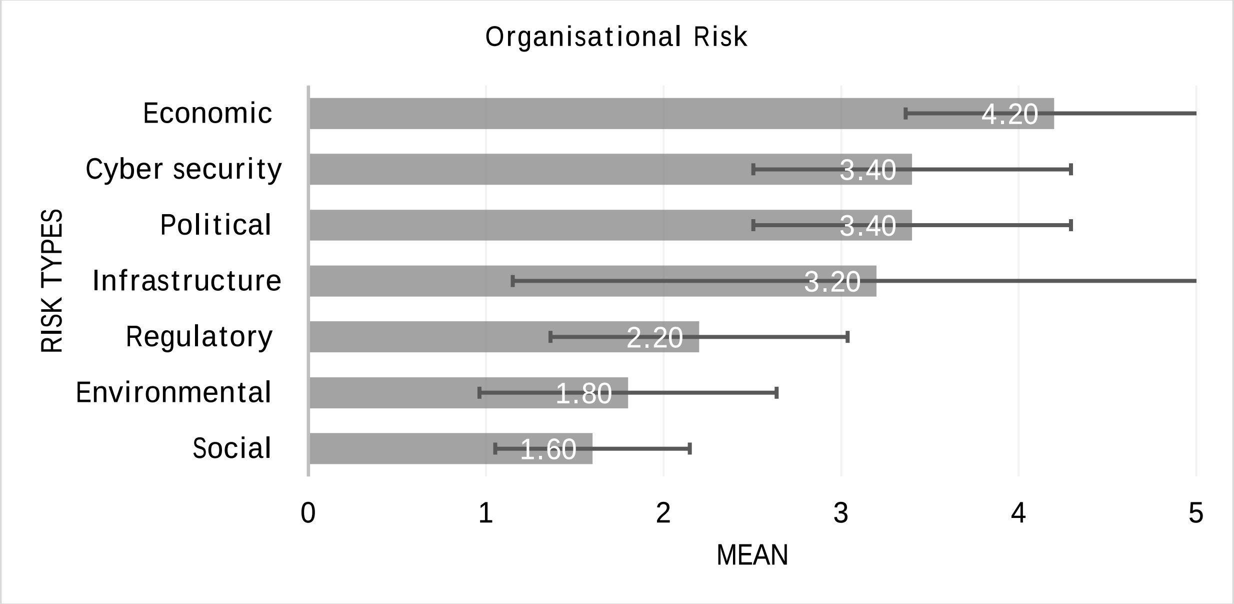

Figure 7: Organisational Risk Interview Results

The highest identified risks in order of magnitude were economic, cyber security, political, and infrastructure. Infrastructure has a high mean with the highest standard deviation, indicating that the current condition of infrastructure development is not influencing all the consultants. The Deloitte [34] study suggests that 36% of Namibian organisations experienced cyber breaches from 2017 to 2019. The organisational risks should be identified for each organisation, taking into consideration the company's needs using order of significance as a guide. Namibia faces economic challenges that impact business stability and influence the investment market, leading to financial risks for organisations. The possible factors are the reduction in public investments, lower commodity prices, and the reduction in growth shown by neighbouring countries [1].

4.1.3 Organisational Risk Management

This section provides insight into the answers from the interviews regarding current risk management practices and implementing a risk management framework. Figure 8 illustrates the responses relating to the organisation's designated risk management team and the implemented risk management framework.

Figure 8: Risk Management in Organisations

The interview findings indicate that only 20% of the interviewed organisations have a designated risk management team, and 40% have a risk management framework incorporated into their operations. These results indicate a low level of established risk management teams and frameworks within the sector. One potential explanation for this low level of risk management maturity is the organisational size of the consulting engineering firms in Namibia. The data indicates that the average size of the organisation is twenty-two employees. The results suggest that smaller organisations focus on ad hoc or targeted risk management without implementing a framework. Key factors that can make the implementation of ERM less applicable, successful, or appealing are the organisational size and the presence of a risk manager [13], [35]. Other factors that can contribute are the monitoring from the board, environmental uncertainty, organisational complexity, and operational industry [12]. The firm complexity, as per the study conducted by Gordon et al. [12], refers to the number of business segments within the organisation. The organisations can be less complex, with employees ranging from two to fifty-five and an average of twenty-two. The lack of complexity in consulting engineering organisations can be a reason for the low-risk management implementation and awareness.

The interviews further indicated that 65% of the projects are within the public sector, and 75% are locally based. Public projects are known for high risks due to the various stakeholders, budget and time constraints, and lengthy approval processes. Additionally, the projects often have a longer duration and are associated with a rigorous public procurement process. These factors play a major role in significantly impacting the outcome of projects. Hwang, Liao & Leonard [36] state that public projects typically outperform public projects, and the performance can be due to higher project schedule control, budget, and cash flow control from the private clients. Changing political priorities can introduce uncertainties and influence the budget and timeline of a project. With the risks linked to public sector projects, consulting engineering firms can improve the success rate of public projects by implementing a risk management framework. A tailored ERM that incorporates project management components will promote the management of project costs, addressing complexities associated with the technical design and positive stakeholder relationships.

4.1.4 Project Risk

In the same manner as the organisational risks, each interviewee rated the project risk as perceived from past project experience. Figure 9 Illustrates the rating of the project risk. The y-axis represents the mean values and the standard deviation for the various project risks.

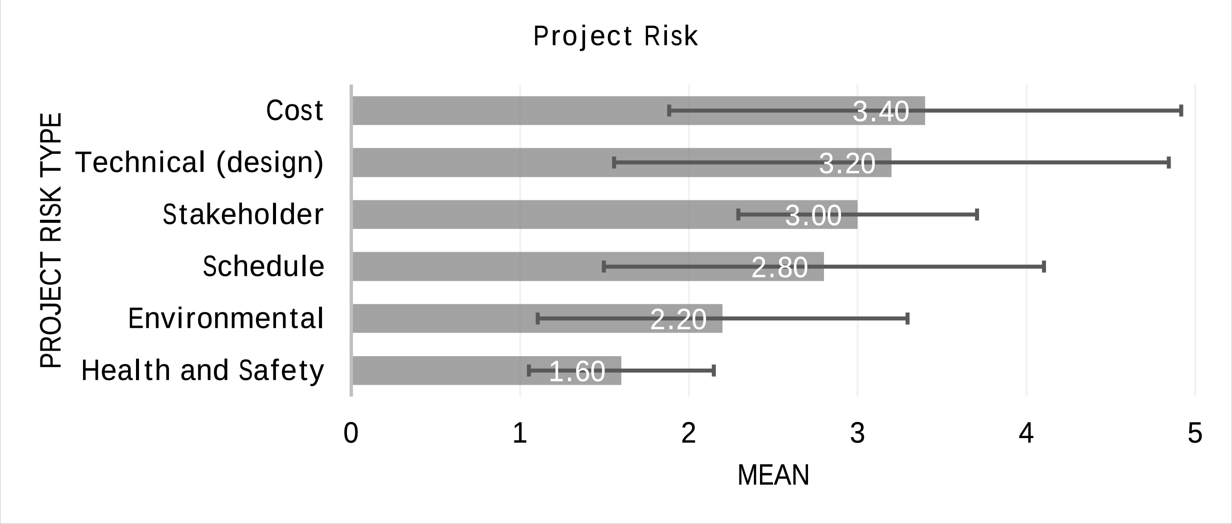

Figure 9: Project Risk Interview Results

The risks associated with cost and shareholders are primary concerns when conducting public projects. Technical design risk is synonymous with the engineering sector. Technical design and scheduling risks increase with the increase in the size and complexity of the project. With the harsh economic climate and slow stabilisation of the construction industry, a holistic risk perspective and enhanced risk awareness can improve the project and operational outcome. With the correct administering of risk management policies, the ERM can improve decision-making and the rate of decision-making. Proactive and future viewing can aid with crisis preparedness and optimise resource allocation for project and risk management. Enhanced risk awareness and management improve stakeholder confidence and can generate future project partnerships.

Beyond effective risk management, ERM aids in the identification and capturing of opportunities. Capturing opportunities can lead to improved performance and profitability of the organisation. ERM, in contrast to project risk, is long-term focused. Organisational stability requires a long-term overview. A limiting factor for the ERM implementation can be the lack of complexity of the consulting engineering organisations in Windhoek.

4.2 ERM Model with Project Risk

Using a standard ERM framework for a consulting engineering organisation, which is primarily project-based, may present some challenges. Each project is unique and includes risks that might not form part of a generic ERM framework. The frameworks typically have a broad risk management approach across the entire organisation. The framework may not provide clear guidance on managing project risks. Projects are also time-sensitive, with a precise start and end date. Each project phase throughout the project lifecycle will have varying degrees of risk.

ERM, being long-term focused and not known to be flexible, can struggle with the dynamic nature of the project. Projects are known for changes in scope, timelines, stakeholders, and enforceable technical challenges. Communication and stakeholder engagement form part of an ERM framework. Frameworks do not prescribe the communication interval, nor will the framework specify engagement levels. Projects require constant stakeholder engagement, including clients, contractors, suppliers, regulatory bodies, and local communities.

Tailoring the framework to include the organisational project-specific context can address the challenges. The tailoring should consist of the following:

- Customise the risk assessment process to include identifying and evaluating project risks. The risk assessment process will have to be done based on project timeline requirements and not per the determined periodic review of the organisational risk register. Project risk should focus on, but not limited to, costing, technical design challenges, stakeholders, and scheduling.
- Project risk management should not form separate entities; the ERM processes should integrate the tools and techniques.
- The ERM policy should have a dedicated document that aligns with the ERM framework but provides guidance on the organisation's project risk requirements and expectations.
- The ERM project risk policy should indicate the risk governance structure to ensure effective communication, accountability, and decision-making related to project risks. Depending on the organisation's size, oversight may also be included, such as risk-based audits.

Balancing the long-term risks against the project risk management needs is essential. An ERM framework's forward-looking, proactive nature can prove valuable within the engineering sector. Figure 10 illustrates the proposed tailored ERM model to include project risk within the ERM framework.

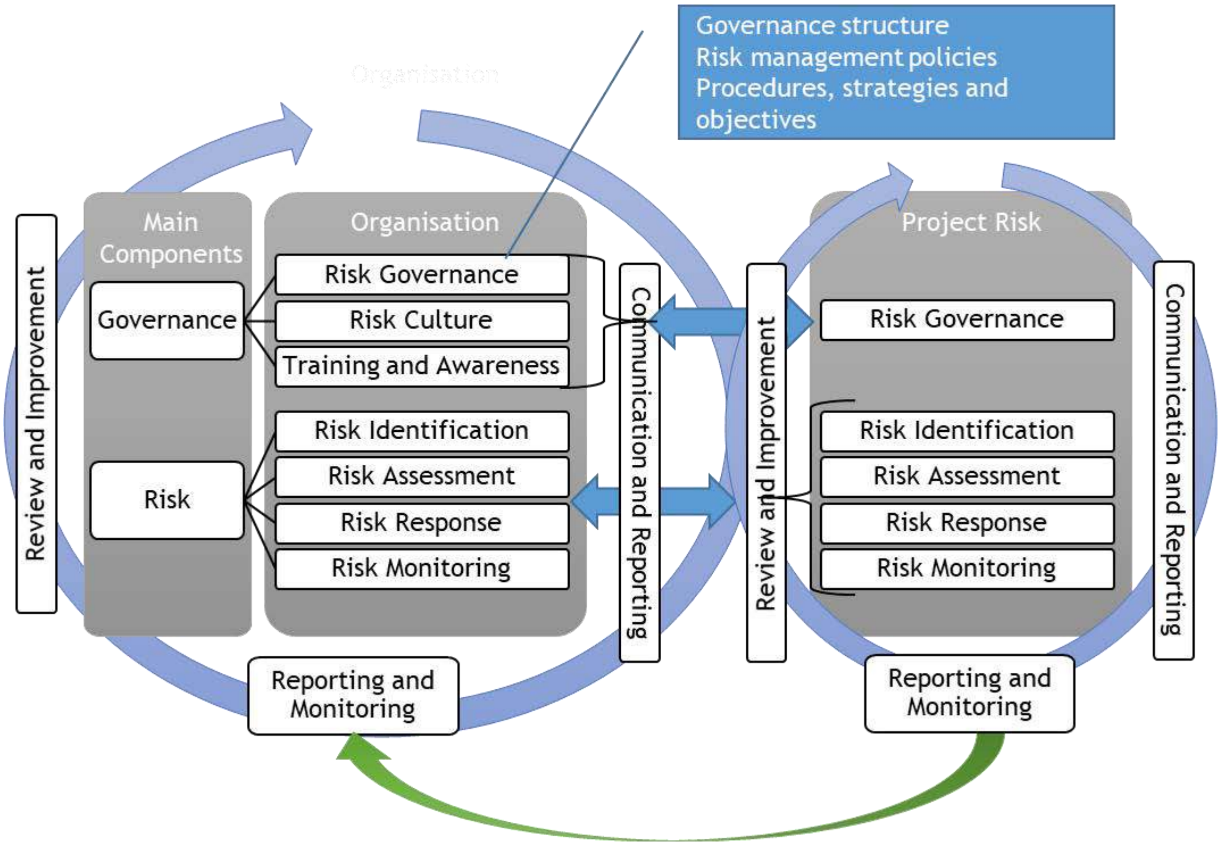

Figure 10: Tailored ERM-Project Risk Model

The model also emphasises the importance of risk culture and training. Training involves interventions to consistently apply existing policies, procedures, strategies and objectives or the diffusion of new ones. Risk culture includes the intentions, attitudes, norms, and behaviours related to risk policies, procedures, strategies and objectives. Both these aspects may significantly influence the organisation's capability to govern risk management effectively.

5 LIMITATIONS

This study focused on Windhoek-based companies, the study might not reflect the conditions in which other engineering companies in Namibia operate. A limited pooled sample is available to extract data from Namibia as it has relatively few engineering firms compared to other professions in the construction industry, such as quantity surveyors and architects. Some companies indicated that they do not have any risk management strategies and would not offer any sensible input into the study. Risk management can be a sensitive topic for organisations, and participants might be reluctant to participate.

6 CONCLUSIONS AND RECOMMENDATIONS

The study's findings identified the general requirements of an effective ERM model. The conducted interviews further obtained the significant organisational and project risks experienced by Namibian consulting engineering organisations registered at ACEN. The identified organisational risks include economic, political, cyber security, and infrastructure risks. The mentioned risks reflect the challenges faced by organisations at the operational level. During the risk identification and prioritisation, consider the order of magnitude of the organisational risk.

The study also highlighted the varying degrees of risk management practices, with some organisations having designated risk management teams and frameworks whilst others manage risks on a project-by-project basis. The interviews indicate a low awareness of risk in the consulting engineering sector in Windhoek. The low-risk awareness limits the long-term and proactive management of risks. The study provides valuable insights and focal points that can guide consulting engineering firms in enhancing their risk management practices. Risk governance and management can improve Namibia's project outcomes and organisational performance. Adopting proactive measures in risk management can contribute to the sector's growth, competitiveness, and resilience in the face of various challenges. Implementing a tailored ERM model will be hindered by the low-risk-aware culture and maturity identified through the interviews.

The findings from this study indicate that the potential enhancement within the Namibian consulting engineering sector is linked to ERM adoption. The low-risk awareness observed in public and Namibian projects presents possible future research. One recommended focal area to aid in advancing and understanding ERM implementation in the Namibian context is conducting an in-depth study of risk perception and management maturity in Windhoek to identify the reason behind the low-risk management awareness. Assessment of the success of the currently implemented risk management frameworks within the engineering sector in Windhoek. Comparative analysis of consulting engineering in Windhoek with Global Best Practices. Incorporate the organisational revenue as part of the organisational risk management evaluation.

Future studies can expand the population sample beyond ACEN-registered consulting engineering organisations and include other built environment sectors. Examples of different sectors within the built environment include contractors, architects, and quantity surveyors.

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THE SUITABILITY OF INCREMENTAL INNOVATION FOR COMPETITIVE DIFFERENTIATION: A REVIEW OF THE SMARTPHONE INDUSTRY

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ABSTRACT

This systematic literature review aimed to determine how suitable incremental innovation can be for competitive differentiation in the smartphone industry. Thirty articles from Scopus and Web of Science databases were examined. The documents were classified in terms of industry state, innovation networks, organisation management, and product development. The following code groups were used to analyse the data: "firm capabilities", "market dynamics", "organisation relationships and strategy", and "product focus". The "firm capabilities" and "market dynamics" groups were the most influential code groups across all documents. These groups determined that the current literature points towards executing customer requirements and adjusting to market trends quickly at a low cost, which is critical to competitive incremental innovation. Further work should aim to find more empirical sources and examine the smartphone industry's imitation characteristics, as the market leaders' actions heavily influence innovation.

Keywords: Incremental innovation, smartphone industry, competitive differentiation

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1 INTRODUCTION

The growing concerns about climate change have put every stakeholder in the global economy in a state of contemplation. Typical industrial processes will have to change. Radical innovation is typically used to get a competitive edge quickly; however, for a number of firms, incremental changes are the only strategies they can support. It would be reasonable to question the competitiveness of incremental innovation. This question would illuminate trends that firms are likely to follow as they navigate the climate change transitions. The smartphone industry is used in this work to explore this question. The smartphone industry constantly evolves, with incremental innovation a key driver of continuous improvement. Companies must differentiate themselves from their competitors to stand out in this highly competitive market. Research has shown that innovation plays a significant role in a company's competitive advantage [1]. As competitiveness and innovation are intertwined, exploring the relationship between these factors regarding a company's survival in the smartphone industry can provide valuable insights for future research.

1.1 Incremental Innovation

Innovation is a multifaceted process which involves individuals generating ideas, innovators bringing those ideas to fruition, and various functions related to a product, process, and organisational development [2]. Innovation is often seen as an opportunity for a company to gain a competitive advantage [1] and is crucial for a firm's survival and long-term growth [3]. The main types of innovation are product, process, and organisational innovation, each with distinct features that need to be managed [4]. Incremental innovation, which involves continuous improvement and slight changes to products or services [5], is the focus of this systematic literature review. Low technology costs characterise this type of innovation and require a company to embed an innovation culture to reap the long-term benefits. In companies with a conservative and hierarchical culture, incremental innovation is more readily embraced [6]. Nakandala et al. [3] states that incremental innovation is the prevailing form of innovation, allowing companies to be flexible and responsive to environmental changes.

1.2 The Smartphone Industry

Smartphones have emerged as the standard configuration in the telecommunications industry due to the growth of mobile devices. Apple introduced the iPhone in 2007, followed by Samsung Instinct in 2008 [7]. The smartphone industry is a hub of innovation, with the top three firms having over 47% of global sales in 2019, totalling 1.5 billion [8]. Firms must differentiate themselves from competitors to survive in this highly competitive environment.

1.3 Competitive Differentiation or Advantage

Competitive advantage is the distinctive capability of a company to surpass its competitors in a market. Possessing such an advantage is crucial in enhancing the company's market position [6]. A way in which companies can boost their competitiveness is through exploitative innovation, which involves improving existing processes or techniques that the company already knows and possesses, like process innovation [9]. Innovation capability, which refers to the type of innovation a firm chooses to pursue, is seen as a means of achieving a competitive advantage [10]. Competitiveness is crucial for their survival and growth as companies compete for resources, technologies, and customers [11].

The purpose of this article is to assess the existing published academic research and provide answers to the following research questions:

1. How sustainable is incremental innovation for maintaining competitive differentiation?

2. Can the smartphone industry benefit from incremental innovation?

3. What are some of the enablers or supporting factors for incremental innovation?

4. What can limit the application of incremental innovation?

To facilitate the investigation of the identified research questions through a systematic literature review of the available literature, the subsequent sections of this paper are structured as follows: the methodology section will first outline the procedures utilised to identify relevant literature. Secondly, the results section will present the findings from the systematic literature review utilising qualitative analysis. Lastly, the discussion section will offer an interpretation of the results, examine their current implications, address the study's limitations, and propose recommendations for future research.

2 METHODOLOGY

This systematic literature review aims to analyse and map existing literature about the topic and research questions.

2.1 Search Strategy

A systematic search strategy based on key terms and relevance with clear inclusion and exclusion criteria was established to identify relevant studies and journals indexed in Scopus and Web of Science, with Mendeley as a referencing tool. The Scopus database was chosen because it is highly regarded as one of the most comprehensive and commonly used databases in engineering, containing the greatest number of abstracts and peer-reviewed articles available [12]; whereas Web of Science is a database known for leading scholarly research in the sciences [12].

Three searches were completed to find the appropriate articles. The first search used the key search terms' innovation', 'incremental innovation' and 'smartphone industry'. The second search used the key search terms' innovation', 'competitive' and 'phone'. The last search used the key search terms' innovation', 'competitive' and 'smartphone'.

The following inclusion criteria were used in selecting the relevant articles:

1. Published in a journal or conference proceedings
2. Published between 2010 and 2023
3. Had relevance to the research questions
4. Indexed in the Scopus or Web of Science databases
5. Written in English

The following exclusion criteria were used in selecting the relevant articles:

1. Technical reports or theses
2. Published before 2010
3. No relevance to the topic
4. Written in languages other than English

2.2 Data Analysis

The journals identified and established a research landscape that included key concepts, theories, and methodologies to broaden understanding of the research topic and identify potential areas for future research.

ATLAS.ti software was used to extract relevant and meaningful data from the identified papers screened for inclusion. The relevant material was consequently coded in ATLAS.ti with 34 codes, which were ultimately grouped into four categories: 'firm capabilities', 'market dynamics', 'organisation relationships and strategy', and 'product focus'. The documents were also grouped into four as follows: 'organisation management', 'overall innovation networks', 'product development' and 'state of smartphone industry'.

The codes were classified into 'supporting factors', 'non-supporting factors' and 'sustainability factors'. Each code was given a prefix per relevant classification: 'SF' for supporting factors, 'NSF' for non-supporting factors, and 'Sus' for sustainability factors. These classifications assisted with identifying the literature that is in 'support' of the research concept, the literature that is 'not supporting' and the 'sustainability' which responded to the main research question and theme of the systematic literature review; 'how sustainable is incremental innovation for maintaining competitive differentiation?'

Sankey diagrams and tables were used in various versions to analyse and establish relationships, and a final representation was made. The Sankey diagrams and the tables provided a simpler presentation of the relationships and results, which are easier to read and recognise. About 66% of the codes were from the supporting factors, 28% responded to the sustainability concept, and only 5% related to non-supporting factors.

2.3 Limitations

The study did not consider unpublished developments in the industry as it was restricted to journals indexed in Scopus and Web of Science databases. Thus, work that was excluded was work relating to confidential metrics of companies' performance in the smartphone industry. The systematic literature review did not include a wide review of work on industries related to the smartphone industry, like the semiconductor industry.

3 RESULTS

The original screening process was based on articles published from 2010 to 2023 (35 articles), with relevant publications ultimately being published from 2009 to 2023, and their number was reduced to 30. The highest contributor was China, followed by South Korea. The UK and Italy contributed equally. The remaining were shared between the USA, France, Thailand, and India.

Out of the 30 papers analysed, 29 made significant contributions relevant to the topic of incremental innovation. However, Lamhaddab et al. [34] had minimal impact on the study, as it focused on the technical challenge of porting applications from iOS to Android devices. The selection of papers was based on keyword searches, which allowed an article with the correct keywords but not the appropriate context to be included in the analysis.

The results were obtained through coding on ATLAS.ti and document analysis using code groups to determine the relationships in the literature. Table 1 shows the different code groups used. NSF stands for Non-Supporting Factors for incremental innovation, SF represents Supporting Factors for applying incremental innovation, and Sus denotes the sustainability of applying incremental innovation in an organisation.

Table 1: Summary of the code groups

Code Group	Number of codes	Codes in the code group
Firm capabilities	15	NSF - Poor Quality Product NSF- Innovation (Time and risk) SF - Category leaders SF - Follower brand SF - Increased product quality SF - Innovation strategy SF - Limited resources SF - Speed to market

Code Group	Number of codes	Codes in the code group
		SF- Low cost SF- Successful product SF-Industrial Technology Development Stage SF-Innovation Network Control Sus - Competitive advantage Sus - Maintain market share Sus-Incremental Innovation Capability
Market Dynamics	16	NSF - Low switching cost SF - Category leaders SF - Customer requirements SF - Follower brand SF - Fragmentation of global production SF - Increased stock performance SF - Innovation strategy SF - Speed to market SF- Adaptive market SF- Low cost SF-Industrial Technology Development Stage Suitability - A niche market Sus - Brand value Sus - Competitive advantage Sus - Maintain market share Sus-Incremental Innovation Capability
Organisation's relationships and strategy	16	NSF - Structural Embeddedness SF - Category leaders SF - Customer requirements SF - Follower brand SF - Increased stock performance SF - Innovation strategy SF - Open innovation SF - Organisational culture SF - Relational Embeddedness SF- Local government support

Code Group	Number of codes	Codes in the code group
		SF- Regulations SF- Short horizons SF-External Sources SF-Innovation Network SF-Innovation Network Control SF-Network Embeddedness
Product Focus	7	NSF - Low switching cost NSF - Poor Quality Product SF - Customer requirements SF - Increased product quality SF- Low cost SF- Regulations SF- Successful product

Next, the code groups were linked to document groups based on the focus of the articles. Table 2 displays the various document groups identified.

Table 2: Identified document groups

Document Groups	Number of Articles	Articles Included
The state of the industry	6	[7], [9], [13], [14], [15], [16]
Organisation Management	10	[17], [18], [19], [20], [21], [22], [23], [24], [25], [26]
Innovation Networks	6	[27], [28], [29], [30], [31], [32]
Product development	8	[33], [34], [35], [36], [37], [38]

3.1 The state of the industry

The articles that focused on the state of the smartphone industry and how firms in competition interact were evaluated with the associated code groups. The diagram in Figure 1 indicates that the firm's capabilities and market dynamics contributed the most to the state of the industry. Tang et al. [16] examined the state of the Chinese mobile phone handset industry, and it highlighted the interaction of regulations affecting the smartphone market. The loose regulation on intellectual property allowed fast-following companies on already established products, enabling successful incremental innovation strategies. Rayna and Striukova [15] put forth the conditions that allow competitive incremental innovation, namely high switching costs between competitors, strong brand value in the market, and the ability to comprehend customer requirements. The article also indicated the importance of suitable market regulations for maintaining incremental innovation as a competitive strategy. Beverland et al. [13] expanded on the strengths of brands in the smartphone industry.

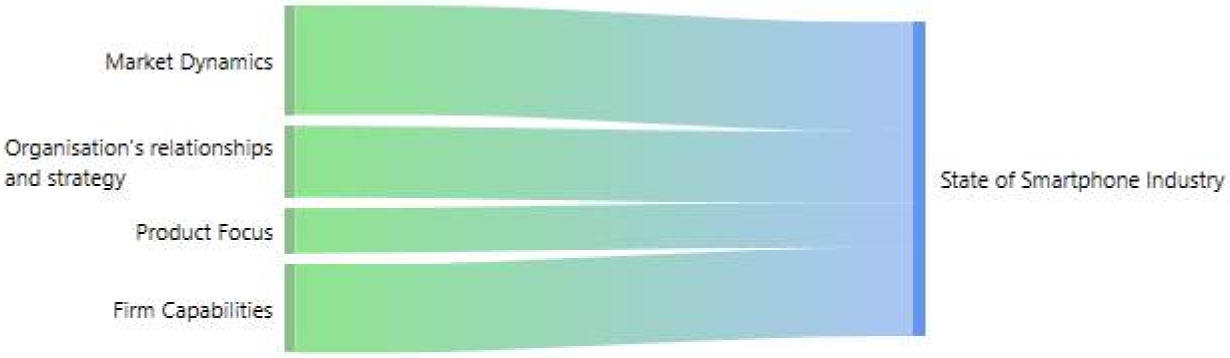

Figure 1: The State of the Smartphone Industry Document Group

The key elements that encouraged a competitive incremental strategy included being able to respond to customer requirements and commanding a strong presence in the market as a category leader. If a firm has a smaller presence within the market, it would have to implement a follower brand strategy that depends on the market's speed and the company's marketing information systems. Wang et al. [9] indicated that smartphone companies that can apply a competitive incremental innovation strategy are embedded in innovation networks with strong relationships between their collaborators. Incremental innovation is also suitable within niche markets of the smartphone industry, and an appreciation of customer requirements is needed for incremental innovation [7]. This can enable follower brands to perform competitively. Lastly, Giachetti and Pira [14] developed a model to investigate the viability of imitating a market leader's innovation strategies, and it found that the rapid imitating of innovation produced by market leaders is not an optimum strategy for a company that is not in a dominant market position.

3.2 Organisation Management

One of the groups of documents identified focuses on organisational management, which involves planning, organising, leading, and controlling resources such as people, finances, materials, and information to achieve organisational goals [39]. Organisational management encompasses various activities, including goal setting, strategy development, policy and procedure establishment, resource management, and day-to-day operations oversight. Notably, the strategies established by an organisation must include innovation capability, which is a recurring theme in organisational management.

Ten articles were relevant to this category, and the analysis was completed based on various codes and code groupings. The coding group with the highest volume of codes was market dynamics, followed by firm capabilities, and finally, the organisation's relationships and strategy. This is shown in the Sankey diagram in Figure 2. The product focus is the coding group with the lowest volume, which implies that how an organisation is managed is more influenced by market dynamics, which include customer requirements, demand for a product and technological advancements.

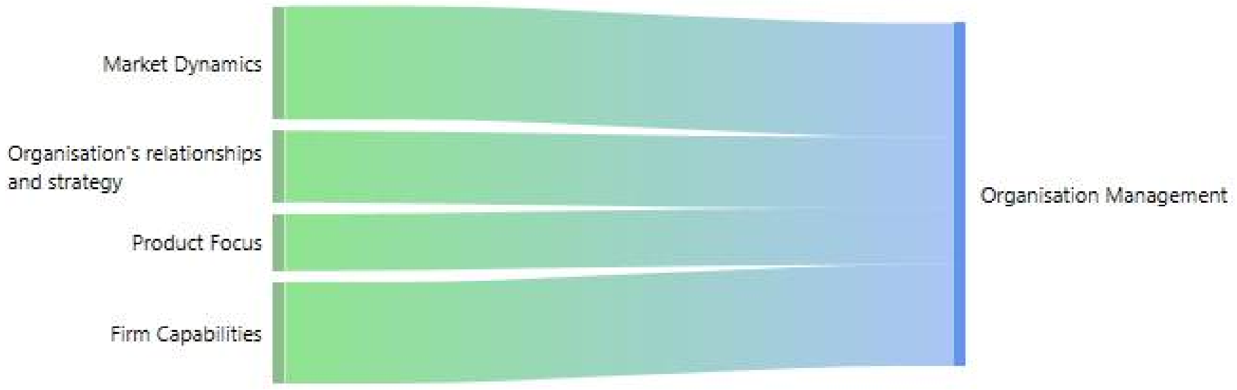

Figure 2: Organisation Management Document Group

Service or product innovation is an indicator of whether an organisation can develop products quickly enough to meet market demands [24]. Customer needs typically drive innovation, and it was found that most of the service or product innovations across leading smartphone manufacturers were incremental [24]. Samsung, for example, had a strong focus on product incremental innovation, which helped it maintain a strong competitive position. As an organisation, Samsung decided on a strategy to incrementally innovate its product offering to gain an advantage in the market.

The study conducted by Alibage and Weber [17] utilised Nokia as its subject. They discovered that the company initially prioritised product innovation, and their research and development efforts were incremental [17]. Nokia was mindful of its customers' demands and introduced mobile phones in various market segments. As the need for smartphones grew, Nokia also released models such as the N-series to cater to this market. However, the difficulty of integrating an appropriate operating system that met customer needs was a significant obstacle that hindered Nokia's success [17]. The company's management primarily focused on hardware innovation while neglecting software innovation, eventually leading to a decline in its market share over time.

Michael Porter argued that organisations should emphasise obtaining a competitive advantage during strategy development [40]. An organisation's capabilities guide the approach to strategy towards or away from incremental innovation. Porter's five forces of competition include threats of new entrants, threats of substitute products or services, and rivalry amongst existing firms, all of which influence the firm's strategy [40]. To support an innovation strategy, speed to market is crucial as it enables an organisation to capture a significant market share and generate profits while other firms are still responding. Furthermore, an organisation must be able to meet the needs of its customers to enhance the functionality of its already existing products [23].

An organisation's resource access also influences its overall strategy and innovation capability. In a study by Yu and Kwan [25], the authors focused on the approach taken by low-end phone markets in China, where limited resources meant that some firms imitated smartphone products from foreign environments. Adaptive entrepreneurship led to incremental innovation, where entrepreneurs exploited the success of others while introducing new ideas, leading to improved profits [25]. As these firms became more competent, they could offer new products to the market, transitioning from mere imitators to incremental innovators. In this study, firms in the Chinese market managed their limited resources and ran their organisations with an imitation strategy, which transitioned to incremental changes to their products.

3.3 Innovation Networks

This article group aims to understand the relationship between the Innovation networks and their effect on incremental innovation capabilities in the smartphone industry. The output of the analysis completed on this document grouping, as shown in Figure 3, indicated that market dynamics and firm capabilities had the most articles related to the impact of innovation networks. An innovation network refers to the relationships amongst firms in the same industry working towards improving and developing new products by sharing knowledge, skills, and expertise. Innovation networks provide firms with a platform to access resources that are beyond their boundaries. These networks are crucial in facilitating incremental innovation [27].

In an innovation network, firms form partnerships and alliances with external firms that share the same interests and objectives, leveraging advancing technologies and making continuous incremental changes to their products. The structure and composition of the network tend to be more important to cultivating incremental innovation capability in the rapidly changing era of technology and industry. Through these networks, companies can gain access to the latest information and tools to use in continuing R&D projects [27].

An important concept one of the authors covered was relational embeddedness [32]. Relational embeddedness describes the level to which the firm is connected to other firms in the industry. Further, it can provide valuable resources and information to enhance incremental innovation, fostering collaboration and promoting competitive benchmarking. This result supports the perception that high relational embeddedness contributes to cohesion, mutual understanding, and trust between innovative firms, thus fostering incremental innovation capability through the recombination of external technological knowledge [30].

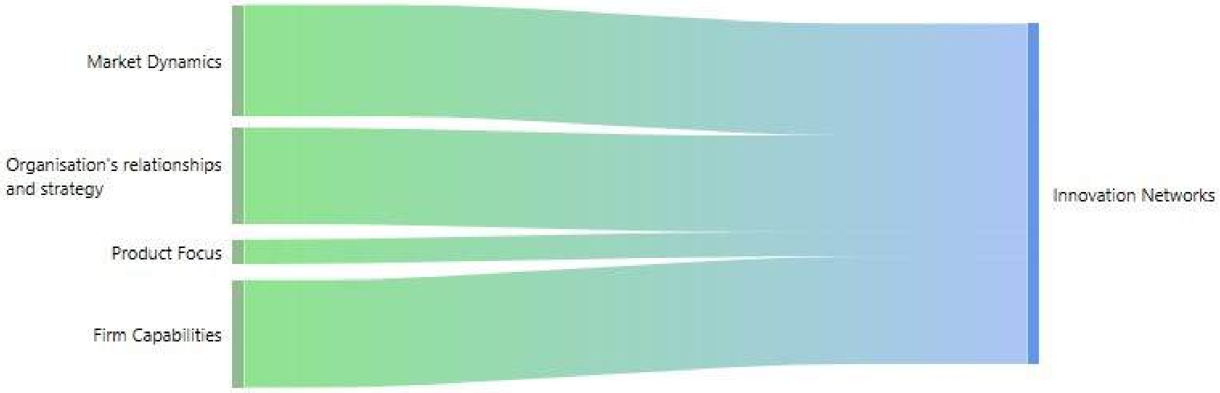

Figure 3: Innovation Networks Document Group

Structural network embeddedness describes the general network topology. It is an interaction that explicitly details who and how a given participant in an innovation network reaches other individuals. Structural network embeddedness highlights the characteristics of a firm's position held inside a network. The firm's network centrality describes its position in the hierarchy and degree of accessibility to resources, which influences incremental innovation capabilities [30].

Open innovation refers to a firm's effort to find, identify, and integrate innovative sources beyond its limits to develop its technologies. Competitiveness facilitates the firm's innovation capabilities, enhancing innovation performance [27].

The study suggests that with innovation networks a firm's limited resources may not limit its capability to innovate. Han et al. [27] argue that many open innovation efforts benefit Small and Medium-sized Enterprises (SMEs). By being part of these networks, they have access to resources and expertise not available in their companies, and the ability to share knowledge and ideas to help them grow their business and remain relevant in the marketplace. Most studies have identified innovation networks as critical contexts for incremental innovation [32].

Relational network embeddedness influences incremental innovation capability positively, while structural network embeddedness influences incremental innovation capability negatively, and open innovation strengthens the relationship between network embeddedness and incremental innovation capability [30].

3.4 Product development/ improvement

Product improvement proved important to sustaining competitive differentiation through incremental innovation by various factors, with it being one of the resultant groupings. Most of the factors were found to be supporting factors, such as meeting customer requirements and increasing product quality. While the non-supporting factors were quite limited, these included low switching costs and poor product quality.

3.4.1 Customer requirements

One of the supporting factors that seemed to affect product improvement more than others was customer requirements. Implementing incremental innovation to customer requirements gives a company competitive strength and plays a crucial role [16]. Apple has proven that simplicity also plays an important role and can also affect consumer expectations [15]. Xie and Liang [24] demonstrate that incrementally adding new functions, such as a higher resolution camera with a targeted customer experience, also contributes to customer requirements. The stance of the innovator is also highly affected by the consumer as latecomers innovate to imitate the first mover's technologies to meet the user's requirements [29]. Figure 4 illustrates the document groups relative to the product development of smartphones. One of the bigger document groups is that of market dynamics, which are influenced by the consumer's requirements.

By allowing users to customise their phones online by selecting features that fit their needs and choices, Xiaomi was able to increase its product competitiveness through customer consultation and needs. It also launched an effective internet marketing campaign to understand and target user needs properly and use them for product improvement design targets [24].

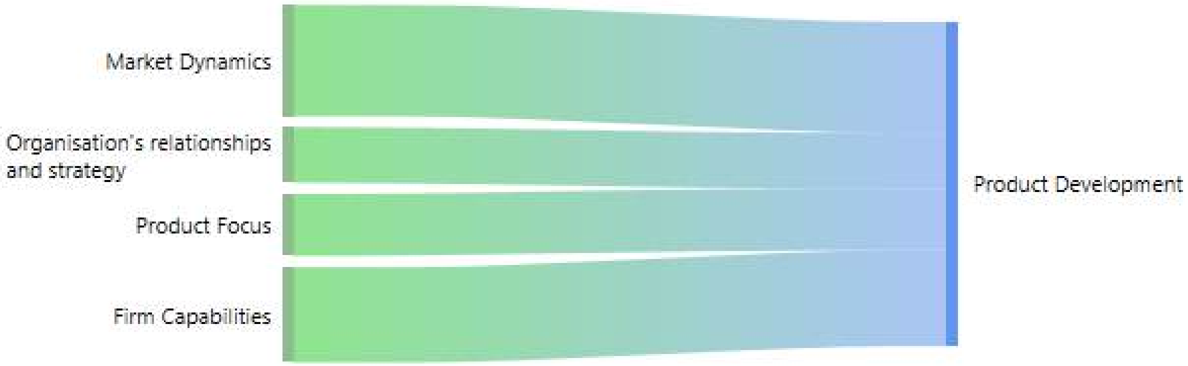

Figure 4: Product Development Document Group

Customer lifestyle and market trends have forced companies to move away from product-focused models and instead improve their ecosystem by focusing on product-plus service platform-based models. Companies such as Apple, Nokia (although a minority in the market), Samsung and Xiaomi with Android, with Apple ranking the highest, are good examples of stable ecosystems providing a holistic solution to their customers [24]. Apple, with its iPhone, is also ahead of all other smartphone innovators in global shipments [22].

By failing to meet the rapid change in consumer needs and tastes and the resultant technological requirements, Nokia and BlackBerry, although initially dominating the market, were surpassed by Apple and Samsung in 2011, with Huawei enforcing its dominance in 2015. This further validates the importance of customer needs and technology as the founding contributors to innovation and the success of the market [31]. HTC also failed to innovate its products continuously to meet consumers' perpetual demand for high-quality value in the smartphone market [29].

Apple, but this time with Microsoft, has emphasised customer requirements by providing value-added solutions that meet the needs of mobile internet users with digital lifestyles. With the high-speed 4G and the advent of 5G networks, the foundation is laid for these innovators to enhance functionality and improve future consumer value [23]. With the aid of more than 28 customer service call centres scattered throughout the United States and staffed by a workforce of over 19,000 employees, Apple can also gather customer feedback on their experience. This approach has compelled businesses to seek novel means of refining their offerings, discovering fresh functionalities that cater to customer requirements, envisaging new customer benefits by creating new product models, and addressing past technical glitches by devising innovative solutions [38]. This further verifies that placing the customer at the heart of the business product, with the user's needs in mind, maybe the most significant competitive advantage in business development [38].

Jia et al. [33] has summarised the five generations of technological waves in the mobile industry into 10-year periods per generation, with the second 10-year period characterised by a continuous cycle of enhancement and adaptation to meet evolving market demands as an incremental innovation wave. This period is also marked by an ecosystem innovation wave encompassing new terminals and applications.

Incremental innovation does not necessarily create new markets. Still, it has been proven to attract a high number of customers due to its ability to meet customer satisfaction, which is identified by actions and feedback [38].

3.4.2 Increased product quality

Following 'customer requirements' is the effect of incremental innovation on increased product quality. Implementation of incremental innovation copies the characteristics of the dominant product and then produces a new quality product, which may provide higher value than the leading product in the market [8]. With the focus on designers, Zhang [38] highlights that the main thrust of incremental innovation is to steadily refine and optimise a product to improve the quality of the product or service, thus delivering a satisfying customer experience. In essence, incremental innovation enables the company to maintain a competitive edge in the market. This value addition and improved product quality have affected the consumer's perceived value and willingness to pay for products, as may be the case with Samsung's smartphone [29].

To provide high-quality mid-priced smartphones, Xiaomi's market positioning has been clear since the beginning. As a result of the value it offers, Xiaomi has gained popularity among Chinese people, and its positioning strategy has provided competence in the smartphone market [24]. Samsung has shown a strong focus on incremental innovation in its products, while Xiaomi is still catching up, although it is promising. Apple upgrades the iPhone yearly, although it is not a keen incremental innovator [24].

3.4.3 Successful products, low cost, and regulations

Incremental innovation requires less time and money than other innovation methods; risks are significantly reduced as improvements are made to existing products, thereby reducing the costs of products [38].

In China's Shenzhen, the low production costs and huge labour force have turned the area into a production hub for mobile phones, which is also encouraged by the lack of strict government regulations. With targeted low-end markets in rural Asia, the Middle East and Africa, incremental innovation is implemented by imitating first movers, resulting in low-cost products [25]. Imitation by follower firms copies the advanced and popular product model, thereby eliminating development costs and offering more consumer satisfaction and product models with lower prices [35].

In 2009, Samsung surpassed Hewlett-Packard to become the top technology company in sales, generating a total revenue of $117 billion. This success story highlights how Samsung, an Asian OEM/ODM, successfully shifted its focus from being a component maker/innovator to becoming a global brand name producer of high-value consumer electronics through architectural innovation. By 2013, Samsung had climbed to the third spot on the Boston Consulting Group's list of the world's most innovative companies [29].

3.4.4 Low switching cost and poor-quality product

These two non-supporting factors have been merged for this systematic literature review due to their limited impact on how they are affected by incremental innovation.

In the Chinese mobile and smartphone market in Shenzhen, which targets low-end markets, refurbished phones sold at a low price often exhibit inferior quality, technological inconsistencies, and possible safety hazards. Due to the installation of illegal and substandard components, these phones may only function properly for a short period or pose a risk to consumers. There is a risk of excessive radiation, overheating, and even explosion [25]. Products not meeting consumers' expectations are not chosen and eventually become obsolete. Companies that consistently produce the same products without innovation or improvement and fail to satisfy their customers may face liquidation [8]. Nokia received constant pressure from the financial markets due to the company's operating system, Symbian, which was struggling to survive and affected Nokia's new N8 smartphone, which relied on the new Symbian operating system [22].

4 DISCUSSION

4.1 Evaluation of Papers

The papers included were most relevant to incremental innovation as the smartphone industry has increased from a dominant design since the introduction of the first iPhone [36]. The theoretical aspects of incremental innovation include small increments on existing products or processes normally employed to maintain or increase market share cost-effectively, with minimum risk involved. The papers agreed with the theory as key findings were that the dominant players in the smartphone industry have been able to quickly adapt to customer requirements by improving their smartphone and operating system designs [21], [24], [35], [36]. Improved efficiency in the manufacturing processes resulted from these improvements, which was theoretically expected [29], [36].

The insights from the articles that covered the state of the industry showed that the market dynamics and firm capabilities influenced the wider industry. The main firm capabilities pertained to how firms in the industry could interpret customer requirements and innovate to meet them. The market dynamics covered how a relaxed regulatory environment in China allows follower brands to apply incremental innovation competitively. The results of the articles that examined organisational management were also greatly influenced by the firm capabilities code group and the market dynamics code group. The important capabilities covered timely innovation that meets customer requirements, and the important dynamics covered the imitation strategies used by Chinese manufacturers to become incremental innovators. Innovation networks' articles made considerable contributions to the market dynamics, organisational relationships and strategy, and the firm capabilities code groups. The capabilities discovered concerned translating the information in innovation networks into executable innovations. The key organisational relationships were the ones that improved a firm's relational embeddedness in a way that enhanced the level of innovation. The papers in the product development group had significant contributions from the market dynamics code group and the firm capabilities code group. The market dynamics group is concerned with the relaxed regulatory environment of follower brands in Shenzhen, China, which implemented incremental innovation on imitations of first movers targeted for low-end markets in rural Asia, the Middle East, and Africa. The capabilities the articles examined agreed on the ideal being customer requirements being addressed and increased product quality at a low cost.

The overall results detailed are all relevant to the topic of incremental innovation. Based on the results given by each of the document groups and the code groups with their respective codes, the current literature strongly emphasises quickly interpreting and meeting customer requirements as a key capability of a smartphone manufacturer practising incremental innovation. This is a reasonable focus consistent with the theory of the topic, as incremental innovation is about improving existing products with existing customers. These customers require appropriate changes, or else they can leave a product. The other key concern addressed across all the document groups was that to succeed in incremental innovation, a firm had to introduce innovations to its smartphones quickly or follow or imitate a first mover quickly. Most of the examples relating to this dynamic were predominantly from the Chinese market as it represents a large proportion of the smartphone manufacturing market. Thus, the discoveries are predominantly associated with the Chinese markets rather than general markets [14], [16], [25]. Due to the regional concentration of the examples, the dynamics of imitation coupled with the state of the regulatory environment indicate an area that would require more research to determine the general case. More research must be conducted to determine the nature of the imitations, as some companies can follow design inspirations, and others could violate patents. The common use of imitation indicates that the influence of a market leader dominates the smartphone industry.

Out of the 30 analysed papers, 29 had significant contributions that could be linked to the topic of incremental innovation. Lamhaddab et al. [34] had little contribution toward the study as it focused on the technical challenge of porting applications from iOS to Android devices. The nature of the selection of papers was dependent on keyword searches. As a result, an article with the requisite keywords, but not the appropriate context, was able to pass the inclusion criteria.

4.2 Specific noteworthy findings/models

The effect of regulation is noted in [16] and [25]. The fact that it can directly affect the market and make Incremental Innovation a competitive strategy is noteworthy. This can alternatively present a barrier to the implementation of Incremental Innovation, as a set of laws could reverse a firm's competitiveness in a changing market. The key enabler of innovation discovered in the analysis was the importance of interpreting and quickly acting on customer requirements. This was mentioned as what keeps Incremental Innovation as a competitive strategy in the smartphone industry.

4.3 Answers to research questions

RQ1: How sustainable is incremental innovation for maintaining competitive differentiation?

In the articles covered in sections one to four, incremental innovation was presented as a sustainable strategy that can be used for some time. The incremental innovation strategy has been competitively employed by Apple for 16 years since 2007 [7], [17], [21], [23], [24], [36], which does support the position of the innovation strategy being sustainable for a significant *period. The articles did not define durations of sustainably maintaining the strategy therefore, further investigation would be required to achieve a quantitative answer.*

RQ2: Can the smartphone industry benefit from incremental innovation?

The smartphone industry has benefited from incremental innovation as the strategy has allowed companies to add new features to their devices and to expand the market efficiently and at low costs [29], [36]. Incremental innovations and increasing features of smartphones have allowed different demographics and different types of customers to be addressed. Well-developed innovation networks have emerged, which in turn have improved the process of producing smartphones [22], [27], [29], [30].

RQ3: What are some of the enablers or supporting factors for incremental innovation?

The results from the analyses of the articles determined that the factors that strongly support incremental innovation were the following:

- Dominant market brand and position to incrementally innovate cost-effectively.
- Active innovation networks to allow for increased innovation.
- Regulations that support a firm's advantage.
- High switching costs between competitors.
- The ability to correctly determine customer requirements and translate them into high-quality product development.

RQ4: What can limit the application of incremental innovation?

The results from the analyses of the articles determined that the factors that strongly oppose and limit the success of incremental innovation include:

- A new radical innovation that causes customers to change their preferences.
- Poor product quality and failed execution of the innovations.
- High costs of adjustment concerning product innovation and production.
- Low customer switching costs between competitors.

The failure to execute innovations that match customer preferences proved to be the biggest factor behind the failures of notable brands, like Nokia and Blackberry, in the smartphone markets [17], [21]. The respective corporations lost market share, even though they had considerable innovation networks and proprietary technologies. They failed to adjust to rapid changes in their environments as they had high adjustment costs.

5 CONCLUSION

Sustainable growth hinges on a company's ability to innovate and continuously provide greater transformative value for its customers. Innovation is the most effective means for businesses to create and capture higher value in the global value chain [38]. Incremental innovation, which involves ongoing product improvement and enriching customer experience, offers long-term benefits, making it an appealing innovation strategy. Market leaders benefit from frequently introducing or adopting incremental innovation to maintain and improve their market share.

The success of smartphone makers like Samsung, Apple, Nokia, and Xiaomi is attributed to their ability to deliver transformative values through competitive products. Apple, for example, combines a dual customer-centric strategy that prioritises enhancing customer experience and seeking input from customers at multiple touchpoints [29]. The firm proactively seeks feedback from its customers through various platforms and uses that data to make incremental changes to the product and get ideas on how the product can be improved to meet the evolving needs and lifestyle of the end user.

Nokia misunderstood the market needs when smartphones became a necessity. The market required not only a mobile phone with basic functions, such as making phone calls and texting, but also a platform that does more operations simultaneously, while users experience new functionalities [21]. The benefits of putting the customer at the core of business development, and designing products with their needs in mind are substantial in today's competitive business landscape.

The impact of a company's culture on its ability to successfully apply incremental innovation cannot be overstated. Employees get comfortable and confident in sharing ideas in an environment that encourages risk-taking and experimentation; therefore, creating a culture and an environment that values innovation and experimentation will result in more ideas, creativity, and skills to drive innovation within the organisation. The objective is to continuously improve the product to align with the market trends and remain competitive in the ever-changing market.

Incremental innovation requires less time and money than other innovation methods; it makes it easier to detect and solve problems that develop throughout the project and allows for fast course corrections. With the resources available, more substantial results are obtained. Incremental innovation development is more affordable, efficient, and less risky. Incremental innovation allows for businesses to achieve desired goals effectively [38].

To complete this systematic literature review, the authors followed a defined methodology that can be replicated in future studies. However, the methodology appears to have some limitations.

In future studies, it would be beneficial to clearly define both the inclusion and exclusion criteria to ensure that only high-quality articles are included in the systematic literature review. Additionally, the authors should develop a quality assessment tool to evaluate the studies' quality and exclude articles that do not meet the minimum quality standards. By doing so, the authors can improve the overall validity and reliability of the systematic literature review.

5.1 Recommendations for future study

In this study, it was evident that consumers play a critical role in determining a firm's competitive advantage in an industry [38]. However, there is a gap, and firms must identify and understand what the market needs [21]. Future research should focus on consumer behaviour and preferences for sustainability in the smartphone industry. This research can assist firms in determining what consumers value in terms of sustainability and how to align their innovation strategies with these values.

The relationships among organisations in the industry were found to have a significant impact on the growth of the business [27], [30]. It is recommended that future studies investigate partnerships and collaborations among smartphone industry stakeholders regarding the use of expertise and resources to advance sustainable innovation. This study can assist in identifying essential partners and collaborative models that can propel sustainability ahead.

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THE SOCIO-ECONOMIC EFFECTS OF AIRBNB AS A DISRUPTIVE INNOVATION ON BUSINESS AND SOCIETY

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ABSTRACT

This study aimed to evaluate the disruptiveness of Airbnb. Forty-one papers were assessed using the PRISMA ScR framework. The results demonstrate that Airbnb has had a disruptive effect mostly on low to middle-income families and neighbourhoods through property price increases, gentrification, and touristification of neighbourhoods. Governments have had a delayed response to Airbnb, primarily because they were caught unprepared to deal with the speed at which the use of its platform has accelerated. Cities have also struggled to regulate Airbnb because of its business model. The response has been to regulate hosts at the local level. These regulations include the move to either prohibit Airbnb, have a cooperative approach with Airbnb, or limit the operation of Airbnb through trade restrictions. There has not been a conclusive study to determine the effectiveness of how cities regulate Airbnb.

Keywords: Airbnb, disruptive innovation, sharing economy, property prices, gentrification, touristification

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1 INTRODUCTION

Innovation and technology are strongly related, each being an enabler of the other. Innovation is defined as creating new products and methods, whereas technology practically implements these innovations [1]. Steenhuis and Pretorius [2] distinguish between three types of innovation - incremental, radical, and disruptive. Radical innovations create entirely new markets or completely change existing markets, such as the invention of the assembly line in the manufacturing process[1]. Incremental innovation is a systematic improvement of existing technology, where the changes are more subtle than radical innovation [2]. Disruptive innovation is similar to radical innovation. However, it does not create new markets nor revolutionise existing markets - it enters established markets with a competitive advantage that incumbents fail to identify and changes the competitive landscape of the industry [1].

Imam [13] defines the sharing economy as an online system where individuals meet the needs of other individuals through the transactional use of their unoccupied assets. The most popular examples of such transactions are ride-sharing services like Uber and short-term rental platforms like Airbnb. This review will focus on Airbnb as a disruptive innovation in the hospitality industry. Short-term rentals are properties occupied only for a short period (typically a week or two). These contrast with long-term rentals, which are more permanent and usually occupied for at least a year, paying monthly or annual rent. Airbnb allows normal citizens (called "hosts") to rent out their holiday homes to tourists or travellers (called "guests") through an online platform as short-term rentals. Airbnb offers guests the benefit of choice and unique local cultural experiences that large hotel chains cannot offer. Hosts benefit financially as their second properties or spare rooms suddenly become additional income sources. Founded in 2008, Airbnb operates in over 100 000 cities, with 6,6 million active listings worldwide as of December 2022 [3].

Disruptive innovation is described as an invention that underperforms compared to a similar product in the market through its primary performance attributes [4]. Airbnb has been considered a disruptive innovation as it has presented an unexpected transformation in the hospitality industry, adversely affecting property prices, society, and local legislation. Airbnb has invested $120 million to stimulate worldwide expansion, meaning its effects are here to stay long-term [5].

The disruptive nature of Airbnb has far-reaching effects beyond the hospitality sector. On a societal level, Airbnb has been blamed for rising property prices in cities worldwide and the gentrification and touristification of neighbourhoods. Franco and Santos [14] investigated the link between rising property prices and Airbnb in Lisbon and Porto, while Garcia-López et al. [15] conducted a similar study in Barcelona. Wyman, Mothorpe and McLeod [16] investigated the matter in the Isle of Palms, South Carolina, providing insights from a North American perspective. Regulations have been introduced in some cities specifically targeted at minimising the effect of Airbnb in and around neighbourhoods [6].

This review aims to offer an overview of the published literature on Airbnb, focusing on its disruptive nature's economic, social, and regulatory effects. Furthermore, the following research questions will be answered:

1. What are the effects of Airbnb on business, with a focus on employment and hotel profitability?
2. What are the effects of Airbnb on society, with a focus on property prices and gentrification?
3. How have local authorities responded to Airbnb?

This review continues by describing the research methodology, including details on how the cited literature was obtained. Following this, the research questions are described, and their relevance to the topic is evaluated. The results and discussion section is split into three subsections, each relating to one of the three research questions, i.e. the economic, societal, and regulatory investigations. The review ends with a conclusion critically evaluating the gathered literature and findings thereof, followed by recommendations for future work.

2 METHODOLOGY

To better understand the current literature about Airbnb and its effect as a disruptive innovation on society and business, as well as to review the literature on the regulatory response to these effects, a scoping review, which is a form of literature review, was elected as the best method to synthesise literature on the topic. The team selected the PRISMA extension for scoping reviews (PRISMA ScR) with its accompanying checklist, as Tricco described it [7].

A scoping review was conducted to investigate the extent of available literature, map and summarise the evidence and inform future research [17]. Applying this to case studies, it becomes evident that scoping reviews can identify case studies implemented more effectively, identify gaps in the literature available, and indicate areas that may require further research [7].

There are, however, some limitations to using scoping reviews to test the application of theory. Firstly, scoping reviews are not meant to be used to determine the quality of evidence in case studies. Therefore, they cannot be used to determine if the associated case studies provide robust or generalised findings; they do not weigh the evidence against the effectiveness of any intervention used in the literature [8]. This can be attributed to not being expected to conduct methodological quality assessment or the risk of bias in the included case studies literature [18]; as a result, scoping reviews are not used to inform policy or decision-making, unlike systematic reviews.

Despite the increase in popularity of scoping reviews, it is noted that their methodological and reporting quality needs improvement [7]. The PRISMA ScR was developed to create a framework that would guide authors to improve the quality of scoping reviews by using a guided checklist [7]. The team used the checklist described in the PRISMA ScR methodology **Error! Reference source not found.**.

2.1 Literature search criteria

The main literature search criteria include only literature published after 2010; two reasons informed this: Airbnb was founded only in 2008, and search results for literature containing Airbnb in the titles and abstracts on Scopus returned the earliest literature published in 2011. The research databases are limited to Scopus and Web of Science. The two databases are among the most respected indices and abstracting services because they have many international submissions [9]. They are increasingly being used globally for different applications by businesses, individuals, and institutions of higher learning, owing to the quality of literature, vast scope of research covered, citation analysis, and advanced search capabilities [10].

Moreover, Scopus has a vast amount of quality literature with high citations [11], which is a critical requirement to ensure the standard of this scoping review aligns with the standard befitting a scoping review. Access to these papers was enabled through the University's library services, and they were limited to English papers.

The team used different search criteria strings when searching the databases. All the search strings were noted meticulously to ensure the repeatability of the search. Many records were returned on the database search, and the research team further refined their search strings to match as many relevant works of literature as possible without including those unrelated to the research question.

The search strategy included combining keywords with logical operators to include or exclude certain text within the literature. The search was then executed only on the title and the abstract portions of the literature.

Table 1: Database search strategy

Search term 1	*Operator*	*Search term 2*	*Operator*	*Search term 3*
Hotel	AND	Employment		
Airbnb	AND	Hotel		
Municipality	AND	Airbnb	AND	Hotel
Municipality	AND	Airbnb		
Hotel	AND	Occupancy	AND	Airbnb
Airbnb	AND	Property	AND	Price
Airbnb	AND	Employment		

The research team designed and developed the search strategy without assistance from information specialists or librarians. As a result, a peer review of the electronic search strategy (PRESS) checklist was not used. Instead, each research team member reviewed the search criteria and database search strategy to ensure that the literature results were repeatable. This was mostly a consequence of the time allocated to complete the research; the team opted to focus on exploring the available literature and peer-review the literature amongst themselves.

The research team found that they had to compromise on a few occasions owing to the limited time to complete the review - which directly affected the evidence collection and the time required to ensure a quality review of the available literature. Although every effort was made to ensure quality and impartiality, there were instances where manual literature searches were used to search for additional literature due to the quantity of literature yielded by the team's own developed search strategy. This created some confusion with fringe literature obtained manually being brought forward.

Using the PRISMA flow diagram assisted a great deal in resolving and consolidating all the literature obtained and the sources from which they were obtained.

2.2 Evidence selection

Two research-member review teams went through the literature to select literature based on the title. Then, a second round of selection was made by the same duo, who selected literature by reading the abstract sections of the chosen literature.

The selected literature was then shared with the rest of the team to read through and review for relevance. A final selection of literature was agreed upon through consensus and critical discussions with the reviewers. The final set of literature was again divided equally between the research team members based on the type of research question the literature was most likely to address. The research team paired themselves in groups of two to deal with a specific research question. The purpose of the sub-groups was to function as a "buddy system" and as peer-reviewers of the literature and their summary of the data.

As part of synthesising the data from the literature, the team members also used some software packages to structure their findings and document the literature under review. These software packages include Atlas.ti, which the team used as a qualitative tool to assist in mapping the literature from different sources to get a general overview and visualisations of the general ideas and arguments of the literature.

The team also used Endnote click to extract literature from different sources and Endnote 20 and Mendeley to store, remove duplicates, sort, document, and reference the literature. The data extracted from the literature were related to the city, social class, regulations instituted, the median salary of hotel staff, profitability of hotels, and social disturbances caused.

Error! Reference source not found. below illustrates how the research team used Atlas.ti to extract the available data based on social disturbances caused across all the literature reviewed for the associated research questions. The visualisation allowed the team to keep track of key concepts and quickly reference them to specific literature or to build a qualitative visualisation to understand better the evidence presented in the literature. A similar approach, Atlas.ti, was used to collect evidence for the remaining research questions.

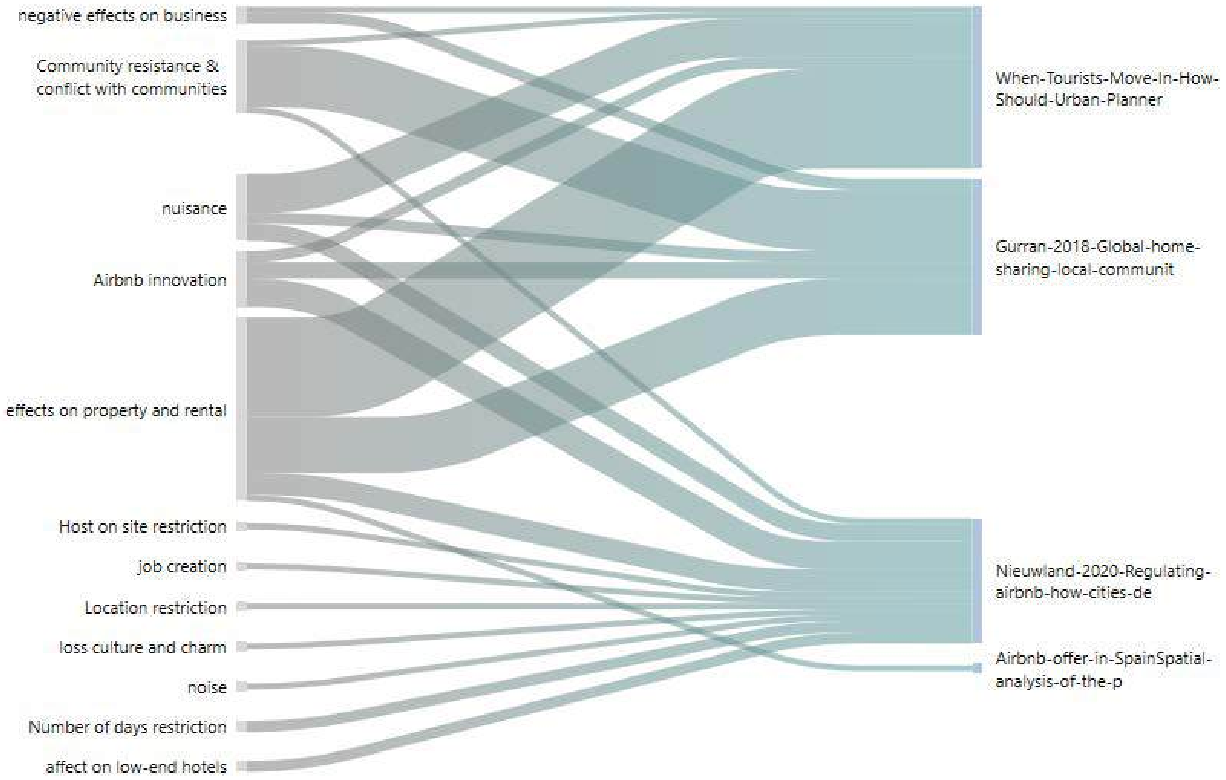

Figure 1: Social disturbance data extraction vs literature source with Atlas.ti

The evidence collection was reviewed, and the findings were summarised for later discussions and formulation of results. The research team used Atlas.ti and its visualisation tool to map out the main discussion points and use those to inform the research team of literature further that could be included or excluded based on the number of tags or references highlighted on Atlas.ti and guide the team towards the discussions and results of the review.

3 RESEARCH QUESTIONS

This review explores Airbnb as a disruptive innovation, how it affects business and society, and how authorities have responded to it. Regarding the business effect of Airbnb, the focal point will be hotel performance because Airbnb is considered a direct competitor in the industry. The investigation will also be on Airbnb's effect on society - i.e., how property and rental prices increase because long-term rentals are converted into short-term rentals and wealthier individuals and companies are buying up available property stock. Finally, an investigation into how local authorities respond to Airbnb is also conducted because Airbnb is unregulated. The following research questions were formulated to guide the initial search and to ensure that substantial literature relating to the topic is captured:

1. What are the effects of Airbnb on business, with a focus on employment and hotel profitability?
2. What are the effects of Airbnb on society, with a focus on property prices and gentrification?
3. How have local authorities responded to Airbnb?

One of the research questions' strengths is that they are specific on what to focus on regarding businesses and society. This helps with narrowing the research and helps by being specific. The barrier must be the cultural diversity of different regions and cities, which might impact the results of the questions.

4 RESULTS AND DISCUSSION

Error! Reference source not found. shows the PRISMA flow diagram for the search results obtained as per the search criteria in **Error! Reference source not found.**; after searching and screening a total of 310 literature papers obtained from both Scopus and WoS databases, a total of 41 literature articles were eventually selected for inclusion in the scoping review. The findings of the literature are discussed next.

4.1 Airbnb as a disruptive innovation

Disruptive innovation is described as an invention that underperforms compared to existing similar products in the market through its primary performance attributes [4]. Airbnb has been considered a disruptive innovation as it has presented an unexpected transformation in the hotel industry, with a spillover effect on employment, property prices, and society. The Airbnb disruption effect will be experienced for a long time as they have recently invested $120 million to focus on worldwide expansion by establishing offices in different countries and providing support services to hosts and guests alike [5].

4.1.1 Disruption in the Accommodation Sector

Airbnb has reshaped the accommodation sector, especially the traditional hotel segment, by attracting many regular customers. Airbnb overtakes traditional hotels for apparent reasons such as ease of checking in/out, cheaper, and more accessibility, and it offers a local experience to guests with greater exposure to the local culture of the area.

Zervas et al. [19] found that as Airbnb listings increase in revenue, a high negative impact was observed mostly in low-end hotels and hotels with low business clientele that are not partnered with the government. A 10% listing increase translated to a 0.37% decline in hotel revenue.

Guttentag and Smith [4] found that the tourism research firm HVS estimated that in the 12 months ending in August 2015, Airbnb caused a direct loss of $451 million for New York City (NYC) hotels alone. An online survey was conducted to measure the extent of the impact of substitution caused by Airbnb, and the result showed that 64% of respondents indicated that they use Airbnb as a hotel substitute [4].

4.1.2 Disruption of Local Government Regulations

Airbnb is a non-legalised short-term rental and, therefore, cannot be taxed by the government. For this reason, Airbnb cannot provide revenue streams to local governments that would have contributed to the local tourist economy. This reveals that Airbnb freely benefits from local governments without being taxed as it would to its competitors in the industry [5]. In addition, Airbnb is not subjected to tourist accommodation health and safety regulation standards, which could pose a high risk to guests if the hosts do not maintain safe standards in their rentals [5].

4.1.3 Disruption on Tourism

Airbnb houses with fully equipped kitchens, which guests can access and utilise during their stay, encourage the guests to prepare their meals instead of spending money on local restaurants; this deprives local restaurants of benefiting fully from tourists around their area. Hosts also sometimes take their guests around for drinks and show them around the area; this directly impacts the tour guide sector, which could have benefited instead of the host acting as a tour guide [5]

4.2 Effect on Business

4.2.1 Hotel Employment

Hospitality industries are experiencing job creation, job change, job destruction, and job shifting due to the emergence of Airbnb. Locals who frequently visit local restaurants could cease to visit the restaurant as they may tend to feel an invasion of their local spaces by Airbnb guests [12]. Hotel occupancy rates have decreased as more people are occupying Airbnbs and seemingly prefer peer-to-peer accommodation, causing a decrease in hotel revenues [5].

Dogru, Mody, et al. [20] state that low-end hotels are the most likely to be substituted by Airbnb; this means that employees working at low-end hotels are most vulnerable to job losses as hotels tend to cut down on staff to compensate for lost revenues. High-end hotels are least likely to be replaced by Airbnb as the economic benefits offered by Airbnb do not drive their customers; instead, they seek security and predictable quality. Dogru, Mody, et al. [20] further illustrate that a 1% increase in Airbnb demand decreased hotel revenues by 0.04% in Texas.

Affordable accommodation prices offered by Airbnb have increased the necessity for leisure-based travel worldwide; hence, an increase in Airbnb guests has led to job creation in the hospitality industry (i.e., entertainment companies, restaurants, and bars) to cater to this high market demand. A positive economic contribution of Airbnb to the New Orleans economy was highly noted, with a total growth of $134 million in revenues and an additional 4480 jobs generated in the tourism sector. However, the hotel segment was negatively impacted by Airbnb [21].

Bashir and Verma [22] noted that the HVS consulting and valuation company, in association with the Hotel Association of New York, issued a financial report that showed that approximately $2 billion in revenue was lost due to Airbnb in the lodging sector. In Austin, the areas with high Airbnb listings impacted the low-end hotels and loss of revenues ranging between 8-10%.

4.2.2 Hotel performance and occupancy rates

Airbnb did not influence hotel profits in Korea since guests preferred traditional hotels over home-sharing [20]. The availability of peer-to-peer (P2P) housing allowed guests to rest in areas not populated by traditional hotels, thus indicating that P2P accommodations were not a replacement for hotels but expanded the geographic scope of tourist activity.

Dogru, Hanks, et al. [23] investigated the financial impact caused by Airbnb on key performance indicators such as occupancy rates (OCC), average daily rate (ADR), and revenue per available room (RevPAR) in Paris, London, Tokyo, and Sydney. Airbnb inventory negatively affected all three performance metrics, visible across all hotel industry segments, from budget to luxury properties.

The effect of Airbnb listings on hotel RevPAR is negative and statistically significant for all Airbnb listings measured apart from shared room listings. A 1% increase in Airbnb listings decreases hotel RevPAR by between 0.016% and 0.031% in these hotel markets. Airbnb listings have been increasing by more than 100% year-over-year between 2008 and 2017 in these four cities as well. Considering such a growth rate, a 100% increase in Airbnb listings reduces hotel RevPAR by between 1.6% and 3.1% in these cities [23]. From these results, one can conclude that Airbnb has risen to become a noticeable player in the hospitality industry, causing marketplace disruption on a noticeable level.

Research also suggests that travellers travelling alone, with a partner, or as friends would prefer a hotel or Airbnb differently. Sainaghi and Baggio [24] suggest that long-trip travellers prefer Airbnb, and short-trip travellers prefer hotels.

According to Sainaghi and Baggio [24], the weekday trend of hotels in Milan suggests that they are predominately visited during the week by business personnel; therefore, the hotel metrics (occupancy, average daily rate, and revenue per available room) are higher during weekdays. The weekend trend of Airbnb stipulates that hotels in Milan during the weekend are more often visited by tourists than business personnel, just as on holidays.

Ram and Tchetchik [25] examined a pattern of hotel occupancy over three periods in Tel Aviv. Two datasets were extracted before Airbnb emerged, and the third dataset was extracted after Airbnb was introduced in the city. The findings suggest a complementary relationship between Airbnb listings and hotel occupancy, meaning that the results do not show any significant effect of Airbnb listing on hotel occupancy.

A study by Xie and Kwok [26] investigated whether hotel price variables are the main drivers of Airbnb penetration. Quality indicators were excluded from the study. A comparison of changes in prices was performed, and it was discovered that Airbnb penetration remains consistent despite the hotel's quality.

4.3 Effect on Society

4.3.1 Effect on property prices

Three research papers explored the impact of Airbnb on property prices in four major cities: Lisbon, Porto, Barcelona, and the Isle of Palms. Franco and Santos [14] analysed Lisbon and Porto, finding that property prices in high-tourist areas surged significantly compared to low-tourist areas, with a 24.3% increase in 2015 and a 32.3% increase in the first quarter of 2016. They noted a direct correlation between Airbnb share and property values, with a 3.2% increase in property values for every one percentage point increase in Airbnb share. Additionally, they highlighted the income advantage of Airbnb over long-term rentals, with property owners needing only to list their property on Airbnb for ten nights to earn the same income as a month-long rental. Garcia-López et al. [15] studied Barcelona and found that Airbnb activity led to a 1.89% increase in long-term rents, a 4.59% increase in transaction prices, and a 3.67% increase in posted prices.

Highly active Airbnb areas experienced even larger increases, with rents rising by 7% and transaction and posted prices increasing by 17% and 14%, respectively. Similarly, Wyman, Mothorpe, and McLeod [16] focused on the Isle of Palms, discovering that properties licensed as short-term rentals were 9-11.5% more expensive than normal properties, while long-term rental properties were 3.2-4.6% cheaper. These findings indicate a direct link between Airbnb activity and property price escalation, particularly in tourist-heavy or city-centre areas. The imbalance created in the housing market favours short-term rental investors over long-term rental opportunities, exacerbating housing crises and pricing middle-class citizens out of their neighbourhoods. Therefore, while Airbnb has revolutionised short-term accommodation, its impact on housing prices is viewed negatively, necessitating regulatory intervention to safeguard citizens while accommodating the short-term rental market.

4.3.2 Gentrification and Touristification

The sale and increase in property prices have been found to displace low and middle-income earners through what the authors described as tourist gentrification [6]. This usually occurs due to the commercialisation of entire neighbourhoods into short-term rental (SRT) stock. As alluded to in the prior discussion, the economic reaction of the housing market when there is a higher demand for property is property and rental increases. The resulting effect is that low to middle-income earners are squeezed out of the area as they can no longer afford to stay or buy there. The other effect that increases gentrification, as found in literature, is the change in the neighbourhood, which can be a result of disturbances such as noise, increased traffic, drunken behaviour, the concern of strangers in the neighbourhood, or the creation of complementary businesses such as bars and laundromats that change the look and feel of the neighbourhood [26].

In this situation, residents quickly leave the area as more and more tourists come in; this effect has been coined as the touristification of neighbourhoods [27].

4.4 Regulatory response

4.4.1 Response from Municipalities

Research revealed that the regulation of Airbnb was established to control or remove any unwanted or undesirable consequences of the platform and encourage those deemed beneficial for society to participate [26]. The regulatory objectives differ from region to region and often between cities in the same region. This is because cities may wish to encourage the uptake of Airbnb to encourage tourism in areas often left out of the tourism routes. In contrast, some cities may wish to limit Airbnb to address various social disturbances often linked with tourists' arrival [28]. The literature review also cited the risk of unlicensed Airbnb hosts not complying with public health and safety standards, which may have a consequence of spreading diseases [28]

Cities around the world have had to respond to these challenges by instituting regulations - it was found that there are generally three regulatory approaches that form the various frameworks of most regulations, as tabulated in Table 2. Nieuwland and van Melik [6] categorised them as Laissez-faire, full prohibition, and limitation through restrictions. A case in point for Laissez-faire is Amsterdam, a city that has adopted a collaborative approach with a set of limitations to regulate Airbnb. This city has made agreements with Airbnb to collect taxes directly from guests on behalf of the city [26].

Anaheim and Barcelona, on the other hand, already have an oversupply of holidaymakers; in this instance, the city has moved from partially banning Airbnb to almost completely banning it[26,28]. In most other cities, a myriad of restrictive regulations have been put in place, including a class of restrictive regulations Nieuwland and van Melik [6] have described as qualitative, quantitative, density, and location restrictions. Table 3 highlights these regulations as they are applied to cities.

Table 2: Main regulatory responses

Regulation	Description
Laissez-faire	A relaxed approach; collaboration is often encouraged.
Full Prohibition	No Airbnb is allowed in a city or country.
Restriction	Limitations of the use of Airbnb based on a set of rules and regulations.

Table 3: Types of restrictive regulations applied

Quantitative	Qualitative	Location	Density
restricts based on the number of guests, and the number of nights per guest, Property is restricted to operate for a number of days/ nights per year	hosts must live in the house, safety provisions provided, hygiene certification, and utility bill to be presented	Restriction of Airbnb in a specific area can also lead to a partial ban or full ban	Restriction based on x number of Airbnb in a specific area

Cities implement various regulations regarding Airbnb to address specific concerns such as quality of life, tourism pressure, affordable housing, and safety [6, 28]. However, enforcing these regulations proves challenging due to Airbnb's online nature, leading authorities to target hosts for compliance rather than Airbnb itself [6]. The lack of physical advertising or branding on premises allows hosts to operate discreetly, flouting regulations. For example, thousands of Airbnb listings were available in New York despite a ban on short-term rentals [28]. Advertising short-term rentals without a license is an offence in Denver and New York, but Airbnb listings often lack address information, making enforcement difficult [6]. Some progress has been made in enforcing compliance, with startups assisting law enforcement and online advertisements requiring license numbers. Stricter penalties are being imposed on violators, with instances of criminal charges against landlords in Los Angeles and fines imposed by cities like Barcelona, San Francisco, Santa Monica, New York, and Anaheim [6,29]. Cooperation between cities and Airbnb is vital for effective regulation and enforcement.

5 CONCLUSION

This review aimed to provide an overview of the effects of Airbnb as a disruptive innovation, how it affects business and society, and how authorities have responded. Research questions were formulated to assist in finding relevant information for the study. Strings of keywords were selected and searched on suitable databases, which also helped remove duplicate articles. The study excluded articles that were published prior to 2010 and were limited to the English language.

The final articles were used as sources to answer the research questions posed. Airbnb is considered a disruptive innovation as it presented an unexpected transformation in the hotel industry that affected employment, property prices, and society. The results of Airbnb listings affecting hotel performance were inconclusive since these claims are geographically limited. In Korea, for instance, Airbnb does not influence hotel performance since guests still prefer traditional hotels. In cities like London, Paris, Tokyo and Sydney, there has been a noticeable negative effect on hotel RevPAR due to increased Airbnb activity. Focusing on findings from four cities across Europe and North America, it is also concluded that Airbnb is partially responsible for increased property prices worldwide. With the emergence of Airbnb, the hospitality industry faces job creation, job destruction, and job-shifting trends. The effect on high- and low-end hotels was found to be different - high-end hotels are less likely to be affected by Airbnb as the target market is different. Regulatory objectives are put in place to control or limit undesirable consequences, with the type of response found to be different across regions. Because Airbnb is an online platform, enforcing these regulations has also proven to be challenging.

Research related to this topic could benefit from a deeper exploration of the theoretical implications of its findings. Although this paper discusses the impacts of Airbnb, it could be advantageous to link these findings more explicitly to broader theories of disruptive innovation and urban economics. Future work can improve on this through systematic literature reviews or data analyses that evaluate Airbnb's effects related to these theoretical frameworks, thereby providing a deeper understanding of the broader economic and innovative trends at play. When a systematic literature review approach is used, it is recommended that the PICO (problem (P), intervention (I), comparison intervention (C), and outcome (O)) model be used to improve the quality of the search strategy [30]. Another limitation is that this research included multiple cities worldwide; however, there is a lack of research within an African context. It is thus recommended that future research focus on African cities.

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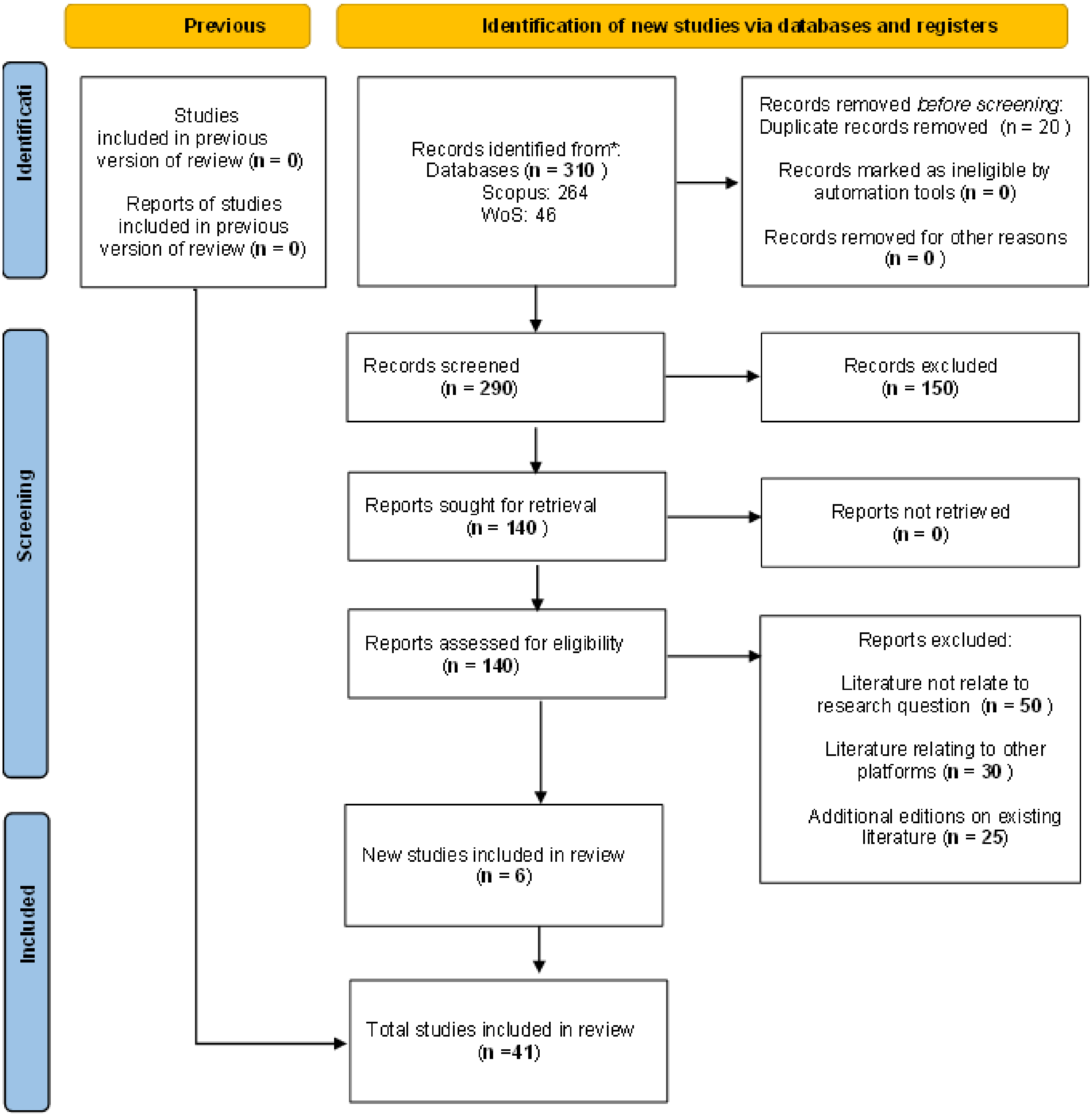
Annexure 1: PRISMA ScR checklist

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM
TITLE		
Title	1	Identify the report as a scoping review.
ABSTRACT		
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.
INTRODUCTION		
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualise the review questions and/or objectives.
METHODS		
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.
Selection of sources of evidence	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.
Critical appraisal of individual sources of evidence	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).
Synthesis of results	13	Describe the methods of handling and summarising the data that were charted.

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM
RESULTS		
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.
Synthesis of results	18	Summarise and/or present the charting results as they relate to the review questions and objectives.
DISCUSSION		
Summary of evidence	19	Summarise the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.
Limitations	20	Discuss the limitations of the scoping review process.
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.
FUNDING		
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.

Annexure 2: PRISMA ScR flow diagram on search criteria results from literature search



ENHANCING DECISION-MAKING IN SOUTH AFRICAN SMMES THROUGH BUSINESS INTELLIGENCE

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ABSTRACT

Small, Medium, and Micro Enterprises (SMMEs) play a crucial role in South Africa's economy, yet they grapple with numerous challenges, often resulting in high failure rates. Despite accumulating substantial data, many SMMEs struggle to derive meaningful insights from their data. Recognizing the critical importance of informed decision-making, this article delves into the adoption of Business Intelligence (BI) solutions within South Africa's SMME sector. The study adopted a mixed-methods approach to investigate the challenges faced by SMMEs in implementing BI solutions. The findings of this article expand on the existing literature on the challenges associated with BI adoption in SMMEs and offer practical recommendations for successful BI adoption by SMMEs in South Africa. This research will be pivotal in enhancing the capabilities of SMMEs to utilize BI for informed decision-making and long-term sustainability.

Keywords: Small and Medium-sized Enterprises, Business Intelligence

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1 INTRODUCTION

In developing countries like South Africa, Small, Medium, and Micro Enterprises (SMMEs) contribute significantly to the economy. These entities not only contribute substantially to the country's Gross Domestic Product (GDP) but also play a pivotal role in job creation and the stimulation of economic growth. Their significance extends beyond economic parameters, influencing social aspects, thus tremendously increasing the competitiveness and economic prosperity of the country [1]. Despite their potential, many SMMEs in South Africa face various challenges, with a substantial number failing shortly after inception. In the dynamic landscape of the modern economy, effective decision-making based on real-time data is imperative for the survival and growth of businesses. The integration of Information Technology (IT) solutions to support and manage business operations is crucial in ensuring that the organization remains competitive. One such solution, Business Intelligence, proves instrumental in facilitating informed decision-making by providing fact-based support systems [2].

BI is a technology-driven process for analyzing data and presenting actionable information to help executives, managers, and end-users make informed business decisions [3]. It encompasses various tools, applications, and methodologies that enable organizations to collect data from internal systems and external sources, prepare it for analysis, develop and run queries against the data, and create reports, dashboards, and data visualizations. These processes are crucial for identifying opportunities, streamlining operations, and gaining a competitive edge in the market.

Despite the potential benefits of BI in enhancing operational efficiency, competitiveness, and sustainability of SMMEs, there is a noticeable gap between the availability of BI technology and its adoption among South African SMMEs. This discrepancy raises questions and concerns about the barriers hindering BI adoption within the SMME sector in South Africa. Given this backdrop, there is an evident need for a comprehensive investigation into why South African SMMEs are not implementing BI solutions as part of their decision-making support systems. Such an investigation is crucial for identifying the specific barriers these enterprises face. Therefore, this study aims to identify and thoroughly understand South African SMMEs' challenges in adopting BI solutions.

2 LITERATURE REVIEW

The adoption of BI solutions has become increasingly essential in this era characterized by rapid technological advancements. The ability to analyse data and make informed decisions has emerged as a critical determinant of organizational success and sustainability. Despite the acknowledged potential of BI to transform business operations through enhanced analytical capabilities, its adoption among South African SMMEs remains limited [4]. This discrepancy raises questions about the barriers to BI implementation among SMMEs. Therefore, understanding the dynamics of BI adoption within SMMEs is crucial, not only for the enterprises themselves but also for policymakers, researchers, and technology providers [5].

2.1 Definition and Evolution of Business Intelligence

Business Intelligence refers to the technologies that turn data into information, information into knowledge, and knowledge into plans that drive cost-effective business actions. According to Pontes & Albuquerque [3], BI involves collecting, analysing, and interpreting business data to support strategic planning and informed decision-making. BI has undergone significant evolution over the past few decades and has grown from being just data processing systems to sophisticated analytical tool that drive strategic decision-making in organizations [5]. Understanding the historical developments and conceptual foundations of BI is crucial for comprehending its current significance and applications within SMMEs.

2.1.1 Origin and evolution of Business Intelligence

The concept of BI was first introduced in the late 1950s by IBM researcher Hans Peter Luhn, who envisioned a system that could provide decision-makers with timely and relevant information for strategic planning [6]. Initially, BI was characterized by simple data processing techniques aimed at organizing, storing, and retrieving information from large datasets. However, with the advent of computer technology and relational databases in the 1970s and 1980s, BI began to evolve into more sophisticated systems capable of performing complex analyses and generating actionable insights [6].

Throughout the 1990s and early 2000s, BI underwent a period of rapid expansion and innovation, driven by advancements in software development, data warehousing, and online analytical processing (OLAP) technologies. This era saw the emergence of enterprise-wide BI platforms, such as SAP BusinessObjects and Oracle BI, which integrated data from disparate sources and provided comprehensive reporting and analytics capabilities to organizations [7]. Additionally, the rise of the internet and e-commerce facilitated the collection of vast amounts of data, further fuelling the demand for BI solutions that could extract value from these data streams.

In recent years, the proliferation of big data, cloud computing, and artificial intelligence (AI) technologies has revolutionized the BI landscape, enabling organizations to leverage massive datasets and advanced analytics techniques to gain deeper insights into their operations and customer behaviours [8]. Modern BI platforms offer features such as predictive analytics, machine learning, and natural language processing, empowering users to make data-driven decisions in real-time.

Despite its evolution, the fundamental goal of BI remains unchanged: to transform raw data into actionable insights that drive business value. Whether it's optimizing operational processes, identifying market trends, or improving customer satisfaction, BI serves as a strategic enabler for organizations seeking to gain a competitive edge in today's data-driven economy [8]. In the context of SMMEs, where resources are limited and agility is paramount, the ability to harness BI effectively can spell the difference between success and failure.

2.1.2 Components of BI

The components of BI encompass a comprehensive ecosystem that facilitates data-driven decision-making within organizations [9]. From data collection and integration to decision support and performance management, each component plays a crucial role in transforming raw data into actionable insights [10]. There are 5 main BI components as shown in the figure below:

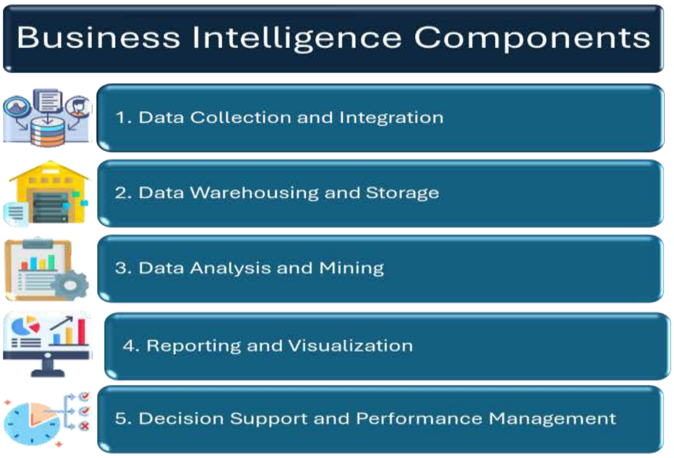

Figure 1: Business Intelligence Components [10]

1. Data Collection and Integration

Data collection and integration form the backbone of any BI system. They involve gathering data from various internal and external sources, including Enterprise Resource Planning (ERP) systems, social media, and Internet of Things (IoT) devices, and consolidating it into a unified format for analysis [11]. The literature emphasizes the importance of sophisticated data integration tools and techniques, such as ETL (Extract, Transform, Load) processes, to ensure that data is accurately and efficiently prepared for analysis [12]. This step is crucial for maintaining data integrity and ensuring that subsequent analyses are based on complete and coherent datasets.

2. Data Warehousing and Storage

Once data is collected and integrated, it must be stored in a manner that supports efficient retrieval and analysis. This is where data warehousing comes in, providing a centralized repository that consolidates integrated data from multiple sources. Unlike traditional databases, which are optimized for transaction processing and day-to-day operations, BI data warehouses are designed specifically for query and analytical processing [11]. The literature highlights the evolution of data warehousing technologies, including the adoption of cloud-based solutions that offer scalability and cost-effectiveness [13].

3. Data Analysis and Mining

Data analysis and mining are at the heart of BI, transforming raw data into meaningful insights. These processes involve the use of statistical models, machine learning algorithms, and data mining techniques to uncover patterns, correlations, and trends within data [14]. Data mining has been noted for its ability to discover hidden patterns and relationships in large datasets, providing a deeper understanding of business operations and customer behaviours [14].

4. Reporting and Visualization

Reporting and visualization tools are essential for communicating BI insights to end-users in an understandable and actionable format. These tools allow users to create dashboards, graphs, and reports that visually represent analysis outcomes [15]. Effective visualization techniques are crucial in enhancing decision-making processes, as they enable users to quickly grasp complex information and identify key trends and outliers [16]. User-friendly reporting and visualization tools are important as they enable non-technical users to explore and interpret data insights independently.

5. Decision Support and Performance Management

BI systems play a pivotal role in decision support and performance management, enabling organizations to align their strategies with data-driven insights. This component involves the application of BI analysis to guide strategic planning, operational improvements, and performance monitoring [17]. Decision support systems (DSS) leverage BI to provide actionable recommendations, facilitating informed decision-making across various levels of the organization [17].

2.2 SMMEs: An Overview

SMMEs refer to businesses with staff and revenue figures that fall below-specified thresholds. It's crucial to emphasize that there is no universally accepted definition for SMMEs, as every country defines it based on its economic conditions. In South Africa, the term 'small business' is officially outlined in Section 1 of the National Small Business (NBS) Act of 1996, amended by the National Small Business Amendment Acts of 2003 and 2004 (NSB Act). According to this legislation, a small business is described as "a distinct business entity, including co-operative enterprises and non-governmental organizations, managed by one or more owners. The NSB Act further categorizes small businesses in South Africa into survivalist, micro, very small,

small, and medium groups, leading to the use of the umbrella term "SMME." The terms 'SMME' and 'SME' are used interchangeably in South Africa.

In 2019, the then Minister of Small Business Development in South Africa, Lindiwe D Zulu, issued a proclamation to amend Schedule 1 of the national definition of small enterprise. This amendment was made in accordance with section 20(2) of the NSB Act No. 102 of 1996. The changes included:

- Adjustment for Inflation- The turnover threshold values in the Small Enterprise Definition were updated to account for inflation, considering that the last revision was in 2003.
- Proxy Reduction- The number of proxies used to define small enterprises was reduced from three to two. The new schedule utilizes two proxies: total full-time equivalent of paid employees and total annual turnover.
- Consolidation of Size/Class Category- The size or class category of the very small enterprises was collapsed into the micro-enterprise category. This modification was made to address user concerns about the unhelpfulness and inconsistency of the very small enterprise category with international practices.

SMMEs play a pivotal role in fostering economic growth and development by significantly contributing to the reduction of the unemployment rate through substantial workforce employment [18]. In South Africa, SMMEs constitute 98.5% of the total businesses, providing employment for 25.8% of the workforce and contributing 39% to the country's gross domestic product (GDP) [19].

The research conducted by Ncube & Zondo [18] emphasizes challenges faced by SMMEs in South Africa, including limited access to finance, regulatory constraints, and infrastructure deficiencies that impede their growth. The research also highlights the influence of socio-economic factors, such as a lack of skills and education, as obstacles to the success of SMMEs [20]. In the context of South Africa, technological advancements have become increasingly crucial for SMME growth, though challenges related to digital literacy and infrastructure disparities persist. Recognizing these complexities in the evolving business landscape is essential for developing targeted strategies and policies aimed at empowering and sustaining the growth of SMMEs in South Africa [21].

3 METHODOLOGY

This study adopted a mixed-methods approach, combining qualitative and quantitative research methodologies to comprehensively understand the challenges associated with adopting BI solutions among South African SMMEs.

The study population consisted of South African SMMEs from a diverse range of sectors, including retail, manufacturing, and services. This diverse selection was to ensure a broad spectrum of insights into BI adoption challenges, reflecting the heterogeneous landscape of SMMEs in South Africa.

Purposive sampling was used for qualitative interviews, focusing on owners or top management, while a combination of convenience and snowball sampling was employed for the survey questionnaire.

Five semi-structured interviews were conducted with SMME owners or top management, each lasting 20-30 minutes. An online survey questionnaire was distributed to a broader range of SMMEs. The questions for both interviews and survey were carefully structured to achieve the research objectives. The interview questions targeted key areas such as business context, data usage, BI awareness, and perceived challenges, ensuring detailed qualitative insights. Meanwhile, the survey questionnaire included both closed and open-ended questions to quantify BI adoption levels, barriers, and support needs. This structured approach across both qualitative and quantitative methods ensured a comprehensive understanding of the multifaceted challenges and opportunities associated with BI adoption among South African SMMEs.

Thematic analysis was applied to the qualitative data obtained from the semi-structured interviews. This involved coding the interview transcripts to identify recurring themes and patterns related to the challenges and perceptions of BI adoption among SMMEs. Descriptive statistics were utilized to summarize the quantitative data from the survey questionnaire. The findings were presented in tables and charts created with Microsoft Excel to provide an overview of respondents' perceptions and experiences regarding BI adoption.

Research contribution

This research significantly advances the understanding of BI adoption challenges among SMMEs in South Africa. By investigating the specific barriers and enablers to BI adoption, the study provides detailed insights for SMMEs and policymakers. This research offers diverse insights by including participants from various industries such as retail, manufacturing, and services. This diversity enriches the study, making the findings applicable across a broad spectrum of business contexts and enhancing the generalizability of the results. Another significant contribution is the practical recommendations derived from the study. These include the need for affordable and accessible BI tools, specialized training programs, financial assistance, and consultancy services. By providing such actionable suggestions, the research not only identifies problems but also proposes feasible solutions to overcome them.

4 RESULTS AND DISCUSSION

4.1 Structured Interviews Findings

The following interview questions were designed to get detailed responses that could provide valuable insights into the current state of BI adoption among SMMEs and the challenges they face.

- **Question 1**: Can you provide a brief overview of your business, including the industry you operate in and the size of your company?

Responses from Participants:

Out of the 5 participants interviewed, 3 revealed that their businesses operate within the manufacturing sector. Among them, two participants employ between 51 to 100 individuals, while the third participant employs 1 to 10 people. Another participant owns a farm, employing a team of 15 people. Lastly, 1 participant described their business as a family-owned retail shop, employing 10 people. This range of businesses showcases a diverse mix of industries and company sizes among the participants.

- **Question 2**: How would you describe the role of data and information in your business operations?

Responses from Participants:

All five participants emphasized the critical role of data and information in their business operations. One participant mentioned using data to track sales trends and customer preferences in their retail store, stating, "*Data can help us understand what products are selling well and adjust our inventory accordingly*."

- **Question 3**: What is your understanding of BI and its potential benefits for your business?

Responses from Participants:

Among the participants, there was a general lack of deep understanding and awareness regarding BI and its potential benefits. While some participants acknowledged hearing about BI as a concept, they struggled to articulate specific applications or advantages within their business contexts. One participant mentioned vaguely that BI might involve analysing data for decision-making purposes but was unable to provide further details. Another participant admitted having limited knowledge about BI and its relevance to their business operations, stating, "*I've heard of BI, but I'm not sure how it could help us*."

- **Question 4**: Have you previously considered or attempted to adopt BI solutions in your business operations? If yes, can you share your experiences?

Responses from Participants:

Regarding previous attempts or considerations to adopt BI solutions, only one participant indicated having explored BI solutions in the past. This participant shared their experience of experimenting with a BI tool to analyse sales data but encountered challenges integrating it with existing systems and training staff to utilize it effectively. Despite initial efforts, they ultimately discontinued the adoption due to resource constraints and limited expertise in BI implementation. The other participants had not actively pursued BI adoption in their business operations.

- **Question 5**: What do you perceive as the biggest challenge in adopting BI solutions?

Responses from Participants:

Among the participants, the predominant challenge perceived in adopting BI solutions centred around the lack of expertise and resources required for implementation. Participants expressed concerns about the specialized knowledge needed for data analysis, software integration, and user training, which may be lacking within their organizations. Financial constraints were also highlighted as a significant barrier, particularly for SMMEs, who may struggle to afford the investment required for BI tools and infrastructure changes. Additionally, participants mentioned potential resistance to change and cultural barriers within their organizations, indicating that employees may be hesitant to embrace new technologies or modify existing workflows.

- **Question 6**: Are there specific resources or types of assistance you believe are lacking for SMMEs in South Africa to successfully implement BI?

Responses from Participants:

Participants highlighted several areas where they believe SMMEs in South Africa lack resources or assistance for successful BI implementation. One common concern was the availability of affordable and accessible BI tools tailored to the needs and budgets of SMMEs. Participants expressed a need for cost-effective BI solutions that are easy to implement and use, without requiring extensive technical expertise. Additionally, participants mentioned a lack of training and educational resources specifically tailored for SMMEs. They emphasized the importance of training programs, workshops, and educational materials designed to help SMMEs understand and leverage BI effectively.

- **Question 7**: How do you see the role of BI evolving in your business strategy in the future?

Responses from Participants:

Participants expressed varying views on the future role of BI in their business strategies. While some participants expressed optimism about the potential of BI to play a more significant role in informing strategic decision-making and driving business growth, others were more cautious in their outlook. Those who were optimistic highlighted the increasing importance of data-driven insights in today's competitive business landscape and expressed intentions to invest further in BI tools and technologies. They envisioned leveraging BI to gain deeper insights into customer behaviour, optimize operational processes, and identify new market opportunities. However, some participants also acknowledged challenges such as limited resources and expertise, which may impact their ability to fully realize the potential of BI in their business strategies. Overall, participants recognized the growing importance of BI in shaping their future business strategies but acknowledged the need for careful planning and investment to leverage BI effectively.

4.2 Survey Questionnaire Findings

4.2.1 Demographics

The survey uncovered respondents' roles within their respective companies to understand the demographic composition. The figure below shows results.

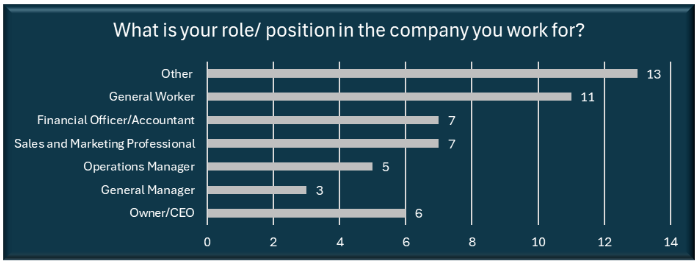

Figure 2: Respondent's Roles

The findings indicate a diverse representation across various positions. Owners/CEOs, General Managers, Operations Managers, Sales and Marketing Professionals, and Financial Officers/Accountants collectively comprise most respondents, reflecting a balanced mix of leadership, operational oversight, and specialized functions within the surveyed companies. General Workers constitute a significant portion of the workforce, highlighting the importance of frontline personnel. Additionally, a notable percentage of respondents identified with various other roles.

The survey further delved into the sectors in which the companies operate, providing insights into the diverse business landscapes represented and the manufacturing sector emerged as the most prevalent, highlighting a significant presence of manufacturing SMMEs in South Africa.

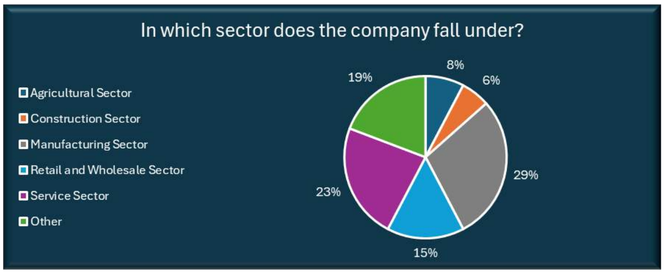

Figure 3: Respondent's Sectors

4.2.2 Business Intelligence Awareness

Business Intelligence was defined to the respondents as a "process of collecting, analysing, and interpreting data to drive informed decision-making and improve business performance". The respondents were then asked about their familiarity with the concept and the figure below shows the breakdown of their responses.

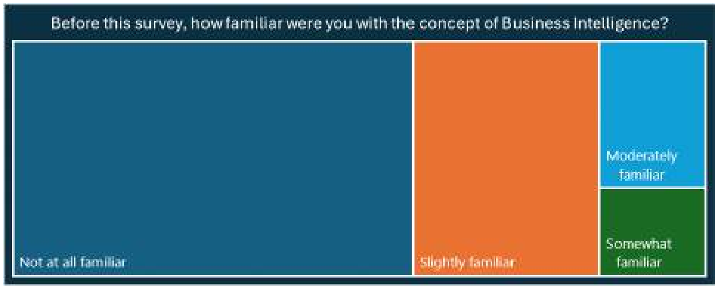

Figure 4: BI awareness levels

Most respondents (30) indicated they were not at all familiar with BI, suggesting a lack of prior knowledge or exposure to the concept. Additionally, 14 respondents reported being slightly familiar with BI, indicating some level of awareness but with limited depth of understanding. A smaller number of respondents identified as somewhat familiar (3) or moderately familiar (5) with BI, suggesting varying degrees of prior exposure and comprehension. Interestingly, none of the respondents claimed to be very familiar with BI prior to the survey. These findings underscore the need for further education and awareness-building initiatives regarding BI concepts and applications among the surveyed population.

The respondents were asked to rate the importance of BI in general and the results are shown below.

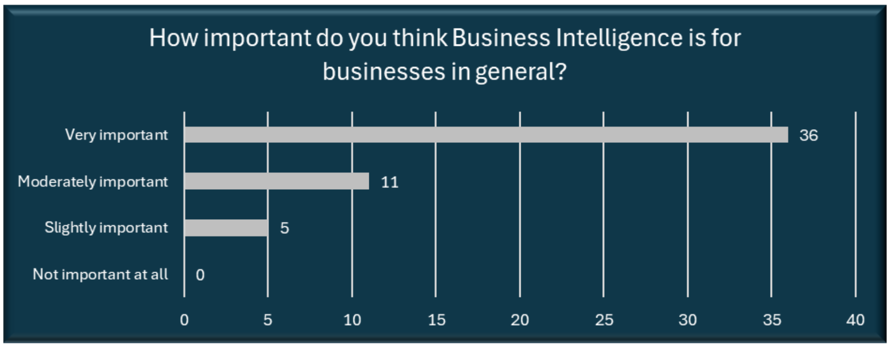

Figure 5: BI importance levels

The survey results indicate a widespread recognition of the importance of BI (BI) for businesses in general. Most respondents (36) rated BI as very important, underscoring its critical role in informing decision-making processes and enhancing business performance. Additionally, a significant portion of respondents (11) considered BI to be moderately important, further emphasizing its value in driving strategic initiatives and gaining competitive advantages. A smaller number of respondents (5) rated BI as slightly important, reflecting a recognition of its relevance albeit to a lesser extent. Notably, none of the respondents rated BI as not important at all, indicating a consensus on its significance in today's business landscape. These findings highlight the widespread acknowledgment of BI as a vital tool for businesses seeking to leverage data-driven insights for success.

4.2.3 BI Adoption levels

The survey reveals mixed adoption of BI tools among SMMEs. About 13 respondents reported using BI tools, indicating a level of investment in data analytics for decision-making. However, 21 respondents stated their organizations do not use BI tools, suggesting potential areas for improvement in leveraging data for insights. Additionally, 18 of the respondents were unsure about BI tool usage, highlighting a need for clarity or awareness regarding BI implementation within their organizations.

Figure 6: Current BI usage levels

4.2.4 Business Intelligence Adoption Barriers

According to the survey responses, the perceived barriers to adopting BI tools vary among respondents. The most cited obstacle, identified by 20 respondents, is the cost associated with BI software and tools, suggesting financial constraints as a significant hindrance to adoption. Additionally, 17 respondents expressed concerns about the unclear benefits of BI adoption, indicating a need for better understanding and communication of the advantages that BI tools can offer to the organization. Furthermore, 9 respondents highlighted insufficient support from management as a barrier, underscoring the importance of leadership buy-in and commitment to successful BI implementation. Finally, 6 respondents cited a lack of technical skills among employees as a challenge, emphasizing the importance of adequate training and skill development to effectively leverage BI tools within the organization. These findings shed light on the multifaceted nature of barriers to BI adoption and underscore the importance of addressing these challenges to realize the full potential of data-driven decision-making.

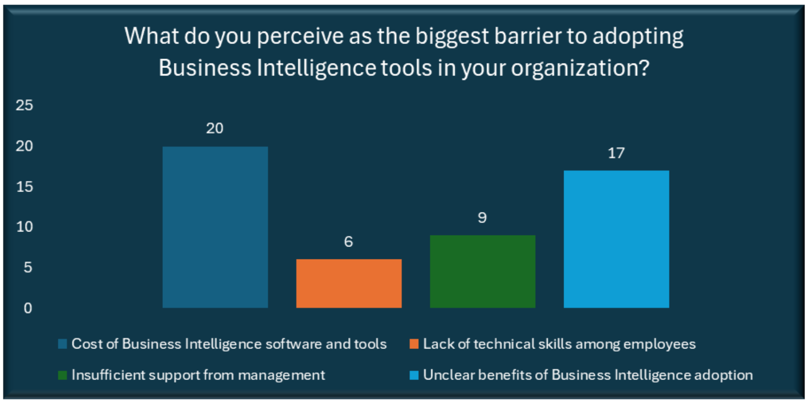

Figure 7: Barriers to BI adoption

The respondents were asked the extent to which the 4 challenges shown on the graphs below are hindering the adoption of BI tools within their organization.

Figure 10: Insufficient Support

Figure 11: Lack of technical expertise

Resistance to change among staff is seen as a significant obstacle to adopting BI tools, with most respondents (25) citing it as a very large hindrance.

Insufficient management support is also recognized as a barrier, with 14 respondents indicating it as a large hindrance and 8 as a very large hindrance.

The survey results reveal that unclear return on investment (ROI) significantly hampers the adoption of BI tools within organizations. Most respondents (24) indicated that unclear ROI poses a large hindrance to BI adoption, while 14 respondents reported it as a moderate hindrance.

The lack of technical expertise is perceived as a significant hindrance to the adoption of BI tools within organizations, with 14 respondents reporting it as a large hindrance and 18 respondents indicating it as a very large hindrance. An additional 8 respondents noted it as a moderate hindrance.

4.2.5 Support needed.

The respondents were asked about the resources that would be the most beneficial for facilitating successful BI implementation in their organization. They were given several options to choose from; also, they were allowed to choose multiple options. Figure below shows the responses.

Figure 12: Support needed.

According to the survey responses, detailed BI adoption roadmaps specific to Small, Medium-sized, and Micro Enterprises (SMMEs) are perceived as the most beneficial additional support or resource for facilitating successful BI implementation in organizations, with 36 respondents indicating their preference for this option.

Regular BI training workshops for employees were also highly favoured, with 29 respondents highlighting their importance in supporting BI implementation efforts. Access to a network of BI professionals for advice was considered beneficial by 27 respondents, suggesting the value of external expertise and support in navigating BI implementation challenges.

Financial assistance programs for BI tool implementation were identified as helpful by 20 respondents, indicating the importance of financial support in overcoming implementation barriers.

Lastly, customizable BI toolkits for small businesses were considered beneficial by 17 respondents, suggesting a need for tailored resources to meet the specific needs and constraints of SMMEs in implementing BI initiatives. These findings underscore the importance of comprehensive support mechanisms and resources in facilitating successful BI implementation within organizations, particularly for SMMEs.

5 CONCLUSION AND RECOMMENDATIONS

This study has highlighted the significant potential for BI to enhance the decision-making and operational efficiency of South African SMMEs. Through a mixed-methods approach, this research identified the barriers hindering BI adoption.

The findings reveal a clear lack of awareness and understanding of BI among many SMMEs, underscoring the need for educational initiatives. Additionally, the financial burden associated with BI tools remains a critical deterrent. However, these challenges present opportunities for targeted interventions. The specific data gathered suggest that addressing these barriers through multi-faceted support mechanisms could enable SMMEs to fully leverage the benefits of BI.

To address the barriers identified through this research, a multi-stakeholder approach is essential. Educational institutions should develop and implement affordable, accessible training programs specifically designed for SMMEs. These programs should cover core BI concepts, tool usage, and data analysis techniques. Additionally, they should collaborate with industry experts to organize workshops and seminars aimed at raising awareness and building BI competencies among SMME owners and employees.

The government and financial institutions should establish subsidies and grants to alleviate the financial burden of initial BI tool investments and ongoing operational costs. Technology providers should be encouraged to develop and tailor BI tools specifically to meet the unique needs and constraints of SMMEs. These tools should be user-friendly and require minimal technical expertise for effective use.

By implementing these targeted recommendations, stakeholders across the board can help South African SMMEs overcome the identified barriers and fully leverage the benefits of BI for enhanced decision-making, operational efficiency, and competitive advantage.

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TOPIC MODELLING OF ACADEMIC PUBLICATIONS IN TIMBER CONSTRUCTION AND ENGINEERED WOOD

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ABSTRACT

Timber construction is considered a sustainable alternative that may illuminate climate change solutions. Industrial Engineers and Engineering Managers are critical in developing sustainable practices. Therefore, identifying research patterns in the timber construction industry may guide focal points for promoting sustainable building and manufacturing practices. Topic modelling using Latent Dirichlet Allocation was used, and the model suggested eight research topics. The results displayed topic distributions with no overlapping topics, minimal topic proximity, and Latent Dirichlet Allocation, indicating a good topic modelling technique for simplistic modelling. The model performance outcomes had an acceptable perplexity score and corresponding loglikelihood score. The topics were labelled with descriptive names based on the modelled keywords, domain knowledge, and insights derived from reviewing timber literature. The study recommended focusing on high-publishing sources for a more controlled dataset and applying clustering algorithms like k-means.

Keywords: timber construction, topic modelling, latent dirichlet allocation, topic labelling, structural engineering, topic proportion.

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1. INTRODUCTION AND BACKGROUND

It has been reported that the construction sector accounts for 30% of greenhouse gas emissions, 25% of global water consumption, and 40% of global energy use because of the development of steel and concrete structures [1]. The South African government released new building regulations in 2013 that seek to promote the development of more energy-efficient buildings by the construction sector in the country [2]. Wood is a building material historically regarded as renewable in the industrial sector and does not harm the environment significantly [3]. Building with timber is an alternative to using steel and concrete. This option is advantageous because it expedites the building process and is promoted as a sustainable solution [3]. The involvement of industrial engineers and engineering managers in addressing these issues is crucial. Their expertise in systems analysis, process optimisation, and data-driven decision-making enables them to identify inefficiencies and develop innovative solutions that enhance sustainability. By leveraging their skills and knowledge, industrial engineers and engineering managers can help transform the construction industry, paving the way for a future where building practices are efficient, cost-effective, and environmentally responsible.

Numerous studies on forestry have been conducted in South Africa, with the primary objective of the research being to encourage the use of timber for construction by outlining its benefits in the socioeconomic context [4]. However, factors preventing the complete adoption of timber construction within South Africa are consumers' common misconceptions regarding the flammability, strength, durability, and total cost of building with wood [5]. Consequently, this research aims to contribute towards promoting timber construction in South Africa by focusing on determining the various aspects being researched and applied in the greater global climate by applying Data Science techniques to empirically analyse and apply predictive analytics to determine the topical patterns and trends over the years.

Data Science contains tools and techniques that can consume a wealth of domain knowledge, like information about the timber field. For South Africa to tap into this green revolution for construction, there is a need to establish networks with the countries and higher education institutions that are spearheading the application of this type of construction in their nations. The development of such a network will allow for creating a collaborative platform for different countries and for the sharing of ideas and resources on how best to apply and gain good results from this process.

Topic modelling can be applied to academic papers on engineered wood and timber construction to discover this network. The information may provide a view of the countries, institutions, types of research, the growth of research, timber culture, etc., that the different nations have applied. Therefore, this research study aimed to use topic modelling to discover the technique's capabilities in consuming digital textual data and provide a summarised view of the advancements made in the engineered wood or timber construction sector. Machine learning-based automated topic modelling is preferred over traditional literature review methods, such as PRISMA or ENTREQ, due to the sheer size of the corpus of documents to be processed. Also, a manual thematic analysis may miss the latent and emerging topics in a large text corpus where a single article may contain multiple topics [6].

2. BIBLIOMETRICS

Bibliometrics is an Information Science approach that aims to provide insights into published literature using statistical methods [7]. These insights highlight academically significant publication trends related to research activities over time and determine the impact of literature on a specific academic field [8]. A natural language processing (NLP) technique called topic modelling is adopted to obtain such insights. Topic modelling is defined as an unsupervised method used on volumes of text to discover interesting topics or themes present in the text based on context (surrounding texts) [9]. Topic modelling has been outlined as effective because it can identify patterns and trends from large digital text databases at a quicker pace, as opposed to humans manually deciphering the information [10]. The technique follows either a rule-based or machine learning-based approach when applying topic generation. As the title states, the rule-based approach is governed by rules that extract the topics from the text based on the keyword frequency [10]. This is achieved by detecting the keywords in the text in a corpus using rule-based methods such as Term Frequency-Inverse Document Frequency (TF-IDF) [10]. The counterpart is the machine learning-based approach that applies an algorithm with its own rules to extract topics - examples are Latent Dirichlet Allocation (LDA) models. However, even with its advantages, topic modelling does present some limitations that can potentially push a researcher to validate incorrect presumptions of their data [10]. LDA has already been implemented in many scientific fields to analyse research trends [9].

3. RESEARCH QUESTION AND OBJECTIVES

To assist with identifying the advancements made in the engineered wood or timber construction sector, this study aimed to answer the following question:

What research topics are actively being explored in the timber construction industry?

The study aimed to achieve the following objectives:

- Collect and prepare academic papers researching the applications of timber construction and engineered wood worldwide.
- Evaluate and select the most suitable technique to conduct topic modelling on the academic papers.
- Determine the optimal cluster of topics covering the field of timber construction using hyper-parameter tuning and pre-processing techniques to obtain the desired outcomes.

4. RESEARCH PROCESS

4.1. Dataset

The source of the data analysed in the study was Scopus. Scopus is a database that stores various academic paper publications, such as peer-reviewed academic papers, conference papers, books, patents, etc., for various industry research topics [7]. The data in the research was extracted using a string query. The keywords used in the advanced search query were the main topical words. The main keywords are “timber”, “construction”, and “engineered wood”. To expand the search, the words “building, and “architecture” are synonyms for these two phrases and were included in the query. The study was limited to focusing on academic papers written in English. Since it is research, the document types used were only academic-based papers such as articles, conference papers, reviews, or book chapters. The search provided a total of 34,711 academic papers. Specific document types, such as erratum, business articles, editorials, letters and retracted articles, were also excluded from the cleaning. The total data size decreased to 34,622, which was eventually processed.

4.2. Latent Dirichlet Allocation Algorithm

LDA is a machine learning-based topic modelling approach [11]. The approach establishes themes discovered within a textual corpus and conducts clustering of the words based on the generated probabilities for each of these words [11]. LDA is identified as proficient at analysing large-scale documents and has produced successful outcomes in both academic and non-academic fields. It is an algorithm that is not new to the extracting of topics. LDA can express competing sparsity between topic distribution in documents (α) and the distribution of words per topic (β) and ensures balance is resolved at the level of the documents [10].

Additionally, the methodology can consider all latent topics with differing probabilities [9]. This is important because, in a corpus, there may be a singular dominant topic, which may overpower other latent sub-topics that are present in the corpus. David Blei, Andrew Ng, and Michael Jordan established the LDA technique [12]. However, the method still presents some limitations in that the latent topics established from LDA are assumed to be independent [10]. This is not always true because there may be topics that are co-occurring. The approach assumes that the words and topics of data are compatible and can be modelled using the bag of words to distribute a particular subject or area of study.

4.3. Model Architecture

The architectural process outlined in Figure 1 involves data acquisition, exploratory data analysis, and pre-processing. The main focus of the study was to model the research topics of academic papers using their abstracts and titles, which were concatenated into a single text column. The text was prepared to remove inconsistencies and improve the topic modelling quality. Topic modelling was then performed by vectorising the data (converting words to numeric vectors) and applying LDA to identify different research topics. Sklearn LDA in the Python library was chosen over Gensim for its simplicity and parameter control [13]. Various iterations were conducted with different parameters to improve the model, and the most optimal outcomes were selected. Once the optimal number of topics was determined and the model trained, keywords were assigned to each topic, and topic labelling took place based on domain knowledge. The resulting clusters were visualised using pyLDAvis. Finally, the topics were analysed and linked to publication trends, institutions, countries, and sources to provide insights into the research landscape.

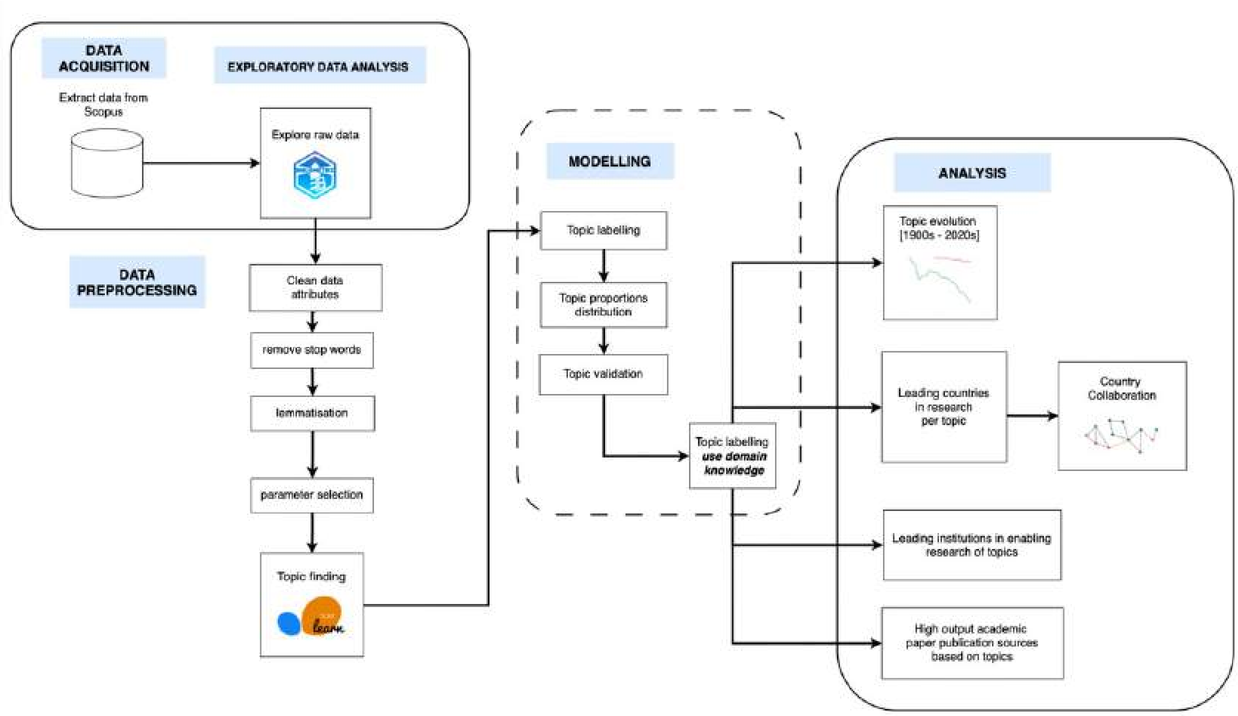

Figure 1: Tool Coordinate System

4.4. Data Pre-processing

Data pre-processing was crucial for ensuring the quality of text data, which in turn influenced the extracted topics and defined relationships. The Python Natural Language Toolkit (NTLK)

[14] and Spacy [15] libraries were used for text pre-processing. The pre-processing steps taken were:

- Cleaning up of dataset features. Data processed from Scopus was concatenated for some columns to create singular features for easy data modelling. The columns extracted from Scopus were either concatenated into a singular feature (e.g., Abstract/Title columns to Themes) or specific information from the initial column was extracted, creating a new feature.
- Remove punctuation, digits, and any weird symbols. This was to ensure that no words were left out during word embeddings due to word embeddings not supporting specific punctuations.
- Replacement of similar words and incorrectly spelt words into one uniform word. During the data pre-processing, it was identified that some text was incorrectly spelled or, depending on the country of origin, words such as characterise and characterise may be spelled differently. As a result, the words were rephrased to reduce noise within the data.
- Removal of inconsistent or unusable data. During the data pre-processing, several inconsistencies were identified, which were removed to avoid introducing noise or skewing the other data items. The data issues identified are outlined in Table 1, and the number or percentage of academic papers removed as a result is outlined in the percentage dropped. The total percentage of documents removed was 10.88%, which is considered not a huge loss compared to the rest of the 90% of the documents left for modelling purposes.
- Tokenisation. Splitting the text into words (terms) for the LDA to process.
- Removal of the stop words. These words are general linguistic terms that do not add value to the overall context of the clustered topics to be extracted and typically have a high frequency within the document word corpus. Words such as “am”, “be”, “the”, etc. are defined by default in the NLTK [14], and the list consists of a total of approximately 40 stop words [11]. Therefore, the standard stopwords were removed to reduce the noise and text dimensionality contained in the corpus. This application also ensured that the clustering focused on words that were considered far more value-adding and essential to establishing various themes. In this study, the topic outcomes for engineered wood and timber construction had uninformative keywords during model development. These words were considered irrelevant as they are regarded as vague concerning the overall topic. These uninformative keywords were regarded as false positive results, which skewed the topical outcomes. As a result, the words were extended into the standard stopwords database and formed part of the exclusions during text pre-processing.
- Normalising of text using lemmatisation. It ensured that the required or necessary words remained for training purposes. Lemmatisation transforms the words to their base by applying a morphological analysis, ensuring the word's meaning is preserved [11]. It was selected over stemming because it reduces text dimensionality, whereas stemming contains the disadvantage of truncating words to their root without considering the word’s context [11].
- Convert text through vectorisation into a document term matrix (numerical array). Vectorisation is essential for efficiently converting textual data into numerical values that topic modelling algorithms can process efficiently.

Table 1 - Number of Academic Papers and the Data Issues

Issue	Number of Rows	Percentage Dropped (%)
Cells with null values	3,133	9.00%
Academic papers with no abstract available	216	0.68%
Academic papers without a clear country assigned	213	0.68%
Publication sources with less than a total of 10 publications in the dataset	165	0.52%

4.5. Parameter Selection and Tuning

N-grams were applied to the text corpus to enhance model quality and diversity. Two or three-word phrases were formed by incorporating bigrams and trigrams, preserving contextual meaning. The ngram_range was set to (1, 3), allowing the combination of words into bigrams or trigrams if they occurred at least once in the corpus. This technique ensured the retention of distinct word meanings and improved topic representation.

Learning decay was a second technique that was applied as part of tuning. The learning decay is a parameter that ranges between 0 and 1 and controls the rate at which the model learns [11]. For Sklearn, the default decay was set at 0.7 [16], which was applied for the baseline model. However, an iterative process was applied to determine this model's most relevant learning decay value. Table 2 shows the parameters applied during the iterations consisting of a Start Value and step size value that increased over time toward the End Value. The iteration calculated the loglikelihood scores based on the three different learning rates and the number of topics.

Table 2 - Parameter List for Optimal Learning Decay

Parameter	**Start Value**	**End Value**	**Step Size**
Number of Topics	4	12	2
Learning Decay	0.5	0.9	0.1

Figure 2 indicates the overtime change to the loglikelihood score as the number of topics and the learning decay changed with every iteration. The selection of the most optimal learning decay followed the elbow method, where the optimal values lay at the point where the graph forms an elbow curve. The elbow method is a graphical representation used to determine the most optimal number of topics for modelling purposes [17]. During the modelling process, different variations of the learning decay and the number of topics were iterated (see Table 2). Figure 2 shows that the optimal K lay at six (6) since that was where the elbow lay with a decent loglikelihood score. However, due to the drawbacks of only using this method, the elbow method was used as a starting point for parameter selection, where additional validation steps were taken by looking at the topic distribution (minimal overlapping) and repetition of words across the different topic clusters. As a result, from the validation steps, the most optimal number of topics was selected as eight (8), where the learning decay was 0.9.

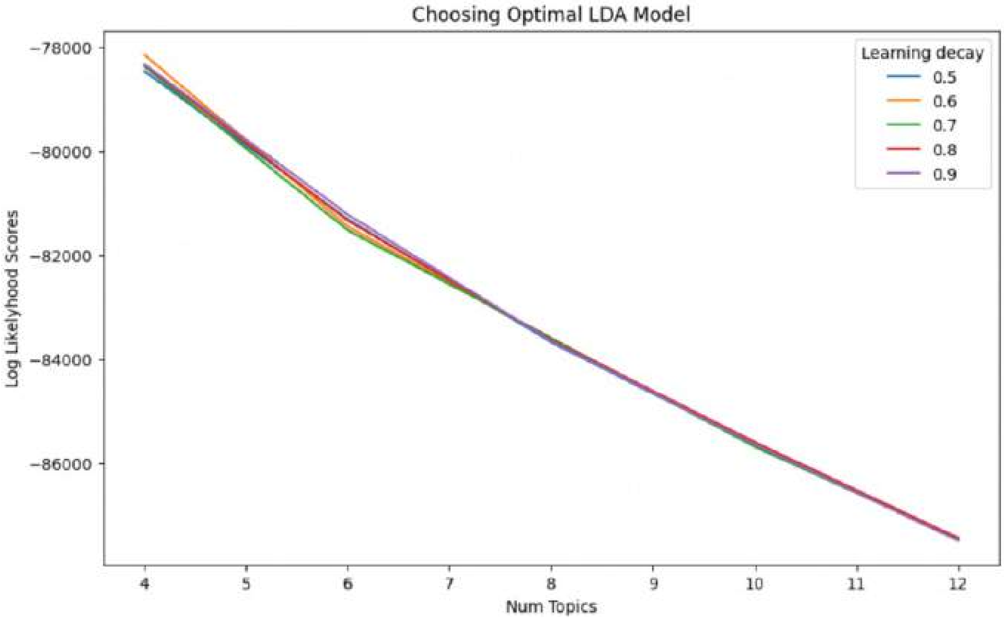

Figure 2 - Choose the Optimal Learning Decay

The third of the hyperparameter tuning steps consisted of another iterative process involving the application of the most optimal min_df (minimum word frequency), max_df (maximum word frequency), and number of topics based on calculating the model perplexity score and number of terms. Table 3 depicts the parameter list for this iteration. The ngram_range was selected from the first technique, and the optimal learning decay was assigned as part of the iteration.

Table 3 - Parameter List for Optimal Min and Max Ranges

Parameter	**Start Value**	**End Value**	**Step Size**
Number of Topics	4	14	2
min_df	0.02	0.05	0.01
max_df	0.85	0.99	0.01

Table 4 displayed 225 iterations, revealing that higher min_df values reduced the number of terms available for modelling due to excluding low-probability words. Decreasing min_df increased the number of terms in the corpus, enabling more comprehensive modelling. Balancing min_df and max_df was crucial to ensure adequate terms for modelling without sacrificing model generalisation. Higher min_df values led to decreased perplexity scores, indicating improved model performance. Conversely, max_df's impact on perplexity was slower and less consistent. Min_df was prioritised during iterations for its significant and rapid influence on model improvement.

The last part of the tuning process was determining the optimal number of keywords to showcase after the model's training. The number of keywords outputted was used for the topic labelling process, and as such, the number of words needed to be sufficient to deduce probable themes or topics. This process was done by experimentation with a different number of keywords, starting with a small N value (number of keywords) and gradually increasing it. This was an iterative process, where the value was increased or decreased based on the keywords and sufficient interpretability [23].

Table 4 - Parameter Selection Outcomes from Iterative Process (Sample)

Topic Number	Min df	Max df	Term	Perplexity	Log Likelihood
4.0	0.02	0.98	386.0	478.047	-607047.700
4.0	0.03	0.98	182.0	239.816	-443106.032
6.0	0.02	0.98	386.0	547.122	-620326.950
6.0	0.03	0.98	182.0	275.746	-454394.790
8.0	0.02	0.98	386.0	599.491	-629320.908
8.0	0.03	0.98	182.0	310.053	-463876.800
10.0	0.02	0.98	386.0	644.444	-636435.249
10.0	0.03	0.98	182.0	343.922	-472259.689
12.0	0.02	0.98	386.0	699.302	-644473.306
12.0	0.03	0.98	182.0	375.635	-479391.959

To summarise, the N value was selected considering the interpretability of the top N keywords using domain knowledge, the quality and high association of the keywords towards a topic, and the objective of the analysis. For hyperparameter tuning, an iterative approach was followed to model a number of the parameters as outlined in the above discussions, and the rest were assumed to be default values.

5. TOPIC VALIDATION

The validation process for the research was vital for ensuring that what was applied to achieve a certain outcome was achieved. Despite the recent acceleration of research in these unsupervised methodologies, the validation techniques applied to topic model evaluations are still in their infancy [18]. The validation process focused on evaluating whether the data was interpretable, could be replicated, and the topics were plausible compared to the academic papers. The validation steps taken in the study were:

- The validation of whether the content of the information extracted was related to the problem statement of this study was conducted by reviewing the academic papers' overall titles and abstract keywords. These were printed out based on the index of a sample of the titles and abstracts to ensure that the “engineered wood” or “timber construction” research area was a common thread.
- If phrases not related to the topics of timber construction or engineered wood were present in the visualisation, then it was proof that there is low validity, and the search strategy needs to be revised.
- Once the model topics were determined, the input academic papers were compared to the output topics. This was done by comparing a sample of the academic paper abstracts against the dominant topic predicted from the topic model. This validation aimed to confirm whether the academic papers' abstract aligned with the topical words and identify the level of misplaced papers towards a topic.
- Applying the most optimal parameters was also crucial in preserving the topic modelling process. This validation step is covered in detail in hyperparameter tuning.

- A subject matter expert in engineering and timber construction and a non-domain person was used in the study to interpret and label the topics. The interpretation was vital because it guided whether the topics were plausible against the research context. Incorporating an expert and non-expert in the interpretation created an opportunity to see whether both individuals interpreted the topics similarly or not.

6. PROCESSING RESULTS

6.1. Topic Labelling

The keywords for each topic were manually reviewed and linked back to the academic papers to determine the appropriate topic label. This process was subjective and required domain knowledge and the ability to cross-reference a sample of the keywords to the raw title and abstract information for some documents.

6.2. Map Topics to Academic Papers

The vectoriser matrix was used to append the topic proportions with the topic labels and retained a table structure consisting of eight (8) columns for each topic and the proportions per academic paper.

6.3. Topic Visualisation

The pyLDAvis [19] was used to graphically represent the distribution of the eight (8) modelled topics. pyLDAvis is a built-in open-source Python library that provides an interactive manner of visualising the clusters found in a corpus [19]. The distribution was able to showcase whether there was any clustering of topics and if any generalisation was still required. It also contained the lambda toggle, which helped select the number of keywords to showcase based on specificity and generality. Once the topics had been labelled and visualised, the data was visualised using Python and some of the data was exported into a CSV and analysed using Microsoft PowerBi. The visualisations focused on the research questions, where the:

- First were the trends that were evaluated per topic. The topic trends were visualised by the years, the independent variable on the x-axis and the dependent variable on the y-axis, the proportions per document per topic. The trends were evaluated as eight (8) separate topic trends over time. This was to analyse the changes in each topic over the years.
- Countries that are leading research per topic were evaluated. The countries were extracted during data pre-processing, where the country was extracted from the affiliations text and cleaned. A co-occurrence network diagram was derived to establish how the countries researching the topics within timber construction relate to each other. The depiction is of every country and its relationship strength with other countries from the total of 168 countries in the dataset.
- Research institutions were evaluated based on the institutions extracted during data pre-processing, where the institution was extracted from the affiliations text and cleaned. Over 10,000 unique institutions were found. Since there were so many institutions on which to focus the analysis, the highest publishing institutions were visualised using a Sankey diagram. Additionally, each document was allocated to the most dominant topic. This was done because each document had a specific topic proportion, but each document was assigned the topic with the highest probability to focus the study. The dominant topic technique was adopted because it is commonly used [20].
- Publication sources were extracted from the academic papers from the publication's column. There was a total of over 6,412 unique publication sources. Like the research institutions, the analysis focused on publication sources that contributed the most

academic papers and were visualised using a heatmap diagram. The highest contributing sources were evaluated according to the eight (8) separate topics and the topic proportions found in each topic across the documents.

7. RESULTS

According to the topics, the model distribution was one of the metrics used to determine satisfaction with the model's performance. The distribution was evaluated based on the spread and centrality of the topics to the (0,0) axes point. Figure 3 is the distribution of the eight (8) topics on a 2-dimensional Principal Component Analysis (PCA) Intertopic Distance Map. Intertopic Distance Maps assist in exploring and interpreting the relationships (diversity, evolution, etc.) contained between topics in a dataset [21]. The visualisation of the map is based on the circles which correspond to a topic, and the size of each circle varies according to the number of words linked to that topic. The study's eight (8) topics are scattered across the map, implying that the word corpus covered a wide range of topical themes. Topics that were closer together had more words in common [21]. Topics 6 and 8 seem relatively close, which may indicate that the topics share similarities. The distribution result of the multidimensional scaling map depicted topic proximity levels that were considered acceptable, as there was no overlapping of any topics. This suggested that the topics were generalised in the model. The margin of topic distribution was another indication of the diversity of the modelled topics.

Figure 3 - LDA Topic Distribution

For this study, the acceptance of whether the model could generalise involved the discussion points mentioned above and a certain level of subjectivity in visually evaluating the graphical representation of the clustering of the topics graphically. The study's topic proportions explained the highly researched topics across the word corpus. Topic proportion is the number of words assigned to a topic divided by the total number of words found in the document [22]. For this study, the topic proportions across all eight (8) ranged between 9% and 20%, as outlined in Table 7.1, where a high proportion indicates a dominant topic. As mentioned, thermal insulation is the dominant topic, followed by structural and seismic engineering practices, at 15,1% and 12.7%, respectively. Interestingly, the Industrial Waste Management topic is the least researched of the eight (8) topics.

Table 7.1 - Interpreted Topics from Topic Keywords

No.	Topic Name	Topic Keywords	Topic Proportion (%)
1	Wood sourcing and preservation	*tree, species, plant, soil, water, density*	12.7
2	Seismic engineering and structural integrity	*frame, seismic, damage, structural, earthquake, masonry*	12.7
3	Environmental sustainability assessment and monitoring strategies	*environmental, sustainability, assessment, cycle, monitor, strategies*	10.5
4	Industrial waste management and safety protocols	*waste, metal, treatment, chemical, safety, industrial*	9.7
5	Structural engineering principles and analytics/practices	*beam, joint, strength, laminate, structural, ben'*	15.1
6	Historical architecture conservation using modern technology	*architecture, historical, century, traditional, technology, conservation*	12.7
7	Environmental sustainability	*energy, heat, emissions, carbon, indoor, biomass*	10.7
8	Thermal insulation	*composites, moisture, thermal, insulation, board, water*	15.9

8. CONCLUSIONS

The study aimed to use topic modelling to determine research topics covered within the timber construction industry. The topics were generated using LDA with a TF-IDF corpus. The dataset consisted of 34,711 academic papers and was extracted from Scopus using the advanced search functionality. The study's findings are discussed according to the objectives outlined in Section 3.

The study's data came from one of several digital journal publication databases, Scopus. The strategy of not limiting journal publication sources as part of the dataset enabled the size of the data sourced from Scopus to include 34,711 journal publications. While working with this data, one advantage of having such a large dataset was that it contained variability, which allowed for a wide range of topic clusters, as evidenced by the hyperparameter tuning where different iterations were performed using topic numbers ranging from four to twelve and obtaining different perplexity score outcomes with each iteration - see Table 4.

However, because of the size of the data, another significant finding was that the amount of information became too large to represent graphically, as evidenced by the need to apply Pareto analytics on the 6,682 unique institutions to downsize them to only the Top 20 research institutions, and similarly with the publication sources, from 6,412 unique publication sources to only the Top 30 publication sources. Because of the magnitude of the data, the scope of the findings had to be narrowed, and focus had to be applied to a limited number of data points. For example, for the smaller contributing countries in the use case - knowing the smaller economy nations may have provided valuable insights, primarily since the dominant countries are generally known.

For this study, the query developed to extract the data was opened too wide, thus resulting in a large dataset that is difficult to control. Prior sampling of the required sample size for a use case study must be established at the start of a topic modelling study. This can direct the researcher to extract relevant, sufficient, and manageable information to gain valuable insights.

The methodology employed in the research used natural language processing techniques, specifically LDA, to conduct the topic modelling. The practicality and effectiveness of using LDA were optimal, evidenced by the model performance where the graphical representation of the optimal topic clusters was demonstrated using pyLDAvis [19] and showed how the topics are distributed. The visuals depicted the nuances present in the topic clusters, where there was no overlapping and minimal proximity of topics to each other, thus indicating model generalisation.

Additionally, the perplexity score linked to the eight (8) optimal topics was 238.9, and the loglikelihood score was -405 566. It was clear that the LDA algorithm is commonly used among topic modelling studies, primarily because it is probabilistic and straightforward to apply [11]. For the alternative approaches evaluated in the study, an observation that was made was that there was not a large selection pool for peer-reviewed academic papers centred on non-probabilistic models, namely Non-Negative Matrix Factorization (NMF) and Latent Semantic Analysis (LSA) for topic modelling purposes [24]. The LDA algorithm demonstrated its ability to create an acceptable topic model with actionable findings. During the study, it was found that there are not enough academic papers using data science-related applications for the field of timber construction. The decision to employ a more straightforward model as the starting point for all the data science opportunities available for analysing this field was more than sufficient [25].

The outcomes from the study provided context to the topics that have been or are being actively researched by academics or research bodies in the field of timber construction. Eight topics were established using LDA with a TF-IDF corpus. They covered a variety of themes, including (1) the importance of the type of wood used in construction and the need for proper reforestation protocols to sustain the wood sourcing; (2) understanding that the method is an environmentally sustainable solution that will also require assessments and monitoring strategies for its advancement in product design and policy-making; and (3) making sure the proper structural engineering principles and practices are followed and take into consideration the method’s environmental sustainability then (4) for the method to thrive, creating a well-received culture of the use of timber in a country. However, during the topic labelling of the eight (8) topics, it was clear that some topics cover similar themes. For example, Topic 2 (seismic engineering and structural integrity) and Topic 5 (structural engineering principles and practices). As much as the LDA technique could obtain the optimal topics, it could not cluster similar topics further into one consolidated theme. Like the study of Muchene and Safari [26], the LDA algorithm could have benefited from integrating, e.g. k-means clustering to reduce the topic clusters further and minimise redundancy [27].

During the hyperparameter tuning, an observation was made on how influential the min_df was towards the model's performance - see Table 4. This contrasts the max_df, which barely impacted the perplexity and loglikelihood scores during model iterations. As evidenced by the keyword topic probabilities that ranged between 0.025 and 0.05, it is clear that the word corpus weights are clustered on the lower end of the probability scale, meaning towards zero (0), and very few values fall on the upper end of the scale, meaning towards one (1).

During the study, assigning a dominant topic to each document was chosen as part of the result pre-processing. This approach is beneficial because it can summarise and apply focus to the most influential topics in each document. However, during the study, there were documents where the dominance of one topic from the other was a slight decimal difference. As a result, this impacted the credibility of assigning a dominant topic to a particular document because the dominance was not too far different from the following topics. To improve on the outcomes of this study, other results pre-processing approaches can be followed that consider that documents can have more than one topic being dominant and how to develop outcomes that integrate this.

Most publications originated from European, British, American, and Asian institutes. The publication sources that contributed the most towards timber construction were discovered in the engineering, materials, and forestry divisions. As a next step to these findings, it would be beneficial to focus any topic modelling towards the top journal publication sources and academic institutions from specific regions to reduce the data size and focus on the impactful areas.

As humanity faces pressing challenges such as climate change, resource depletion, and technological disruption, the role of industrial engineers and engineering managers becomes increasingly vital. By illuminating problems and devising innovative solutions, industrial engineers and engineering managers can drive progress and sustainability. This study contributes to that endeavour, providing a foundation for ongoing research and practical applications in timber construction, ultimately guiding us toward a more sustainable and resilient future.

9. RECOMMENDATIONS

Research opportunities or future work that can be considered to improve upon this study are:

- The study can be condensed to focus on high-volume publishing sources in the timber construction industry to have a more controlled dataset for the topic modelling process and better data insights.
- Instead of identifying the dominant topic and assigning it to one document based on the highest topic proportion, an approach that considers combining topics with similarly proportioned values per document can be applied as an improved alternative.
- Once the optimal cluster of topics is established, consider applying clustering such as k-means to the optimal topics to combine similar themes and prevent redundancies.

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THE APPLICATION OF OPTIMISATION TECHNIQUES IN CRICKET: A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

Operations research represents a scientific procedure that offers a quantitative motive for problem-solving and decision-making by characterising functional relationships as intricate mathematical models. Intuitively, the benefits presented by optimisation theory as a subset of operations research denote a testament to its involvement with distinct industries, including sports such as cricket. Cricket is a global phenomenon that polarises purpose by adopting a quasi-religious significance for selected audiences. This study aims to investigate existing literature involving optimisation applications in cricket team selection and batting order sequencing by conducting a systematic literature review. Accordingly, this study reveals prospective research opportunities by recognising fundamental shortcomings in existing literature. Therefore, this study contributes to academia and industry by identifying the potential research gap involving decision-making of player selection and ordering using optimisation theory. While this investigation primarily considers optimisation procedures within cricket, it is recommended that future studies pursue parallel research for alternative sports.

Keywords: batting order, cricket, optimisation, systematic literature review, team selection

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1 INTRODUCTION

Modern decision-making has become increasingly complex due to constantly changing social, technological, and intellectual factors [1]. The persistent changes brought about by the Fourth Industrial Revolution exert additional pressure on adjudicators to exercise the correct choices under varying conditions [2]. Consequently, decision-makers can no longer depend on personal intuition and experience alone to draw reliable conclusions [1]. Therefore, utilising scientific methods such as operations research to sustain decision-making proves invaluable as it offers superior solutions based on quantitative evidence [1].

Operations research comprises numerous components, including optimisation theory, of which mathematical optimisation forms a subset concerned with finding the best solution subject to some constraints [3]. Accordingly, mathematical optimisation seeks an optimal solution from a set of alternatives using models describing the functional relationships among entities [1]. The decision-making capabilities introduced by this domain sustain its involvement in various global industries, such as logistics [4], [5], finances [6], [7], politics [8], [9], healthcare [10], [11], and sports [12], [13], [14]. Many sports regularly utilise different optimisation techniques for improved decision-making, with cricket being one of the most prominent [15].

Cricket, one of the oldest sports globally, experienced somewhat of a cultural transformation over the prior two decades with the introduction of its shortest format [16]. Traditionally, the sport enjoys an elite status owing to its rich history spanning multiple centuries [17]. However, modern-day cricket has since become a multi-billion-dollar business industry, with substantial revenue accumulated through player, coach, and team performances [18]. This transformation produces smaller margins among international and domestic teams, signifying the importance of adequate decision-making as a competitive means [19]. Accordingly, utilising mathematical optimisation to derive conclusions is essential as it enhances the scientific nature of decision-making using quantitative evidence void of prejudice and bias [1].

As with any team sport, player selection and positioning dictate success [20]. Therefore, the best players must be selected to maximise general team performance. Cricket is distinct in that participants perform differently under varying internal and external phenomena. Match conditions significantly influence cricketing performance, providing that selectors may opt to include players having more adaptability than their counterparts. Additionally, players fulfil particular roles within the side, underpinning the significance of team selection in obtaining a balanced squad accommodating all playing abilities. However, although player selection is crucial for success, the corresponding arrangement of the chosen side is equally important as cricketers embody dissimilar strengths and weaknesses. Therefore, employing mathematical optimisation techniques for team selection and batting order optimisation proves essential for maintaining an uncontested advantage in an ever-changing sport such as cricket [21].

Swartz [22] discusses different research directions involving cricket, including team selection and batting order optimisation. The study [22] mentions the lack of quantitative research within the sport, signifying a need for further work concerning analytical methods. Therefore, the current study aims to investigate existing literature involving optimisation applications in cricket team selection and batting order sequencing by conducting a systematic literature review. To accomplish this aim, the study identifies the following objectives:

- to provide a concise overview of cricket and mathematical optimisation;
- to determine the number of studies that use optimisation techniques for cricket team selection and batting order optimisation;
- to identify which optimisation techniques are applied for cricket team selection and batting order optimisation;
- to investigate the predominant playing formats considered by existing literature; and
- to provide valuable recommendations for prospective research.

This study reveals the optimisation techniques considered by existing literature, consequently exposing those yet to be explored. Theoretically, this study contributes by offering prominent research opportunities recognised by the gap in existing literature disclosed by the limitations of the resultant findings. Practically, this study contributes by revealing the methods available for empirical player selection and ordering. Accordingly, the current work contributes to both academia and industry, demonstrating the value of utilising analytical techniques to optimise cricket team selection for best performance.

The paper is outlined such that each succeeding passage logically complements the preceding content. Following the introduction in Section 1, Section 2 presents a traditional literature review that provides insight into cricket and mathematical optimisation. Thereon, Section 3 describes the systematic literature review method and protocol, followed by a discussion of the consequent research results. Finally, Section 4 concludes the study by summarising the content, accompanied by applicable limitations and recommendations for future work.

2 LITERATURE REVIEW

Section 2 provides a concise overview of cricket and mathematical optimisation, signifying the background needed to comprehend the essence of the study.

2.1 Origin of cricket

The sport of cricket polarises purpose by assuming a quasi-religious significance for some and a mere form of entertainment for others [23]. Cricket, often hailed as the gentleman's game [24], is the second most popular sport on the planet, with approximately 2.5 billion supporters [22], [25]. In its simplest form, cricket denotes a game played using a single bat and ball [23]. Modern sources credit the English for the invention of cricket, although the exact origin of the sport is somewhat unknown [23], [24]. Malcolm [23] claims that the sport contains Celtic roots, first played by the Scottish and Irish, approximately 500 Anno Domini. Contrarily, Groombridge [26] and Pradhan *et al.* [27] discuss its potential origin in France, with Mote [28] mentioning the likely ancestry of cricket in Iceland and Flanders. However, regardless of the widespread speculation regarding the origin of cricket, the earliest unambiguous reference to the sport as an entity was made in 1597 [27].

2.2 Gameplay and laws of cricket

Cricket is an intricate game played between two teams, each containing eleven members with one substitution [29]. The game is played on an annular field encompassing a central 20-meter strip, called the pitch [30]. The pitch confines a wicket on each opposing side, comprising two horizontal bails balanced on three stumps [30]. Surrounding the wicket on each side of the pitch is a crease, demarcated by white lines, specifying the legal play for both teams [31]. Additionally, the circular field encompasses a 27-meter inner circle, measured from the centre of each wicket [32]. The inner circle contains two semicircles of radius 27 meters surrounding the width of the pitch, converged by two parallel lines [32].

The objective of cricket is to maximise the number of runs achieved such that it is more than the total scored by the opposing team [30]. A coin toss, performed between the captains of each side before the initiation of the game dictates which team bats or bowls first [33]. The bowling team uses all eleven players to restrict the number of runs accumulated by the batting side [34]. Alternatively, the batting team uses two batsmen to score runs, with the relationship between these players known as a partnership [35]. The purpose of each individual batsman is to accumulate runs while simultaneously defending their wicket [36]. Players score runs by striking the ball and running to the opposite end of the pitch before any fielder dislodges the bails of the wickets [37]. Likewise, players obtain runs by striking the ball beyond the boundary of the field [37]. Further, teams gain runs, known as extras, from law infringements committed by the bowling side [29]. Figure 1 shows a cricket ground depicting the discussed phenomena.

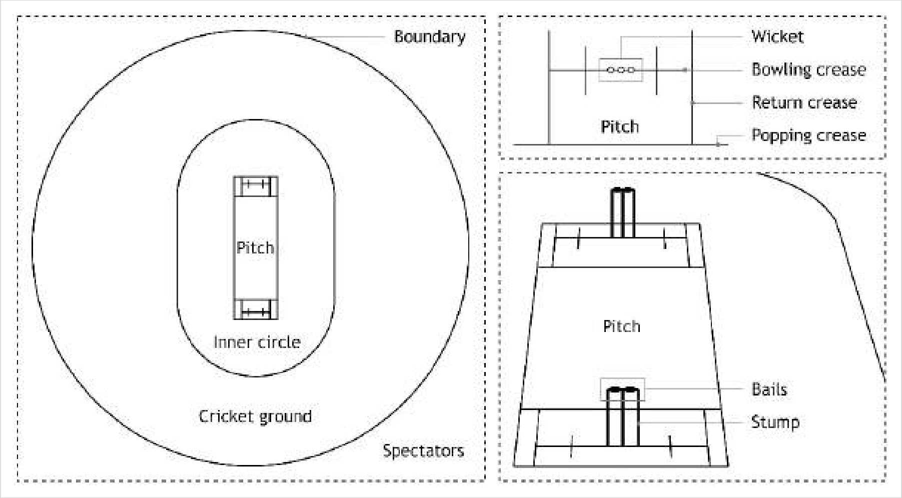


Figure 1: Cricket ground [32]

The period in which a particular team bats is called an innings [29]. The duration of an innings depends on the number of predefined overs as stipulated by the match format [33], [36]. An over comprises six legal deliveries [33], which involves propelling the cricket ball along the length of the pitch toward the wicket guarded by the batsman. Intuitively, the purpose of the bowling team is to minimise the runs accumulated by the batting team [30]. Accordingly, the bowling team can restrict the number of runs scored by terminating the batting innings of the opposing side either through the accumulation of ten wickets or the completion of the defined number of overs [29], [34]. The bowling team accumulates wickets by dismissing the batsmen of the opposing team [29]. Once the bowling side has dismissed a cricketer, the player deemed out is replaced by the subsequent batsman in the specified lineup [38]. After a particular side has completed their batting innings, the opposing team receives an opportunity to bat [34]. Consequently, the team that scored the most runs after both teams completed their batting innings is deemed the winner of the match [39].

2.3 Formats of cricket

At an international level, cricket comprises three official formats, classified based on limited and unlimited overs [40]. Unlimited overs cricket, also known as test cricket, refers to games played without an upper bound placed on the number of overs per innings [41]. Test cricket represents the earliest form of the game, played over five days, with each side having two independent opportunities to bat [33]. Alternatively, limited overs cricket involves formats containing a predefined number of balls, allowing play to conclude in a single day [33]. Limited overs cricket takes the form of One Day Internationals (ODIs) and Twenty20s (T20s) [42]. ODIs generally encompass a minimum span of eight hours [43], with each team having 50 overs to bat [33]. T20s represent the shortest international format, taking approximately three to four hours to complete, with each team allowed 20 overs to bat [43]. Since its introduction, interest in limited overs cricket, especially T20s, has grown significantly globally [44].

2.4 Overview of mathematical optimisation

Operations research is a scientific method for decision-making that uses mathematical models to describe functional relationships among entities [1]. Operations research denotes a broad field comprising various techniques, of which mathematical optimisation is perhaps the most significant [45]. Sinha [45] defines mathematical optimisation as a decision-making approach concerning the adequate utilisation of finite resources to accomplish some desired objective. Accordingly, mathematical optimisation seeks an optimal solution by deriving the best result among multiple alternatives subject to several constraints [1]. Williams [46] mentions the importance of mathematical optimisation models by signifying their proficiency in revealing underlying relationships between entities that would otherwise not be apparent. Sharma [1] provides the subsequent provisions for formulating a mathematical optimisation model:

- Decision variables: Represent controllable factors whose values are obtained by solving the defined problem.
- Objective function: Denotes the criteria employed for evaluating alternatives based on different decision variable values to optimise performance.
- Constraints: Refer to the policies and regulations limiting the use of selected resources, expressed as inequalities or equations.

Mathematical optimisation encompasses two classifications, including discrete and continuous [47]. Discrete optimisation requires variables that form part of a discrete set [48]. Conversely, continuous optimisation permits a continuous range of values for the model parameters [1]. Further, mathematical optimisation problems can adopt a constrained or unconstrained nature [1]. Constrained optimisation problems impose fixed limitations on their corresponding values that mandate adherence without exception [1]. Alternatively, in unconstrained optimisation problems, restrictions on the use of finite resources are not inflicted [1]. Finally, optimisation problems are considered deterministic or stochastic [49]. Deterministic models are those in which the parameters and functional relationships are known with certainty [1]. Alternatively, if the model contains at least one random variable, the problem is said to be stochastic [1]. Stochastic models provide a more realistic representation of practical occurrences since they accommodate the unpredictability involved in selective phenomena [49].

2.5 Classification of optimisation techniques

Multiple sources provide dissimilar views on the classification and terminology of optimisation techniques [50], [51], [52]. Accordingly, the joint classification provided by Ayalew *et al.* [53], Russenschuck [3], Subramanyam *et al.* [54], Khodr *et al.* [55], and Sharma [1] are considered in this study. Ayalew *et al.* [53] classify optimisation techniques into three categories, namely traditional methods, artificial intelligent, and hybrid artificial intelligent approaches. Among these three categories, Ayalew *et al.* [53] specify procedures such as linear programming, nonlinear programming, integer programming, simulated annealing, genetic algorithms, and fuzzy logic. Likewise, Russenschuck [3] offers a detailed overview of techniques concerning numerical procedures, such as dynamic programming and network flow theory. Subsequently, Subramanyam *et al.* [54] and Khodr *et al.* [55] view data envelopment analysis as a distinct optimisation technique, with Sharma [1] offering a descriptive handbook comprising various additional methods, such as Markov chains and goal programming.

2.6 Mathematical optimisation techniques

Section 2.6 describes the different optimisation techniques applicable to this study, furnishing the background necessary to comprehend the results of the succeeding review.

2.6.1 Linear and integer programming

Linear programming denotes the foundation of combinatorial optimisation [56], first proposed by Dantzig in 1947 as a means for solving complex logistics problems [1]. Linear programming is a deterministic method that optimises some linear function subject to a finite set of linear constraints [1]. Accordingly, in linear programming, the amount of each resource employed is proportionate to the value concerning each related decision variable [1]. However, in 1958, Gomory extended prior work conducted by Dantzig, Johnson, and Fulkerson by applying cutting planes that ensure an integer solution, leading to the creation of integer programming [57].

Integer programming problems are those in which at least one variable adopts a nonfractional discrete state [58]. Integer programming problems are deemed pure, mixed, or binary based on the provisions of the model constraints [58]. An integer programming problem is said to be pure if all decision variables are integer-valued [1]. Conversely, a mixed integer programming problem limits some, but not all, of the decision variables to integer quantities [1]. A binary integer programming problem provides a set of constraints that restricts the decision variables to either zero or one [1]. Equations (1), (2), and (3) offer the compact formulation of a binary integer programming problem having n decision variables and m constraints [1]:

$$\text{Minimise} \quad Z = \sum_{j=1}^{n} c_j x_j \tag{1}$$

$$\text{Subject to} \quad \sum_{j=1}^{n} a_{ij} x_j \geq b_i, \;\; for\; i = 1, 2, \ldots, m \tag{2}$$

$$x_j = 0 \; or \; 1, \;\; for\; j = 1, 2, \ldots, n \tag{3}$$

From the compact formulation, c_j represents the cost coefficient associated with the decision variable x_j [1]. Similarly, a_{ij} denotes the constraint coefficient and b_i the related constraint requirement, with the decision variable x_j bounded to either 0 or 1 [1].

2.6.2 Goal programming

Goal programming denotes an approach used for solving multi-objective optimisation problems by finding a satisfactory trade-off among numerous conflicting and incommensurable goals at different priorities [1]. Goal programming was first mentioned in 1955 [59] but only explicitly introduced by Charnes and Cooper in 1961 [1]. This approach satisfies the model goals in an ordinal sequence and aims to achieve a satisfactory level for each goal rather than an optimal result [1]. Accordingly, this method analyses the exact, over, and underachievement of goals by integrating deviational variables that monitor the degree to which the target performance values are not achieved [60]. Deviational variables are two-dimensional since they provide the negative and positive divergence from each model goal and sub-goal, denoting the equivalent of slack variables employed in linear programming [59]. The deviational variables that permit underachievement or overachievement of the target value for the ith goal is expressed as [1]:

- d_i^- = underachievement of the target value (negative deviation).
- d_i^+ = overachievement of the target value (positive deviation).

The standard formulation of a goal programming model assumes a similar notation as used for linear programming [1]. However, in goal programming, the deviations from the target values relating to the model goals are minimised by placing the relevant deviational variables directly in the objective function [60]. Equations (4), (5), and (6) provide the standard formulation of a goal programming problem combining preemptive priorities and weighting [60].

$$\text{Minimise} \quad Z = \sum_{i=1}^{m} \sum_{k=1}^{n_i} P_i (w_{ik}^- d_i^- + w_{ik}^+ d_i^+) \tag{4}$$

$$\text{Subject to} \quad \sum_{j=1}^{n} a_{ij} x_j + d_i^- - d_i^+ = b_i, \;\; for\; i = 1, 2, \ldots, m \tag{5}$$

$$x_j,\; d_i^-,\; d_i^+ \geq 0, \;\; for\; i = 1, 2, \ldots, m; \;\; for\; j = 1, 2, \ldots, n \tag{6}$$

From the preceding formulation, the objective function Z denotes the minimisation of the sum of deviations from the target values associated with the model goals [60]. The coefficients w_{ik}^{-} and w_{ik}^{+} signify the non-negative weights assigned to each of the $k = 1, 2, \dots, n_i$ subgoals within the ith goal comprising the preemptive priority factor P_i [60]. The P_i parameter specifies the priority level allocated to each goal, with a_{ij} the constants pertaining to each variable x_j [1].

2.6.3 Simulated annealing

Simulated annealing is a popular meta-heuristic introduced in 1983 by Kirkpatrick, Gelatt, and Vecchi [61] for solving complex black-box optimisation problems [62]. The method is based on an analogy to thermodynamics in which materials are heated and cooled until some final state is achieved [61]. Simulated annealing iteratively compares the values of the present solution to those pertaining to the newly selected solution [63]. Improving solutions are accepted, with the related temperature parameter offering the likelihood of accepting inferior solutions [63].

2.6.4 Genetic algorithm

Holland introduced the genetic algorithm in 1975 as a nature-inspired approach following the theory of evolution proposed by Darwin [64]. Genetic algorithms contain three phases, namely crossover, mutation, and fitness selection [65]. The algorithm starts with an initial population containing various individuals with related chromosomes [64]. Next, a fitness function is used to determine the goodness of each solution, with parent chromosomes subsequently selected to produce offspring using crossover and mutation [64]. The offspring then replace the current individuals of the population following an analysis of their related fitness [64].

2.6.5 Data envelopment analysis

Data envelopment analysis is a linear programming approach, first defined in 1978 by Charnes, Cooper, and Rhoades [66]. The aim of data envelopment analysis is to determine the efficiency of different decision-making units in converting inputs into outputs [66]. This approach allows simultaneous consideration of numerous inputs and outputs without any assumptions on the distribution of the data [66]. The efficiency of each unit is acquired based on the proportionate change in inputs and outputs, with the entities compared using an efficiency frontier [66].

2.6.6 Dynamic programming

Bellman first introduced dynamic programming in the 1950's [67] as a technique for analysing sequential decision processes [68]. Dynamic programming involves dividing a complex problem into multiple subproblems and using the subproblem solutions to find a general solution to the complete problem [69]. Accordingly, dynamic programming structures optimisation problems into numerous stages, each sequentially solved to obtain a final solution [1].

2.6.7 Fuzzy logic

Fuzzy logic, founded in 1965 by Zadeh, aims to mimic practical decision-making by considering imprecise and vague values instead of binary true or false statements [70]. Therefore, fuzzy logic deals with subjectivity, ultimately providing a better representation of reality by bridging language and human intelligence [71]. Fuzzy logic allocates degrees of membership to entities using the unit interval zero and one, where real numbers on this interval denote partial truths ranging from absolute false to absolute true [72].

2.6.8 Markov chain

In 1905, Markov developed the Markov chain, which is a probabilistic model that describes the sequence of system events, with the likelihood of each event realising depending only on the preceding state [1]. Markov chains model the behaviour of a system over time, enabling future state prediction using a finite matrix of transition probabilities [1]. The matrix of transition probabilities encompasses the conditional probabilities of being in some future state given the attainment of some current state [1]. Markov chain analysis assumes that the system starts in some initial state, with all states mutually exclusive and collectively exhaustive [1].

3 SYSTEMATIC LITERATURE REVIEW

Section 3 introduces the method and protocol used to investigate existing literature, with the resultant findings subsequently discussed and the opportunities for future work conveyed.

3.1 Research method and research results

Modern research mandates synthesising information from a seemingly infinite supply so as to ensure that only relevant material is considered [73]. There are various research methods for synthesising knowledge [73], with systematic reviews being one of the most prominent [74]. A systematic review assumes a methodological nature as it evaluates all existing literature on a particular research question [75]. The power of such a review predominantly lies in its ability to better the general foundation of knowledge concerning a specific subject [76].

The study presents a systematic literature review with a protocol adapted from the guidelines proposed by Kitchenham *et al.* [75] and Kitchenham [77]. The protocol comprises six dissimilar stages, including research question conceptualisation, search process, inclusion and exclusion criteria, quality assessment, data collection, and data analysis. Figure 2 outlines the selected protocol, depicting the systematic nature of the discussed procedure.

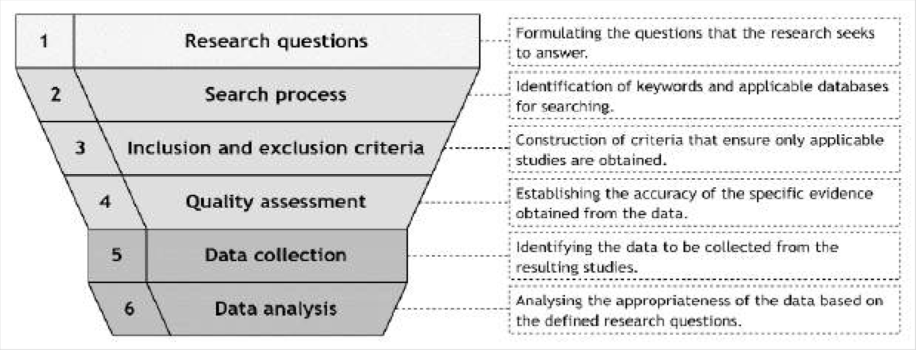
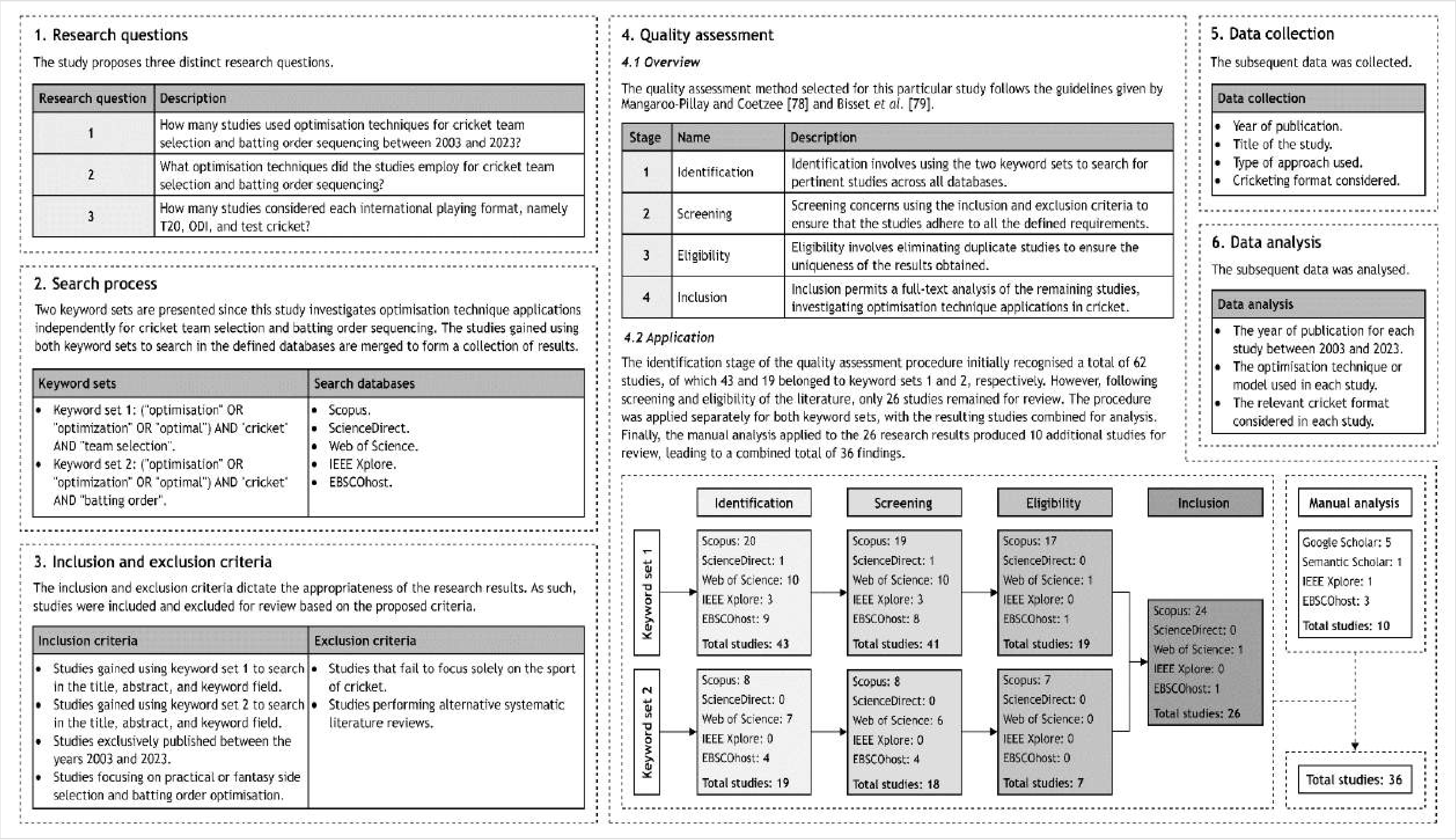


Figure 2: Research protocol stages [75], [77]

Figure 3 demonstrates the application of the research protocol depicted in Figure 2. Foremost, three research questions are identified, which guide the course of the study by outlining the particular focus of the review. Next, the search process involves selecting suitable keywords and databases for extracting evidence from existing literature. Accordingly, two keyword sets are formulated, with five prominent databases used to identify the studies, including Scopus, ScienceDirect, Web of Science, IEEE Xplore, and EBSCOhost. Thereon, inclusion and exclusion criteria, with a quality assessment method adapted from the guidelines proposed by Mangaroo-Pillay and Coetzee [78] and Bisset *et al.* [79], are used to confirm the accuracy and sufficiency of the research results. Finally, data collection and analysis transpire, ensuring the adequate answering of the initially defined research questions.

The quality assessment method yielded 26 distinct research results, shown by the information outlined in Figure 3. However, the authors of these papers frequently referred to alternative studies exhibiting a dissimilar combination of the defined keyword sets. A manual analysis was used to determine the relevancy of these studies by inspecting the titles and abstracts of the referenced work. The manual analysis revealed 10 additional studies, introducing a combined aggregate of 36 distinct findings. Table 1 summarises the original 26 research results, whereas Table 2 provides the supplementary 10 studies. The numbering convention in Table 2 continues from Table 1 so as to ease the cross-referencing of studies in subsequent content.



1. Research questions

The study proposes three distinct research questions.

Research question	Description
1	How many studies used optimisation techniques for cricket team selection and batting order sequencing between 2003 and 2023?
2	What optimisation techniques did the studies employ for cricket team selection and batting order sequencing?
3	How many studies considered each international playing format, namely T20, ODI, and test cricket?

2. Search process

Two keyword sets are presented since this study investigates optimisation technique applications independently for cricket team selection and batting order sequencing. The studies gained using both keyword sets to search in the defined databases are merged to form a collection of results.

Keyword sets	Search databases
• Keyword set 1: ("optimisation" OR "optimization" OR "optimal") AND "cricket" AND "team selection". • Keyword set 2: ("optimisation" OR "optimization" OR "optimal") AND "cricket" AND "batting order".	• Scopus. • ScienceDirect. • Web of Science. • IEEE Xplore. • EBSCOhost.

3. Inclusion and exclusion criteria

The inclusion and exclusion criteria dictate the appropriateness of the research results. As such, studies were included and excluded for review based on the proposed criteria.

Inclusion criteria	Exclusion criteria
• Studies gained using keyword set 1 to search in the title, abstract, and keyword field. • Studies gained using keyword set 2 to search in the title, abstract, and keyword field. • Studies exclusively published between the years 2003 and 2023. • Studies focusing on practical or fantasy side selection and batting order optimisation.	• Studies that fail to focus solely on the sport of cricket. • Studies performing alternative systematic literature reviews.

4. Quality assessment

4.1 Overview

The quality assessment method selected for this particular study follows the guidelines given by Mangaroo-Pillay and Coetzee [78] and Bisset *et al.* [79].

Stage	Name	Description
1	Identification	Identification involves using the two keyword sets to search for pertinent studies across all databases.
2	Screening	Screening concerns using the inclusion and exclusion criteria to ensure that the studies adhere to all the defined requirements.
3	Eligibility	Eligibility involves eliminating duplicate studies to ensure the uniqueness of the results obtained.
4	Inclusion	Inclusion permits a full-text analysis of the remaining studies, investigating optimisation technique applications in cricket.

4.2 Application

The identification stage of the quality assessment procedure initially recognised a total of 62 studies, of which 43 and 19 belonged to keyword sets 1 and 2, respectively. However, following screening and eligibility of the literature, only 26 studies remained for review. The procedure was applied separately for both keyword sets, with the resulting studies combined for analysis. Finally, the manual analysis applied to the 26 research results produced 10 additional studies for review, leading to a combined total of 36 findings.

5. Data collection

The subsequent data was collected.

Data collection
• Year of publication. • Title of the study. • Type of approach used. • Cricketing format considered.

6. Data analysis

The subsequent data was analysed.

Data analysis
• The year of publication for each study between 2003 and 2023. • The optimisation technique or model used in each study. • The relevant cricket format considered in each study.

Figure 3: Research protocol application

Table 1: Final research results of quality assessment

No.	Year	Title	Approach	Format	Reference
1	2023	Optimization of team selection in fantasy cricket: a hybrid approach using recursive feature elimination and genetic algorithm.	Random forest recursive feature elimination and genetic algorithm.	ODI	Jha *et al.* [80].
2	2022	A balanced squad for Indian Premier League using modified NSGA-II.	Genetic algorithm.	T20	Verma *et al.* [81].
3	2021	Predicting optimal cricket team using data analysis.	Subjective weighting system.	T20	Jadav *et al.* [82].
4	2020	Extraction of strong and weak regions of cricket batsman through text-commentary analysis.	Text-based mining using a regular expression matching algorithm.	T20	Rauf *et al.* [83].
5	2020	Machine learning-based selection of optimal sports team based on the players performance.	Machine learning using a random forest algorithm.	ODI	Shetty *et al.* [84].
6	2020	Best'11 strategy in cricket using MCDM, rough matrix and assignment model.	Multi-criteria decision making, rough matrices, and integer programming.	ODI	Vijayabalaji & Balaji [85].
7	2020	An innovative super-efficiency data envelopment analysis, semi-variance, and Shannon-entropy-based methodology for player selection: evidence from cricket.	Data envelopment analysis, semi-variance, and Shannon entropy.	ODI	Adhikari *et al.* [86].
8	2019	Decision making in cricket: the optimum team selection.	Integer programming.	T20	Saikia *et al.* [87].
9	2019	A sequential principal component-based algorithm for optimal lineup and batting order selection in one day international cricket for Bangladesh.	Sequential principal component analysis.	ODI	Shanto & Awan [88].
10	2018	Team selection using multi-/many-objective optimization with integer linear programming.	Integer programming.	T20	Chand *et al.* [89].
11	2016	A new model for player selection in cricket.	Composite indices.	T20	Saikia *et al.* [34].
12	2016	Optimal lineups in Twenty20 cricket.	Relative value statistics and simulated annealing.	T20	Perera *et al.* [90].
13	2016	An objective approach of balanced cricket team selection using binary integer programming method.	Integer programming.	T20	Bhattacharjee & Saikia [91].
14	2014	On performance measurement of cricketers and selecting an optimum balanced team.	Integer programming.	T20	Bhattacharjee & Saikia [92].
15	2013	Team selection after a short cricket series.	Integer programming.	ODI	Lemmer [93].
16	2013	Multi-objective optimization and decision making approaches to cricket team selection.	Genetic algorithm.	T20	Ahmed *et al.* [94].
17	2013	Selecting the optimum cricket team after a tournament.	Integer programming.	T20	Bhattacharjee & Saikia [95].

No.	Year	Title	Approach	Format	Reference
18	2012	A multi-stage integer programming approach to fantasy team selection: a Twenty20 cricket study.	Integer programming.	T20	Brettenny *et al.* [96].
19	2011	Cricket team selection using evolutionary multi-objective optimization.	Genetic algorithm.	T20	Ahmed *et al.* [21].
20	2011	Integer optimisation for the selection of a Twenty20 cricket team.	Integer programming.	T20	Sharp *et al.* [97].
21	2010	Optimal batting orders in cricket.	Dynamic programming.	All	Norman & Clarke [98].
22	2009	Applying genetic algorithm to select an optimal cricket team.	Genetic algorithm.	ODI	Sathya & Jamal [99].
23	2007	Dynamic programming in cricket: optimizing batting order for a sticky wicket.	Dynamic programming.	Test	Norman & Clarke [100].
24	2006	A mathematical modelling approach to one-day cricket batting orders.	Markov chain.	ODI	Ovens & Bukiet [101].
25	2006	Optimal batting orders in one-day cricket.	Simulated annealing.	ODI	Swartz *et al.* [37].
26	2003	Dynamic programming in cricket: choosing a night watchman.	Dynamic programming.	Test	Clarke & Norman [102].

Table 2: Final research results of manual analysis

No.	Year	Title	Approach	Format	Reference
27	2019	A DEA model for selection of Indian cricket team players.	Data envelopment analysis.	Test	Chaudhary *et al.* [103].
28	2017	Optimal one day international cricket team selection by genetic algorithm.	Genetic algorithm.	ODI	Kumarasiri & Perera [40].
29	2014	Moneyballer: an integer optimization framework for fantasy cricket league selection and substitution.	Integer programming.	T20	Das [104].
30	2014	Cricket team selection using data envelopment analysis.	Data envelopment analysis.	T20	Amin & Sharma [105].
31	2011	Selection of cricket players using analytical hierarchy process.	Fuzzy analytic hierarchy process.	N/A	Kamble *et al.* [106].
32	2010	Integer optimisation for the selection of a fantasy league cricket team.	Integer programming.	T20	Brettenny [107].
33	2009	Integer optimization for the selection of a Twenty20 cricket team.	Integer programming.	T20	Lourens [108].
34	2006	Selecting a limited overs cricket squad using an integer programming model.	Integer programming.	ODI	Gerber & Sharp [109].
35	2004	A criterion for comparing and selecting batsmen in limited overs cricket.	Two-dimensional framework.	ODI	Barr & Kantor [110].
36	2003	Cricket team selection using genetic algorithm.	Genetic algorithm.	ODI	Omkar & Verma [111].

3.2 Discussion of research results

Section 3.2 discusses the different research results by answering the initially defined research questions, offering valuable insight into probable opportunities for prospective work.

3.2.1 Research question 1: How many studies used optimisation techniques for cricket team selection and batting order sequencing between 2003 and 2023?

Figure 4 presents a bar chart exhibiting the distribution of the combined 36 findings based on the year of publication. Figure 4 demonstrates that most of the work involving cricket player selection and sequencing was executed between 2009 and 2014, with a corresponding total of 14 publications. Further, Figure 4 indicates that 2020 contains the most publications on this topic, showing an aggregate of 4 unique studies.

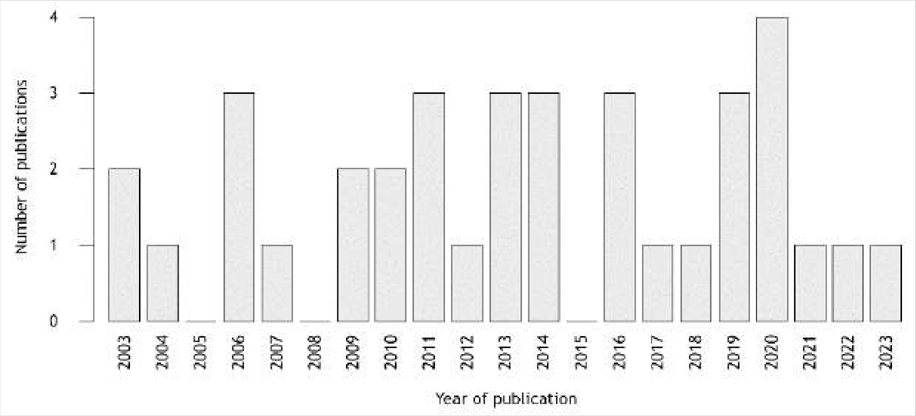


Figure 4: Number of studies published between 2003 and 2023

Although the keyword sets formulated in Figure 3 specifically limit the scope of the review to mathematical optimisation, many of the resultant studies employ alternative approaches, such as statistical methods. However, the focus of this study involves deterministic and stochastic optimisation techniques with the consideration of heuristics and solution-based methods. Therefore, considering the approaches followed by the research results, the study consults existing literature to ensure an accurate classification of the employed techniques. Figure 5 presents the number of studies that utilised optimisation techniques, classified using the framework introduced in Section 2.5. Figure 6 shows the applicability of the databases by demonstrating the number of studies given by each source. The subsequent illustrations offer valuable insight into the adequacy of the review by illustrating the relationships between the distinct study approaches and sources.

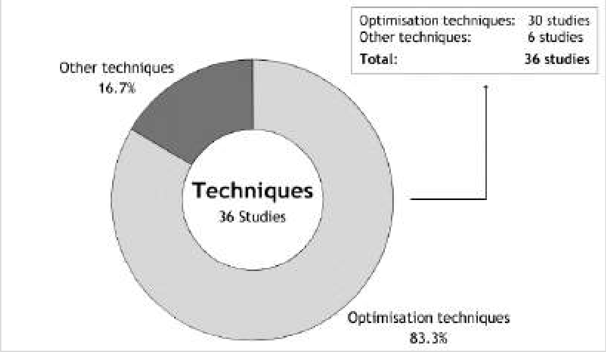


Figure 5: Studies per technique

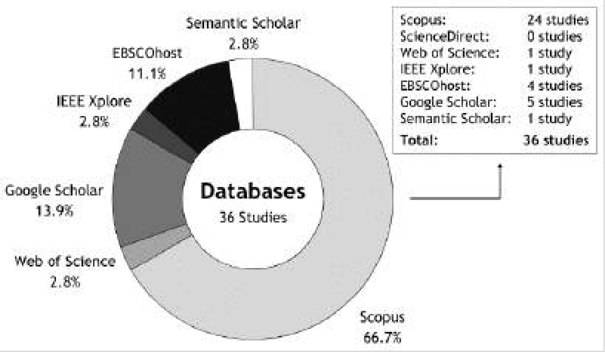


Figure 6: Studies per database

Numerous studies combined multiple approaches, such as statistical models and optimisation algorithms. Therefore, all studies that used optimisation techniques for problem formulation or solving were classified as such. Hence, Figure 5 reveals that, between 2003 and 2023, 30 studies used optimisation techniques for cricket team selection and batting order sequencing. Figure 6 encompasses databases not initially defined as part of the search process, associated with the supplementary studies obtained from the manual analysis. Figure 6 shows that Scopus accounts for 66.7% of the results, offering insight for future studies pursuing parallel work.

3.2.2 Research question 2: What optimisation techniques did the studies employ for cricket team selection and batting order sequencing?

The preceding subsection shows that 30 studies used optimisation techniques, such as integer programming, simulated annealing, genetic algorithms, data envelopment analysis, dynamic programming, fuzzy logic, and Markov chains. Figure 7 offers a bar chart depicting the number of studies considering each optimisation technique, recalling the classification in Section 2.5.

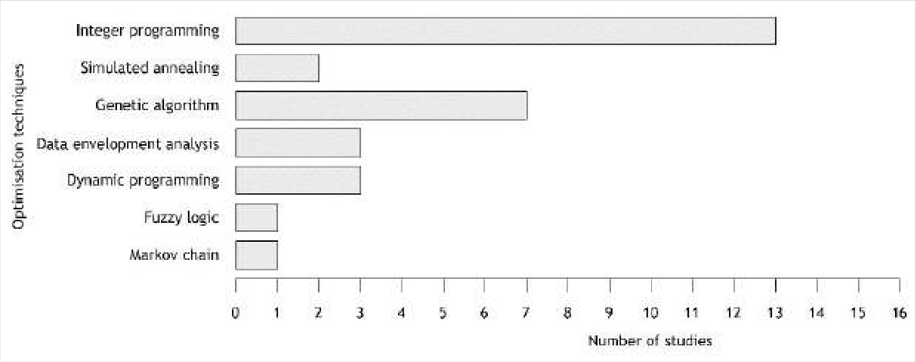


Figure 7: Number of studies per optimisation technique

As discussed, various studies utilise numerous techniques for team selection and batting order optimisation. Therefore, considering Figure 7, the studies were classified based on the specific procedures employed to select and sequence cricketers. As such, 13 and 3 studies conducted player selection and ordering using integer and dynamic programming, respectively. Similarly, 2, 7, and 1 papers used simulated annealing, genetic algorithms, and fuzzy logic, respectively. Finally, 3 studies applied data envelopment analysis, whereas only 1 considered a Markov chain approach. Table 3 lists the studies associated with each optimisation technique in Figure 7.

Table 3: Studies associated with each optimisation technique

Technique	Name	Study	Total
1	Integer programming	6, 8, 10, 13, 14, 15, 17, 18, 20, 29, 32, 33, 34	13
2	Simulated annealing	12, 25	2
3	Genetic algorithm	1, 2, 16, 19, 22, 28, 36	7
4	Data envelopment analysis	7, 27, 30	3
5	Dynamic programming	21, 23, 26	3
6	Fuzzy logic	31	1
7	Markov chain	24	1

3.2.3 Research question 3: How many studies considered each international playing format, namely T20, ODI, and test cricket?

Recall from Section 2.3 that cricket, at an international level, comprises three official formats viz. T20, ODI, and test. However, certain studies provide models with necessary adjustments so as to ensure their applicability in all playing formats. Accordingly, in such cases, the match form used to test the model is considered the applicable playing format. From Table 1, Study 21 involves all playing formats as it provides two unique models for optimising batting lineups in limited and unlimited overs cricket. Further, Study 31 does not consider a particular format and instead offers a general method for player ordering. However, team selection and batting order optimisation significantly depend on the playing format. Therefore, Table 2 shows that the suggested formats are not applicable (N/A) to Study 31 owing to its generic model. Figure 8 presents the number of studies associated with each format, considering Study 21 separately for T20, ODI, and test cricket. However, Figure 8 excludes Study 31 as its proposed procedure does not specifically consider any of the three mentioned game structures.

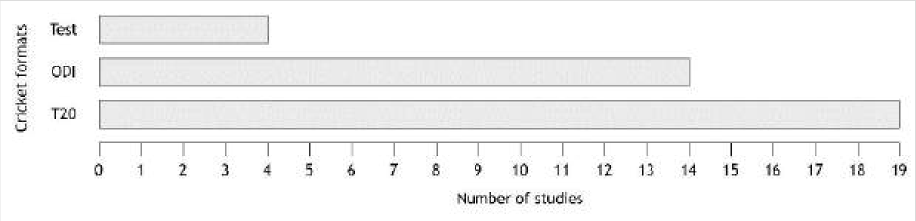


Figure 8: Number of studies per cricket format

Figure 8 illustrates that 4, 14, and 19 studies perform either team selection or batting order optimisation for test, ODI, and T20 cricket, respectively. Accordingly, most research on team selection and batting order optimisation predominantly focuses on limited overs cricket, with minor consideration of the test playing format.

3.3 Research opportunities

The results from the systematic review indicate numerous opportunities involving cricket team selection using mathematical optimisation techniques. The findings reveal that current team selection methods in existing literature provide limited flexibility concerning the treatment of multiple objectives and constraints [106]. Accordingly, these procedures fail to permit any deviation from the preconceived target values subject to achievement. Further, Chand *et al.* [89] mention the conflicting nature of cricketing abilities formulated as objectives. Therefore, future research can consider using a goal programming approach to find an acceptable team that balances the trade-off between these conflicting and incommensurable playing abilities. The recommended approach in goal programming introduces more flexibility in team selection by accommodating the contrasting nature between the different abilities through deviational variables that allow marginal divergence from the presumed target values. Assembling a team using goal programming will better reflect the practical environment as it depicts the dynamic nature of selection rather than simply finding the best players to form an optimal side.

Further, the review shows various studies considered team selection in T20 leagues, focusing on the IPL. However, most of these papers select the playing eleven rather than the universal squad of tournament-based cricketers obtained from the player auction. Accordingly, many of these studies perform team selection from the baseline, neglecting fundamental auctioning rules and regulations, including player retention, budgetary constraints, mandatory Indian players, and franchise exchanges. Also, these studies fail to distinguish between the IPL mini and mega-auction, each of which presents different provisions for player selection owing to dissimilar retention rules. Swartz [22] sustains these findings by mentioning that prior research has not yet investigated the IPL auction in detail, recommending player selection within this domain as potential work for prospective research. Accordingly, future research can extend the existing work by offering a unique mathematical model that enables cricket team selection specifically within the dynamic player auctioning process.

Recall from the preceding subsection that only 4 studies considered team selection and batting order optimisation within test cricket. Accordingly, a significant opportunity exists for future research to model batting lineups in test cricket, with each team having multiple opportunities to bat under different scenarios containing distinct uncertainties. Future studies can consider employing stochastic programming with resource, which utilises corrective action to combat undesirable results [112]. Stochastic programming with resource involves postposing decisions to future stages after experience obtained from initial findings has removed some or all of the underlying uncertainties [112]. Therefore, future studies can utilise this approach to maximise the number of runs achieved by optimising the batting lineup for the second innings using the experience gathered and the uncertainties observed during the first innings.

4 CONCLUSION, LIMITATIONS, AND RECOMMENDATIONS

Section 4 summarises the study by recalling the core details associated with each preceding passage, followed by the related limitations and recommendations.

4.1 Study summary

Mathematical optimisation, as a subset of operations research, contains multiple applications, with cricket being no exception. Cricket is a complex bat-and-ball game played by 22 members across various formats. Success in cricket significantly relies on player selection and ordering owing to its multidisciplinary nature [94]. Therefore, utilising quantitative methods to attain optimality involving squad composition and player sequencing becomes essential. Accordingly, this study provides a unique systematic literature review investigating optimisation technique applications in cricket team selection and batting order optimisation.

The systematic literature review conducted in this study follows a research protocol based on the guidelines specified by Kitchenham *et al.* [75] and Kitchenham [77]. The protocol yielded 26 distinct research results, comprising studies concerning cricket team selection and batting order optimisation. However, the authors of these consequent studies frequently referred to alternative papers having a dissimilar combination of the defined keyword sets. Accordingly, these supplementary studies were included for review following a manual analysis, producing a combined total of 36 distinct research results.

The 36 research results were discussed and evaluated, signifying their corresponding methods, playing formats, and application areas. The analysis showed that 30 studies used optimisation techniques, such as integer programming, dynamic programming, simulated annealing, Markov chains, fuzzy logic, genetic algorithms, and data envelopment analysis. Further, the review showed that limited overs cricket has received the most attention, with significant prospects yet to be explored for test cricket. Accordingly, the study offers a comprehensive framework for future research by revealing the considerations and related limitations concerning existing research, signifying its holistic contribution to academia and industry.

4.2 Limitations and recommendations

The study comprises selected limitations and recommendations subsequently summarised:

- The study uses multiple keyword sets to assess optimisation technique applications in cricket team selection and batting order sequencing. As such, it is recommended that future research broaden the search to all sports by eliminating the keyword: cricket. Removing this keyword and excluding all nonathletic studies will offer valuable insights into solving similar player selection and ordering problems in alternative sports.
- The review exploits five prominent research databases: Scopus, ScienceDirect, Web of Science, IEEE Xplore, and EBSCOhost. Therefore, an opportunity exists for future work to extend the current search by including further recognised databases. Considering additional databases may produce supplementary results, furthering insight into team selection and batting order sequencing using mathematical optimisation techniques.
- Cricket is a sophisticated game lacking no shortcomings in statistical data or numerical phenomena. Accordingly, it is recommended that future studies examine optimisation technique applications involving alternative aspects of cricket. Additional applications of optimisation techniques in cricket worth investigating involve forecasting of possible match-fixing within T20 leagues and general score prediction.

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DEVELOPING MACHINE LEARNING-BASED MODELS FOR OPTIMAL MAINTENANCE SCHEDULING WITHIN THE FOOD INDUSTRY

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ABSTRACT

In the context of the food industry, precisely the company used as a case study, unplanned machine downtimes are mainly caused by ineffective maintenance scheduling that impacts organisational profit. To address this challenge, the study explores predictive maintenance within the food industry and its application to reduce machine inefficiencies and improve overall decision-making. First, a theoretical background on predictive maintenance and machine learning is provided, followed by the development of the random forest and decision tree models. Company data is pre-processed, and the models are trained and tested using scientific methods from academic literature, including cross-validation and hyperparameter tuning. One-year future predictions are made for three retail line machines, aiding in proactive maintenance decision-making to reduce unplanned machine downtime. Subsequently, this study contributes towards academia and industry by providing actionable insights for optimising maintenance scheduling and production processes in the food industry.

Keywords: Machine learning, Maintenance scheduling, Food industry, Predictive maintenance

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1 INTRODUCTION

All machines, equipment, and devices responsible for producing products are bound to wear and tear. Records of maintenance activities date back to ancient Egyptian times. An old Egyptian document dated 600 b.c. mentions a stoppage of cedar wood required to maintain the sacred boat of Amun Ra [1]. The Industrial Revolution incentivised the need for maintenance strategies to be redesigned to adhere to the advancements in technology in the industrial sector. **Table 1** discusses the impact of the Industrial Revolution on maintenance practices.

Table 1: The correlation between the industrial revolutions and maintenance types [1]

Industrial revolution	**Type of Maintenance**	**Overview of the correlation between the Industrial Revolution and maintenance type**
Industry 1.0	Reactive	The first industrial revolution began in England, transforming energy sources, transportation, information transfer, and manufacturing. James Watt's invention of the steam engine in 1765 marked the beginning. The increased complexity of machines and increased productivity led to the evolution of maintenance methods. Reactive maintenance was costly and caused unanticipated downtime and productivity losses.
Industry 2.0	Preventive	The Second Industrial Revolution began in 1870, revolutionising society with mass manufacturing and inventions. As machines became more complex, preventative maintenance emerged to reduce downtime and improve equipment performance. Manufacturers now focus on routine inspections, maintenance, and repairs to prevent breakdowns and maintain equipment's overall performance.
Industry 3.0	Productive	Advancements in manufacturing, computer technology, and marketing and management procedures marked the Third Industrial Revolution. Productive Maintenance (PM) emerged after World War II, combining Corrective and Preventive Maintenance with an analytical, data-driven approach. PM improves equipment lifespans, reduces downtime, and reduces costs. Reliability-centered Maintenance (RCM) and Total Productive Maintenance (TPM) were developed during this time. RCM focuses on determining maintenance needs for physical assets, addressing issues like neglected maintenance or wear, and improving machine uptime, cost-effectiveness, and risk awareness. TPM, developed by Seichi Nakajima in 1971, emphasises employee involvement, efficiency, and machinery preservation. Both techniques aim to minimise downtime and mitigate accidents involving various professions, including maintainers and operators.
Industry 4.0	Predictive	The fourth industrial revolution is rapidly expanding due to the global interconnection of the Internet. Predictive maintenance, a method combining big data analytics and artificial intelligence, aims to identify patterns and trends in asset failure. It requires real-time monitoring and alarms based on predictive methods like regression analysis. Fundamental elements include sensors, cyber-physical

		systems, the Internet of Things, big data, cloud computing, networks, artificial intelligence, mobile networks, and WiFi.

This paper will specifically focus on predictive maintenance. An important predictive maintenance component is proactive maintenance. Instead of depending exclusively on set schedules or reactive repairs, it entails carrying out maintenance tasks proactively based on the equipment's predicted demands [2]. Maintenance staff may plan and schedule maintenance work, guaranteeing optimal resource allocation and minimal disturbance to production by predicting future equipment failures. Proactive maintenance combined with predictive analytics will be crucial in developing a company's predictive maintenance strategy plan.

Predictive systems are fundamentally dependent on continuous improvement. A predictive system is iteratively updated and improved based on feedback, performance reviews, and new data. Updating prediction models, modifying maintenance strategies, implementing new sensor technologies, and incorporating customer and equipment operator input are all examples of continuous improvement.

1.1 Types of machine learning techniques

Some standard predictive modelling techniques in machine learning include:

- **Linear regression:** This type of regression model falls within supervised learning. It is a statistical approach that simulates the relationship between one or more independent variables and the dependent variable [3]. The method finds the best-fitting line by fitting a linear equation to the training data and minimising the difference between the predicted and actual values. During training, the method adjusts the slope and intercept to reduce the mean squared error between the predicted and actual values.
- **Logistic regression:** This type of regression model falls within supervised learning. It is a statistical method that describes and explains correlations between binary dependent variables and one or more nominal, interval, or ratio-level independent variables. By using the known values of other variables and a discrete target variable, logistic regression enables you to forecast the unknown values of the target variable. The modelling technique is primarily used for binary classification tasks, where the objective is to predict the probability of an observation belonging to one or more classes [4]. The model uses the output obtained by the linear regression function as input and a sigmoid function (S-form curve) to estimate the probability for the specific class.
- **Decision trees:** A powerful and understandable predictive modelling method used for both classification and regression applications within supervised learning. It is a supervised learning technique with a tree-like structure where each leaf node represents the final prediction or class label, and each interior node represents a choice based on a feature [5]. Making predictions by making a series of binary decisions depending on the values of the input characteristics, decision trees divide the feature space into regions. Recursively building the tree with the most illuminating elements at the top creates a hierarchical collection of simple rules to grasp and comprehend.
- **Gradient boosted model:** This ensemble machine learning method is used for classification and regression tasks within supervised learning. Its foundation is boosting, which joins several decision trees to produce a more reliable and accurate prediction model. Gradient boosting builds decision trees progressively, each aiming to fix the mistakes caused by the one before it [6]. The model emphasises data items that prior trees misclassified or projected incorrectly to increase overall prediction accuracy. It is an effective model for handling complex, non-linear relationships in data due to its flexible nature, handling various data types and feature combinations.

- **Neural networks:** Artificial neural networks (ANNs), often known as neural networks, are a class of strong and adaptable machine learning models that take inspiration from the structure and operation of the human brain. The machine learning model uses both supervised and unsupervised learning. They can comprehend complicated patterns and correlations among the data and are especially effective at processing complex, high-dimensional data. Neurons, the linked units of neural networks, are arranged into three levels: an input layer, one or more hidden layers, and an output layer [7]. Every neuron receives an input, performs a mathematical transformation, and then generates an output that serves as the input for the layer below it. Weights are assigned to the connections between neurons. Backpropagation, which uses optimisation techniques to reduce the error between expected and actual results, adjusts these weights during training.
- **Random forest:** This is a popular and effective ensemble learning method used by classification and regression applications within supervised learning. It is a member of the bagging family of algorithms and combines the predictions of multiple decision trees to boost generalisation performance, decrease overfitting, and increase accuracy [8]. Each decision tree in a random forest is trained using a randomly chosen portion of the training data, and a randomly selected subset of characteristics is considered at each split point during tree building. The trees' variety and unpredictability contribute to the reduction of variance and increase the model's resistance to noisy or complicated input.

1.2 Case studies and applications

A few case studies regarding predictive maintenance will be discussed in this section. The real-life application of these studies will be discussed, and commonalities will be identified. The largest chemical business in the world, "Badische Anilin und Soda Fabrik" (BASF), translates to Baden Aniline and Soda Factory in English. The company has made digitalisation a part of its corporate strategy to streamline maintenance procedures and minimise unplanned downtime. To provide remote monitoring and control of its power distribution substation's operations and asset health, the Beaumont, Texas, facility used EcoStruxure Asset Advisor from Schneider Electric. The IoT-enabled solution uses asset sensors for continuous asset condition monitoring and predictive analytics to find possible asset failure concerns. By collaborating with Schneider Electric's Connected Services Hub, BASF additionally benefits from individualised, proactive guidance on avoiding breakdowns and enhancing maintenance strategies. Over 100 condition variables for 63 substation assets were gathered, measured, and computed in the use case. The digital dashboard offers 24/7 visibility into the substation's global health index and particular asset statuses [9]. The cloud-based system connects assets, enabling the plant to monitor the condition of the motors powering the process, motor control centres, and electrical distribution equipment. The plant can make informed decisions, optimise asset health, and increase the effectiveness of vital electrical distribution assets with round-the-clock data access and professional advice, which will eventually increase plant uptime, performance, productivity, and safety.

Alcoa's predictive maintenance strategy attempts to make the company more stable and profitable. At its Fjarðaál aluminium smelter in Iceland, a proof-of-concept (POC) experiment was conducted to automate predictive maintenance and decrease downtime and maintenance costs. The system is scaled to at least 1,000 assets in Fjarðaál and is enterprise-wide scalable. Senseye was chosen to integrate and synchronise the plant's OSIsoft PI ecosystem's equipment sensor data with maintenance data in its Oracle EAM solution. Without any settings or alert levels, the system automatically forms models and commences learning. Isolated peaks in raw data illustrate patterns and hidden failures. Predictive analytics determines what is happening and why, offering prognostic recommendations about the asset's remaining usable life. Operators are automatically alerted of situations that require attention and can further investigate the fault for more information. Alcoa decreased unscheduled machinery downtime by up to 20% and achieved full ROI in 4-6 months [9]. After completing the POC, the solution expanded to other sections of the business, emphasising identifying the best corporate reasons to continue.

Duke Energy Renewables, an owner/operator of wind and solar farms in the United States, has effectively automated the profiling and detection of faulty contactors on one of its wind turbines. The turbines have six contactors that ensure smooth generator ramp-up and synchronisation with the electrical grid. When any of the six contactors fails, the turbine experiences downtime for 2 to 10 days for diagnostic and repair. Turbine contactors fail more frequently at one location than at others. Automating the prediction of approaching failure would enable predictive maintenance, reduce downtime, lower maintenance costs, and improve spare parts inventory management.

A model was trained to search for the contactor fault error code and credible leading indicator signals using Seeq's automatic profiling tool. The model discovered 12 instances of the error code, most of which occurred within a few months preceding a breakdown [9]. No false positives existed before the outage, and no further fault codes or forecasts were generated once all contactors were replaced. Once approved, the model may run indefinitely and provide automated notification when something goes wrong. The results are encouraging, and Duke Energy Renewables intends to apply this model to the other turbines at the site and investigate additional failure mechanisms. The return on the capability to detect a generator before failure and respond proactively can save the company hundreds of thousands of dollars.

The case study uses the CRISP-DM (Cross-Industry Standard Process for Data Mining) methodology, which provides detailed guidance for implementing data mining and consists of the following six phases: Business understanding, data understanding, data preparation, modelling, evaluation, and deployment [10]. Data mining falls within data pre-processing and involves cleaning data to improve models' accuracy. The case mainly considers the prediction of failures and the root causes of two bottleneck machines in the engine component line. High dimensional data is obtained from a newly installed sensor system, control system (programable logic controller), production monitoring system, and maintenance system.

From the case studies, it is evident that predictive maintenance is an essential topic in all industries. Based on the current knowledge regarding the application of machine learning for predictive maintenance, this study aims to propose a predictive maintenance strategy plan as an example that will enable any company to make proactive decisions, effectively reducing machine inefficiencies experienced. Due to confidentiality, the data or the company name may not be displayed. However, the article will provide a guideline on how to use machine learning to enable proactive maintenance decisions.

2 RESEARCH METHOD

Figure 1 provides a holistic view of the inputs that were required, the process that was conducted, and the output that was delivered to achieve the research aim.

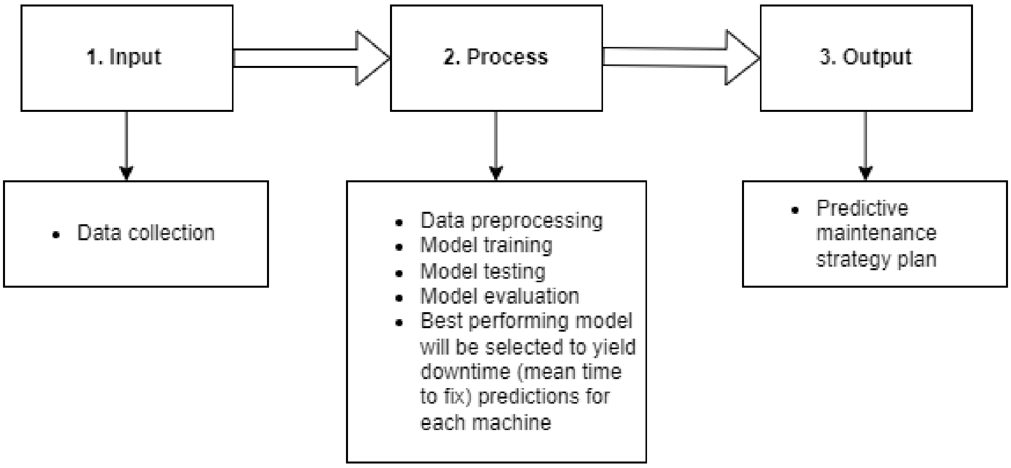
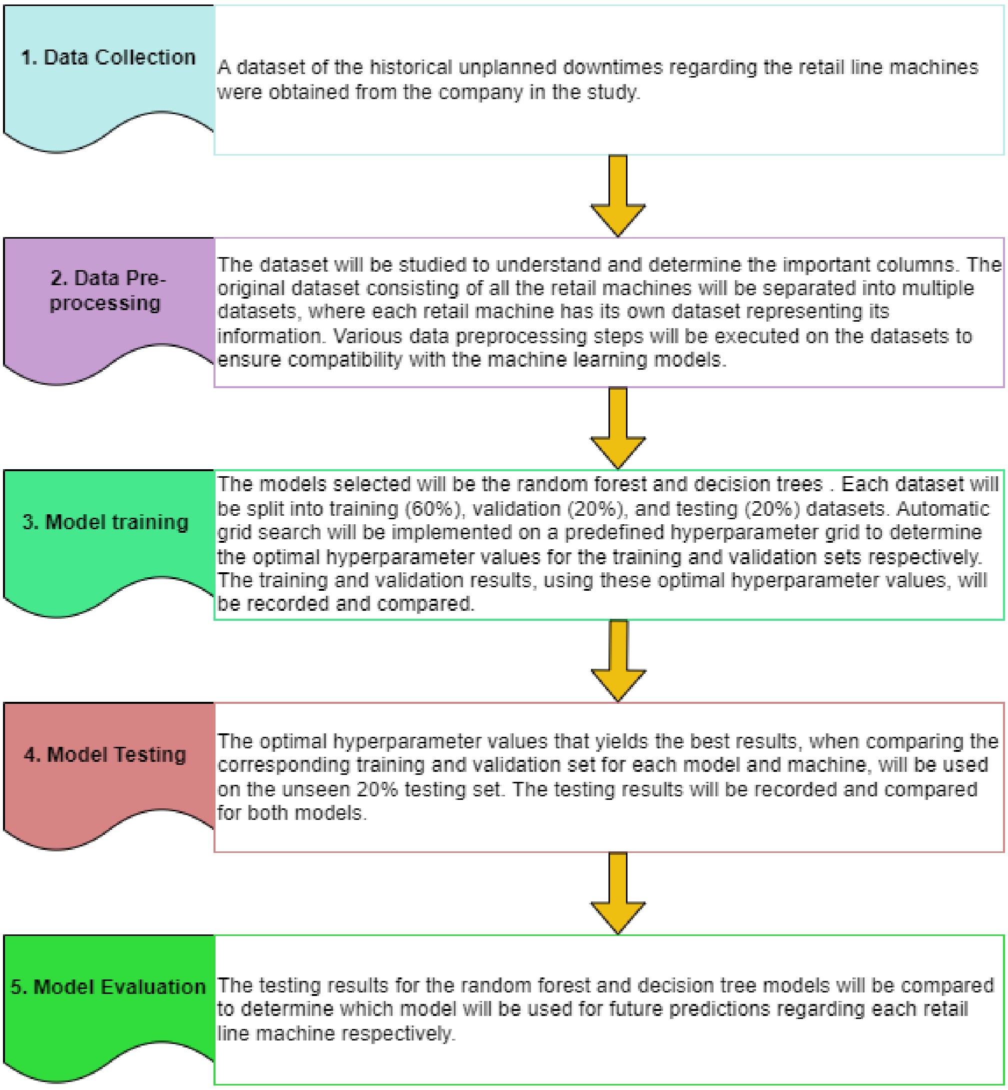


Figure 1: Holistic view of the road towards achieving the project's aim

Two machine-learning models were trained, validated, and tested on pre-processed datasets. The model that yielded the best results when comparing the performance metric results of the selected models was used to predict future mean time to fix (downtime) values for each machine within the production line. The machine learning model predictions were used to develop a predictive maintenance strategy plan with literature to assist the company used as a case study in making proactive maintenance decisions, reducing asset failures, and improving equipment longevity. The following approach/process will be used to develop the machine learning models for the various retail line machines [11]:



A dataset of the historical unplanned downtimes regarding the retail line machines were obtained from the company in the study.

The dataset will be studied to understand and determine the important columns. The original dataset consisting of all the retail machines will be separated into multiple datasets, where each retail machine has its own dataset representing its information. Various data preprocessing steps will be executed on the datasets to ensure compatibility with the machine learning models.

The models selected will be the random forest and decision trees . Each dataset will be split into training (60%), validation (20%), and testing (20%) datasets. Automatic grid search will be implemented on a predefined hyperparameter grid to determine the optimal hyperparameter values for the training and validation sets respectively. The training and validation results, using these optimal hyperparameter values, will be recorded and compared.

The optimal hyperparameter values that yields the best results, when comparing the corresponding training and validation set for each model and machine, will be used on the unseen 20% testing set. The testing results will be recorded and compared for both models.

The testing results for the random forest and decision tree models will be compared to determine which model will be used for future predictions regarding each retail line machine respectively.

Figure 1: Scientific method for the development of the machine learning models [11]

The scientific method discussed in **Figure 2** was used to provide a conceptual design solution for predicting the mean time to fix for the different production line machines. The random forest and decision tree machine learning models were used to predict the mean time to fix (unplanned machine downtime) for each production line machine dataset. For this study, three production line machines were used as an example.

3 THE APPLICATION OF MACHINE LEARNING

3.1 Verification and validation of machine learning models

3.1.1 Data pre-processing

The following preliminary pre-processed steps were executed on the original raw dataset using R-studio, Excel, and Python (Spyder IDE):

I. Removed unnecessary columns using Excel and import data into R-studio:

The data columns were reduced to only three, namely Date, Machine, and Downtime. All other columns were irrelevant and not required for analysis or model development purposes since they didn't provide any meaningful insights. R-Studio software was used to apply data pre-processing to the Excel sheet containing the three columns (Date, Machine, Downtime). The Excel dataset was imported into R-Studio using the "readxl" package.

II. Downtime column pre-processing using R-Studio:

All the rows containing a 0 or N/A entry in the Downtime column were eliminated from the dataset.

III. Aggregation of duplicate entries using R-Studio:

Duplicate entries of the same machine having multiple downtimes in one day were summed together, ensuring unique data entries for the dataset.

IV. Separation of the dataset to obtain a dataset for each retail line machine using Excel:

The preliminary pre-processed dataset was exported back to Excel, where the dataset was separated using the Machine column. The filter function in Excel was used to create a separate dataset for each retail line machine, resulting in 6 distinct Excel sheets (one for each machine).

V. Removal of Machine column for each newly formed dataset using Excel:

Each of the newly formed datasets, representing one retail line machine each, resulted in the removal of the machine column for each of the newly formed datasets since this column would not provide any meaningful insight for the machine learning models.

VI. Outlier removal for the Downtime columns using Python (Spyder IDE):

The final data pre-processing step was done using Python, where each dataset's outliers (in the Downtime column) were removed using the Interquartile Range method (IQR). The rest of the model development process was executed using Python (Spyder IDE).

VII. Final pre-processed datasets

This process resulted in three pre-processed datasets in total. Each dataset consists of two columns: Date and Downtime.

3.1.2 Training, validation and testing of the regression models

In this section, model training and model testing of the scientific method for developing machine learning models are executed. The results obtained from the machine learning models were evaluated using the performance metrics: MSE (Mean Square Error), RMSE (Root Mean Square Error) and R^2.

I. Machine 1

The model training procedure was followed to obtain Machine 1's training - and validation set results. **Appendix A** illustrates the training and validation results obtained for Machine 1 for both machine learning models. Figure 2 provides an outline regarding the training and testing methods used. **Table 2** demonstrates the training and validation results for machine 1.

Table 2: Comparison of the training - and validation set results for Machine 1

Machine learning Model:	Conclusion When comparing training - and validation results:
Random Forest	The training set yielded an R^2 Value of 0.77, which is better than the validation set value of 0.73. In conclusion, the optimal hyperparameter values for the training set were used on the unseen testing set.
Decision Tree	The training set yielded a better MSE and R^2 value; thus, the optimal hyperparameter values for the training set were used on the unseen testing set.

After training and validating both machine learning models, model testing was done using the conclusions made in **Table 2**. The model testing procedure was followed to obtain the testing set results for the random forest and the decision tree model, illustrated in **Table 3**.

Table 3: Testing set results for Machine 1

Random Forest Model (Testing Set)	
Optimal hyperparameter values (Training set)	**Testing set results (Performance metrics)**
n_estimators = 150 max_depth = None min_samples_split = 5 min_samples_leaf = 2	MSE = 188.43 MAE = 10.34 R^2 = 0.67
Decision Tree Model (Testing Set)	
Optimal hyperparameter values (Training set)	**Testing set results (Performance metrics)**
max_depth = 5 min_samples_split = 5 min_samples_leaf = 2	MSE = 275.04 MAE = 11.59 R^2 = 0.54

Table 3 illustrates that the random forest model provided better MSE, MAE, and R^2 values when compared to the decision tree model. The random forest model was used to make future predictions regarding the unplanned downtime Machine 1 experienced. The same process was repeated for the other machines in the following subsection.

II. Machine 2

The training - and validation set results for the random forest and the decision tree model are illustrated in Appendix A. Figure 2 provides an outline regarding the training and testing methods used. Comparing the training - and validation set results for the random forest and the decision tree model, respectively, the following conclusions were drawn:

Table 4: Comparison of the training - and validation set results for Machine 2

Machine learning Model:	**Conclusion When comparing training - and validation results:**
Random Forest	The training set yielded better MSE, MAE, and R^2 values than the validation set values. In conclusion, the optimal hyperparameter values for the training set were used on the unseen testing set.
Decision Tree	The validation set yielded better MSE, MAE, and R^2 values than the training set values; thus, the optimal hyperparameter values for the validation set were used on the unseen testing set.

After training and validating both machine learning models, model testing was done using the conclusions made in **Table 4**. The same model testing procedure was repeated for Machine 2 to obtain the testing set results for the random forest and the decision tree model, illustrated in **Table 5**.

Table 5: Testing set results for Machine 2

Random Forest Model (Testing Set)	
Optimal hyperparameter values (Training set)	**Testing set results**
n_estimators = 50 max_depth = None min_samples_split = 5 min_samples_leaf = 2	MSE = 385.51 MAE = 14.51 R^2 = 0.61
Decision Tree Model (Testing Set)	
Optimal hyperparameter values (Validation set)	**Testing set results**
max_depth = None min_samples_split = 5 min_samples_leaf = 2	MSE = 281.04 MAE = 11.56 R^2 = 0.72

Table 5 illustrates that the decision tree model provided a better MSE, MAE, and R^2 value when compared to the random forest model. The decision tree model was used to make future predictions regarding the unplanned downtime Machine 2 experienced. The exact process was repeated for Machine 3 in the following subsection.

III. Machine 3

The training - and validation set results for the random forest and the decision tree model are illustrated in Appendix A. Figure 2 provides an outline regarding the training and testing methods used. Comparing the training - and validation set results for the random forest and the decision tree model, respectively, the following conclusions were drawn:

Table 6: Comparison of the training - and validation set results for Machine 3

Machine learning Model:	**Conclusion When comparing training - and validation results:**
Random Forest	The training set yielded a better R^2 Value of 0.72 when compared to the validation set value of 0.52. In conclusion, the optimal hyperparameter values for the training set were used on the unseen testing set.
Decision Tree	The training set yielded a better R^2 value of 0.83 than the validation set value of 0.78; thus, the optimal hyperparameter values for the training set were used on the unseen testing set.

The conclusions in **Table 6** were followed to obtain model testing results for both regression models, which are displayed in **Table 7**.

Table 7: Testing set results for Machine 3

Random Forest Model (Testing Set)	
Optimal hyperparameter values (Training set)	**Testing set results**
n_estimators = 150 max_depth = 5 min_samples_split = 2 min_samples_leaf = 2	MSE = 427.05 MAE = 16.88 R^2 = 0.71
Decision Tree Model (Testing Set)	
Optimal hyperparameter values (Training set)	**Testing set results**
max_depth = 10	MSE = 223.61

min_samples_split = 2 min_samples_leaf = 2	MAE = 12.11 R^2 = 0.85

Table 7 illustrates that the decision tree model provided a better MSE, MAE, and R^2 value than the random forest model. The decision tree model was used to make future predictions regarding the unplanned downtime Machine 3 experienced. In the following subsection, the same process was repeated for Machine 4.

3.2 Future predictions

3.2.1 Machine 1

This section illustrates and discusses the future predictions for Machine 1.

Future predictions were made from the last recorded data entry (in the pre-processed Machine 1 dataset) up until one year into the future. **Figure 3** illustrates the future predictions obtained for Machine 1 using the best random forest model.

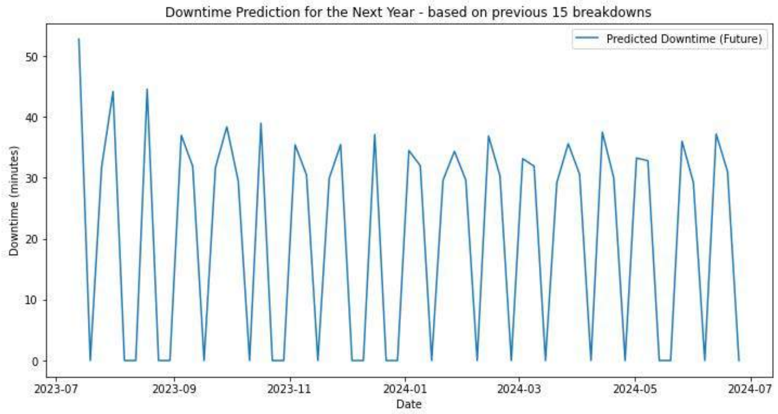


Figure 3: Future Predictions for Machine 1

The actual historical pre-processed dataset of Machine 1 was used to calculate the average amount of days between two consecutive breakdowns, which yielded approximately 12 days. A Future Dates data frame was created, storing the future dates for which predictions were made. It was selected that predictions should be made for every sixth day (in six-day intervals) based on half of the average interval between two consecutive breakdowns (12 days). The best random forest model was used to make downtime predictions for these specific days in the Future Dates data frame. A prediction threshold was created to filter out predictions that were considered insignificant. A prediction threshold of 75% of the mean for the downtime column was selected. Any predicted downtime value below this threshold value was considered insignificant and was recorded as 0 predicted downtime. The prediction results displayed in **Figure 3** are an output of the dates for which the model predicts a significant downtime event will occur and the corresponding predicted downtime duration for this event.

3.2.2 Machine 2

This section illustrates and discusses the future predictions for Machine 2.

Future predictions were made from the last recorded data entry (in the pre-processed Machine 2 dataset) up until one year into the future. **Figure 4** illustrates the future predictions obtained for the Labeller machine using the best decision tree model.

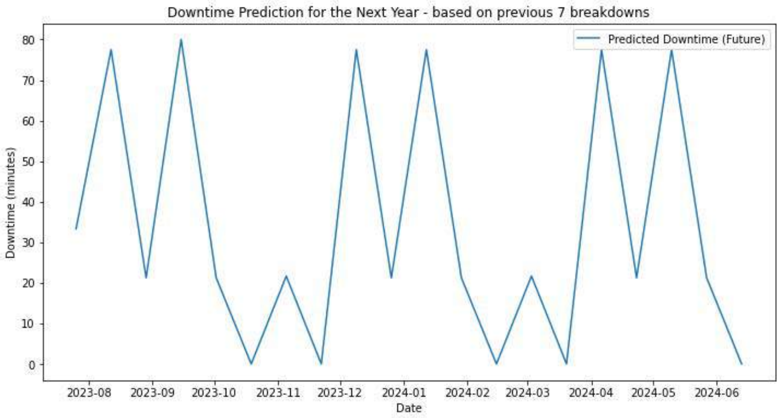


Figure 4: Future Predictions for Machine 2

The actual historical pre-processed dataset of Machine 2 was used to calculate the average amount of days between two consecutive breakdowns, which yielded approximately 34 days. A Future Dates data frame was created, storing the future dates for which predictions were made. It was selected that predictions should be made for every 17th day (in 17-day intervals) based on half of the average interval between two consecutive breakdowns (34 days). The best decision tree model was used to make downtime predictions for these specific days in the Future Dates data frame. A prediction threshold was created to filter out predictions that were considered insignificant. A prediction threshold of 50% of the mean for the downtime column was selected. Any predicted downtime value below this threshold value was considered insignificant and was recorded as 0 predicted downtime. The prediction results displayed in **Figure 4** are the output of the dates for which the model predicts a significant downtime event will occur and the corresponding predicted downtime duration for this event.

3.2.3 Machine 3

This section illustrates and discusses the future predictions for Machine 3.

Future predictions were made from the last recorded data entry (in the pre-processed Machine 3 dataset) up until one year into the future. **Figure 5** illustrates the future predictions obtained for the BEV Capper machine using the best decision tree model.

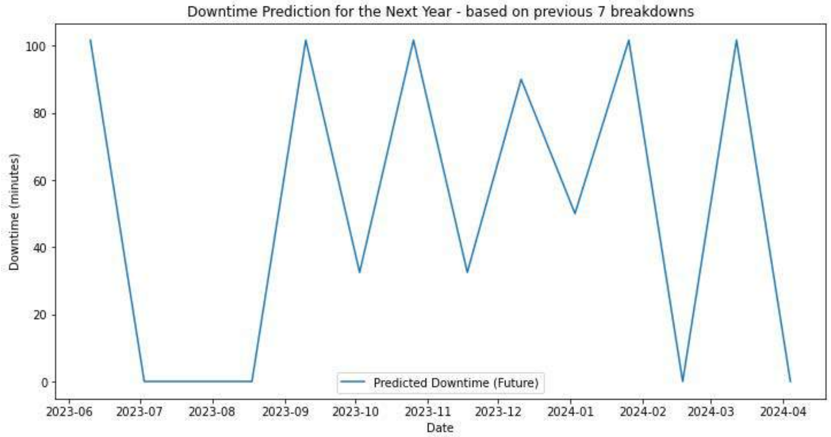


Figure 5: Future Predictions for Machine 3

The actual historical pre-processed dataset of Machine 3 was used to calculate the average amount of days between two consecutive breakdowns, which yielded approximately 46 days. A Future Dates data frame was created, storing the future dates for which predictions were made. It was selected that predictions should be made for every 23rd day (in 23-day intervals) based on half of the average interval between two consecutive breakdowns (46 days). The best decision tree model was used to make downtime predictions for these specific days in the Future Dates data frame. A prediction threshold was created to filter out predictions that were considered insignificant. A prediction threshold of 75% of the mean for the downtime column was selected. Any predicted downtime value below this threshold value was considered insignificant and was recorded as 0 predicted downtime. The prediction results in **Figure 5** are the output of the dates for which the model predicts a significant downtime event will occur and the corresponding predicted downtime duration for this event. The same process will be repeated for the Graham Sleever machine in the next section. Predictive maintenance strategy plan

The predictive maintenance strategy plan is a set of actions and guidelines that leverage the predictive models developed for the retail line machines. The following predictive maintenance strategy plan was developed for the retail line machines by utilising the model predictions:

3.2.4 Machine 1 (6-day interval predictions):

- ✓ High-priority machine for maintenance
- ✓ Four days before a predicted downtime event: Perform a thorough visual inspection and condition-based assessment on Machine 1. Identify any possible warning signs or abnormalities regarding the machine's performance [12].
- ✓ Three days before the predicted downtime event, based on the inspection findings, Ensure the required spare parts are available for repair/maintenance [13].
- ✓ Two days before the predicted downtime event: Perform the required maintenance on the machine based on the findings obtained from the inspection/assessment. If no warning signs or abnormalities were identified during the inspection, essential routine maintenance should be performed [14].

3.2.5 Machine 2 (17-day interval predictions):

- ✓ Five days before a predicted downtime event: Perform a thorough visual inspection and condition-based assessment on the Machine 2. Identify any possible warning signs or abnormalities regarding the machine's performance [12].
- ✓ Four days before the predicted downtime event, based on the inspection findings, Ensure the required spare parts are available for repair/maintenance [13].
- ✓ Two days before the predicted downtime event: Perform the required maintenance on the machine based on the findings obtained from the inspection/assessment. Basic routine maintenance should be performed if no warning signs or abnormalities were identified during the inspection [14].

3.2.6 Machine 3 (23-day interval predictions):

- ✓ Five days before a predicted downtime event: Perform a thorough visual inspection and condition-based assessment on the Machine 3. Identify any possible warning signs or abnormalities regarding the machine's performance [12].
- ✓ Four days before the predicted downtime event, based on the inspection findings, Ensure the required spare parts are available for repair/maintenance [13].
- ✓ Two days before the predicted downtime event: Perform the required maintenance on the machine based on the findings obtained from the inspection/assessment. Basic routine maintenance should be performed if no warning signs or abnormalities were identified during the inspection [14]. Implementing this predictive maintenance strategy plan by utilising the predictions made by the machine learning models can yield the following benefits for company X:

- **Reduced unplanned machine downtime:** Proactively addressing potential machine-related issues before they lead to unplanned machine downtime will increase the production rate obtained by the retail production line [15].
- **Efficient resource allocation:** Utilising the predictions can ensure that resources such as spare parts and labour are allocated efficiently, thus reducing operational expenses [16].
- **Preventive maintenance schedule:** Focusing on the specific dates for which the model indicates a higher risk for unplanned machine downtime can further reduce operational expenses and disruptions [16].
- **Threshold-based alerts** Can reduce unplanned machine downtime and production losses [17].
- **Optimised budget allocation:** Machine predictions can improve financial planning and allocation of funds for maintenance-related tasks [18].
- **Improved overall equipment efficiency (OEE):** Implementing the maintenance strategy plan for the retail line machines can improve the OEE, which indicates better equipment utilisation, reduced waste, and an increased production rate [19].
- **Customer satisfaction:** Reducing the unplanned machine downtimes experienced by the retail line machines will improve the production rate, and consequently, customer demand can be more easily satisfied [20].

4 CONCLUSIONS AND FUTURE RECOMMENDATIONS

Machine learning models were developed using historical unplanned machine downtime. The developed models were verified and validated. Future predictions for each retail line machine were delivered and used to develop a predictive maintenance strategy plan. Implementing the predictive maintenance strategy plan will enable Company X to make proactive decisions regarding maintenance. Possible benefits regarding this implementation include reduced unplanned machine downtime, improved production rate, efficient resource allocation, optimised maintenance budget allocation, and an improved OEE [16]. The project only utilises the random forest and the decision tree machine learning model. Other machine learning techniques can also be used to develop a predictive model. The machine learning models in this study were developed using only two columns. Additional feature columns can be implemented to improve the predictive power of the models possibly.

It is important to note that developing machine learning models is a continuous process that requires constant updates and modifications as new data is obtained. Continuously monitoring the model's performance and accuracy to make informed modifications is crucial to the benefits the model will provide the company.

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6 APPENDIX A

6.1 Machine 1

Table 8: Training - and validation set results for Machine 1

Random Forest Model				
Hyperparameter Grid (Automatic grid search)	**Optimal hyperparameter values (Training set)**	**Optimal hyperparameter values (Validation set)**	**Training Results (Performance metrics)**	**Validation Results (Performance metrics)**
n_estimators: [50, 100, 150] max_depth: [None, 5, 10] min_samples_split: [2, 5] min_samples_leaf: [1, 2]	n_estimators = 150 max_depth = None min_samples_split = 5 min_samples_leaf = 2	n_estimators = 50 max_depth = 10 min_samples_split = 5 min_samples_leaf = 2	MSE = 185.42 MAE = 10.55 R^2 = 0.77	MSE = 142.39 MAE = 8.67 R^2 = 0.73
Decision Tree Model				
Hyperparameter Grid	**Optimal hyperparameter values (Training set)**	**Optimal hyperparameter values (Validation set)**	**Training Results (Performance metrics)**	**Validation Results (Performance metrics)**
max_depth: [None, 5, 10, 20] min_samples_split: [2, 5, 10] min_samples_leaf: [1, 2, 4]	max_depth = 5 min_samples_split = 5 min_samples_leaf = 2	max_depth = 5 min_samples_split = 10 min_samples_leaf = 4	MSE = 362.75 MAE = 14.75 R^2 = 0.56	MSE = 384.20 MAE = 13.88 R^2 = 0.33

6.2 Machine 2

Table 9: Training - and validation set results for Machine 2

Random Forest Model				
Hyperparameter Grid (Automatic grid search)	**Optimal hyperparameter values (Training set)**	**Optimal hyperparameter values (Validation set)**	**Training Results (Performance metrics)**	**Validation Results (Performance metrics)**
n_estimators: [50, 100, 150] max_depth: [None, 5, 10] min_samples_split: [2, 5] min_samples_leaf: [1, 2]	n_estimators = 50 max_depth = None min_samples_split = 5 min_samples_leaf = 2	n_estimators = 50 max_depth = None min_samples_split = 2 min_samples_leaf = 2	MSE = 182.89 MAE = 9.94 R^2 = 0.71	MSE = 208.41 MAE = 10.40 R^2 = 0.69
Decision Tree Model				
Hyperparameter Grid	**Optimal hyperparameter values (Training set)**	**Optimal hyperparameter values (Validation set)**	**Training Results (Performance metrics)**	**Validation Results (Performance metrics)**
max_depth: [None, 5, 10] min_samples_split: [2, 5] min_samples_leaf: [1, 2]	max_depth = 5 min_samples_split = 2 min_samples_leaf = 1	max_depth = None min_samples_split = 5 min_samples_leaf = 2	MSE = 128.42 MAE = 7.73 R^2 = 0.80	MSE = 69.54 MAE = 6.26 R^2 = 0.91

6.3 Machine 3

Table 10: Training - and validation set results for Machine 3

Random Forest Model				
Hyperparameter Grid (Automatic grid search)	**Optimal hyperparameter values (Training set)**	**Optimal hyperparameter values (Validation set)**	**Training Results (Performance metrics)**	**Validation Results (Performance metrics)**
n_estimators: [50, 100, 150] max_depth: [None, 5, 10] min_samples_split: [2, 5] min_samples_leaf: [1, 2]	n_estimators = 150 max_depth = 5 min_samples_split = 2 min_samples_leaf = 2	n_estimators = 100 max_depth = 10 min_samples_split = 5 min_samples_leaf = 2	MSE = 265.08 MAE = 12.20 R^2 = 0.72	MSE = 216.28 MAE = 9.45 R^2 = 0.52
Decision Tree Model				
Hyperparameter Grid	**Optimal hyperparameter values (Training set)**	**Optimal hyperparameter values (Validation set)**	**Training Results (Performance metrics)**	**Validation Results (Performance metrics)**
max_depth: [None, 5, 10] min_samples_split: [2, 5] min_samples_leaf: [1, 2]	max_depth = 10 min_samples_split = 2 min_samples_leaf = 2	max_depth = 5 min_samples_split = 2 min_samples_leaf = 2	MSE = 151.52 MAE = 7.36 R^2 = 0.83	MSE = 99.77 MAE = 6 R^2 = 0.78

UTILISING DATABASE MANAGEMENT SYSTEMS AND STATISTICAL PROCESS CONTROL TO ELEVATE QUALITY ASSURANCE FOR AGRICULTURAL PERISHABLES

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ABSTRACT

Inefficiencies within agricultural packhouse operations undermine both quality assurance and profitability. However, to address the inefficiencies, the following industrial engineering tools are developed in this study: a decision support system (DSS) that leverages the power of database management systems (DBMS) and statistical process control (SPC). This industry-wide solution transcends the limitations of isolated data and reactive quality control. The DSS captures real-time operational data by seamlessly integrating a robust DBMS with Excel and Power BI, identifying previously hidden insights. Advanced SPC algorithms analyse this data, providing insight into dimensions of defect patterns and process variability. This study contributes towards literature and the entire agricultural industry by following a data-driven revolution in quality assurance. The proposed framework offers a blueprint for potential integration across diverse operations, fostering a paradigm shift towards proactive, data-driven quality control.

Keywords: citrus packhouse operations, decision support system, quality inefficiencies, operational inefficiencies, defect identification

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1 INTRODUCTION: BACKGROUND AND INTRODUCTION

The Citrus Agriculture and Processing Industry in South Africa has experienced significant expansion over the past decade. 2010, the industry covered 56,338 hectares, growing to 86,808 hectares by 2019 [1]. One of the main factors contributing to this growth is the export of fresh citrus fruit, which has contributed significantly to the industry's increasing revenue. Packhouses are a crucial section of the citrus industry as they are responsible for arranging, grading, and packaging the fruit according to market requirements. The demand for fresh citrus fruit remains high worldwide throughout the year, which demands a continuous supply of high-quality produce [2]. Given the industry's growth and the critical role of packhouses, it becomes a priority to improve operational efficiency and quality control procedures continuously. Addressing the challenges faced by packhouse operations and quality inefficiency will contribute to the industry's continued growth and enhance the quality of South African citrus as a premium product in the global market.

Company-X, which will be used as a case study, is a leading citrus exporter in the country and operates three packhouses that sort, grade, and pack citrus fruits for export to international markets. The citrus production and packing company were established over one hundred years ago. Production primarily focuses on the high-value export market. It concentrates on a diverse citrus basket that includes seeded and seedless lemons, Valencia types such as Turkeys, Midnight, Delta, and late Valencia variations, as well as other citrus kinds [3].

A citrus packhouse's purpose is to maintain the quality of the fruit received from the orchards while preparing it for export. This involves cleaning the fruit, treating it to prevent the development of postharvest diseases, enhancing its appearance and shelf-life, sorting it into size and class categories, and packaging it according to market requirements [4]. The packhouse is a crucial component of the citrus industry, where various operations are conducted to ensure the quality and efficient packaging of the fruit.

These operations involve various tasks, starting with fruit sorting, where trained personnel carefully examine each fruit and separate them based on their characteristics, such as size, colour, and appearance. Following sorting, the fruit goes through a grading process, where it is categorised based on specific quality standards, such as external appearance, blemishes, and internal attributes. After grading, the fruit is prepared for packing, where it is carefully placed into boxes, considering factors like weight distribution, packaging materials, and labelling requirements. During these operations, quality procedures ensure that only the highest quality fruit is selected for packaging. This involves conducting quality checks and adhering to strict standards to meet export market requirements.

The company aims to produce as many classes 1 and 2 fruits as possible for the export market. The highest drop from the potential output to the actual production documented in the season was more than 37%, and a significant loss in export output potential. These daily losses of the potential production are due to uncalculated and unforeseen defects only discovered after the fruit has been tipped in the packhouse. **Figure 1** shows the potential loss in daily output due to packhouse operational and quality inefficiencies.

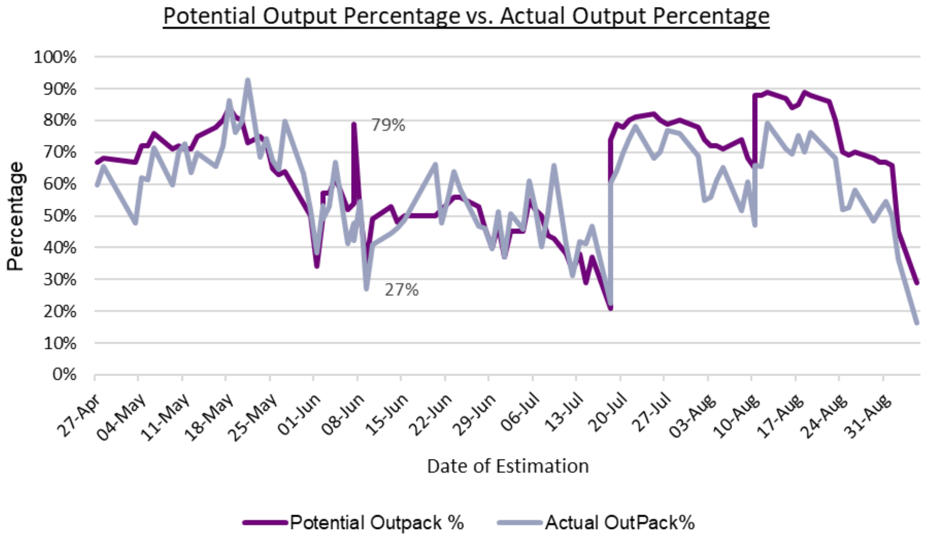


Figure 1: The loss in daily output potential due to packhouse operational and quality inefficiencies.

The decrease in potential pack-out for Company-X is due to the following identified inefficiencies: Insufficient Fruit Quality, Suboptimal Resource Allocation, Suboptimal Packing Pattern, and Time to Identify Issues. Based on the background, the packhouse operations are experiencing operational and quality inefficiencies, posing significant challenges to overall performance and final product quality.

This study aims to address the operational and quality inefficiencies in the citrus packhouse by developing a DSS. The project scope includes the citrus packhouse operations and quality procedures, particularly those involving human decision-making. These include preparation of daily operations, fruit sorting, grading, packing, quality checks, and addressing identified quality defects.

A systematic literature review (SLR) conducted by Van Der Merwe et al. [5], which is the first part of this study, includes a comprehensive and systematic search of existing scholarly literature on a specific topic to provide an overview of the current state of knowledge, identify research gaps, and inform the development of research questions and objectives. The SLR investigated existing research and identified gaps in agricultural quality procedures within citrus packhouses. Focusing on four research questions, the review analysed 33 relevant studies from databases such as Science Direct, Scopus, Web of Science, EBSCO Host, and Emerald Insight. These studies covered various aspects of packhouse operations, including data analytics, industry 4.0, lean management, and quality control. The findings demonstrated diverse quality procedures, systems, and technologies in packhouse operations. The review provides valuable insights into the current state of research, emphasising the significance of data analytics, industry 4.0, lean management, and quality control in optimising packhouse operations for citrus production. Future research in this field should explore integrating these approaches and technologies to develop comprehensive and efficient quality procedures within packhouse operations. It would be beneficial to investigate these approaches' effectiveness and practical implementation challenges, supporting industry practitioners and researchers. In conclusion, the SLR identified a range of quality procedures, systems, and technologies used in citrus packhouses. This knowledge can guide future research and facilitate continuous improvements in quality procedures within agricultural packhouses.

The paper is outlined as follows. The research method is explained in Section 2. A current state and a root cause analysis are conducted in Section 3, followed by a concept design in Section 4. The development of the system is demonstrated in Section 5, followed by the verification and validation in Section 6. Conclusions and future recommendations are provided in Section 7.

2 RESEARCH METHOD

For the project approach, the waterfall methodology was utilised. A waterfall methodology is a project approach where all requirements are gathered at the beginning of the project, and then a sequential project plan is created to accommodate those requirements [6]. The outline of this method is demonstrated in **Figure 2.**

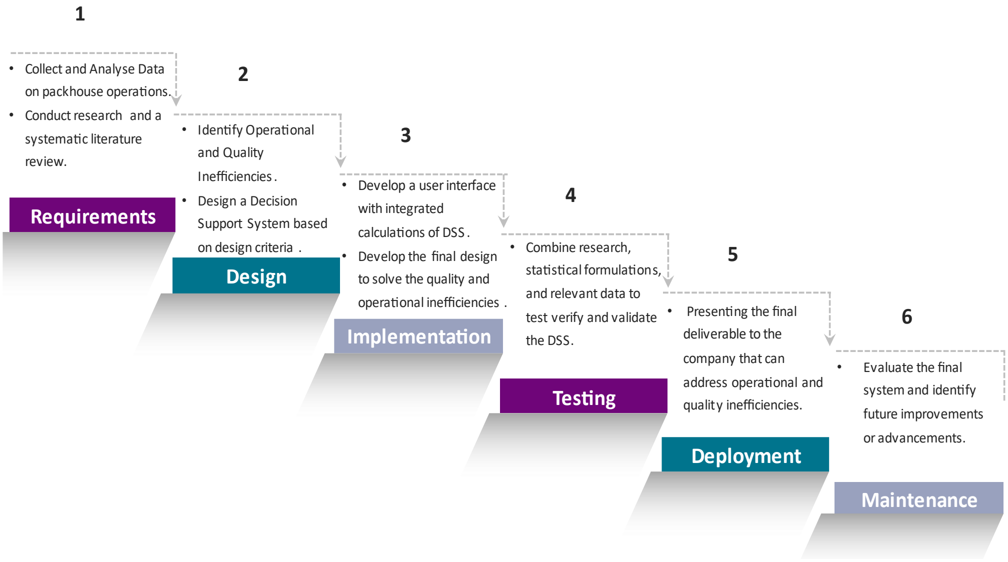


Figure 2: The Waterfall Methodology Project Approach Followed

Figure 2 illustrates the Waterfall Methodology; each stage is designed to ensure a systematic and structured progression toward the successful completion of the project. These stages include:

1. **Requirements:** Case studies and a SLR referred to in Section 1 are conducted to enhance the research process further.
2. **Design:** Once the operational and quality inefficiencies have been identified, the project will develop accurate and data-driven solutions.
3. **Implementation:** After the system's conceptual design is developed in Section 4, the project is evaluated, and the most suitable alternative based on predetermined decision criteria is chosen.
4. **Testing:** The research findings, calculations, and relevant data are integrated and implemented to conduct solution verification in the system.
5. **Deployment:** The verification and validation are completed, and the final design is presented and validated in Section 6.
6. **Maintenance:** The project does not conclude with the design of the deliverable. A thorough evaluation will be conducted to assess the effectiveness and performance of the system in Section 6. Additionally, any potential areas for improvement and future recommendations will be identified and addressed.

3 THE CURRENT STATE AND ROOT CAUSE ANALYSIS

3.1 Current state analysis

The current state analysis provides valuable insights into the existing processes and quality procedures, allowing the identification of inefficiencies in the packhouse's operations and quality procedures. **Figure 3** illustrates the defects influencing the reduction in fruit quality received by the packhouse from the orchards [3].

Entomological defects:	Climatological defects:	Plant disease defects:	Physiological defects:	Defects due to insufficient Picking discipline:
•Red Scale •Bladder early •Bladder Leave •Bollworm •Surveyor •Tortrix •Mealybug •Mealybug present •Page Jumper •VKM/Carob Moth •Mites	•Hail •Sunburn •Wind	•Black Spot •Melanosis •Alternaria •Greening •Sooty mold •Spoiled	•Cracked Shell •Oleo •Cracked Fruit •Malformed fruit •Cracked Peel •Chemical burn •Off Season •Color	•Tear out stalks •Long stems •Picking injuries

Figure 3: Categories of defects influencing the decrease in fruit quality.

The defects are classified into several categories. By identifying these specific defect categories, the packhouse managers can focus on addressing each defective category and enhancing overall fruit quality. The packing time throughout the day is demonstrated in **Figure 4**. The data in **Figure 4** is calculated from extensive time and motion studies.

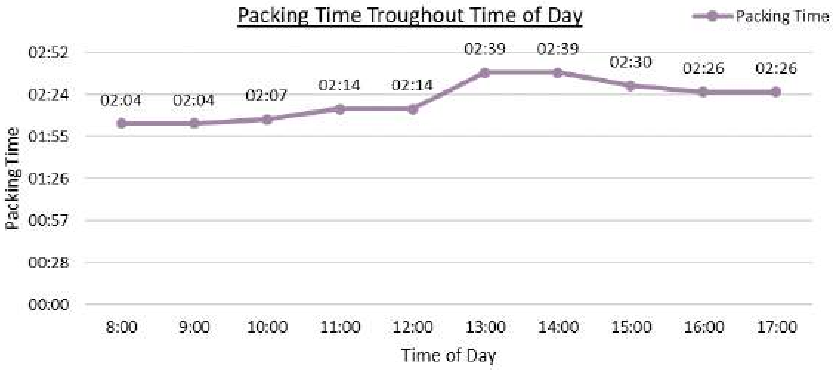


Figure 4 shows that the maximum average cartons packed by one packer with the current average speed is twenty-three cartons per hour.

3.2 Root cause analysis

In this section, a comprehensive analysis of the citrus packhouse operations and quality procedures is conducted to address the root cause of the operational and quality inefficiencies. Various industrial engineering tools, including time and motion studies, the Ishikawa Diagram, and the 5-Why analysis, are utilised to achieve this analysis successfully.

The 5-Why analysis from Section 3.1 enables a systematic approach to identify the root cause of the operational and quality inefficiencies. By repeatedly asking "why" and delving deeper into the underlying factors contributing to each problem, insights are gained into the fundamental causes of inefficiencies. The results are demonstrated in **Figure 5**.

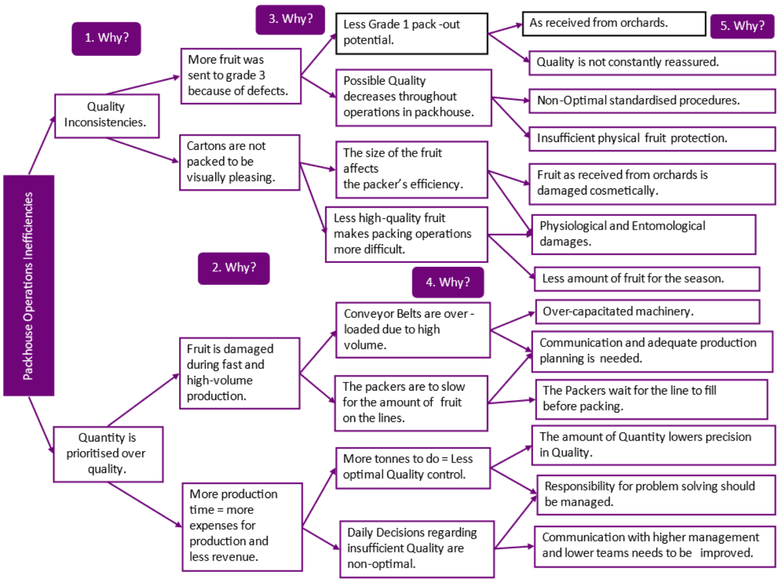


Figure 5: 5-Why Analysis of Company-X

The root cause analysis suggests a need for a systematic approach to identifying and addressing defects in the packhouse. This absence of a structured problem-solving process contributes to difficulties in identifying defects as they occur, leading to delayed defect resolution. Additionally, there appears to be a lack of data-driven decision-making, postponing the ability to make informed decisions based on real-time data. The Ishikawa diagram in **Figure 6** provides a structured way to identify and display potential causes of a specific problem or effect.

Figure 6: Ishikawa Diagram of Company-X

Figure 6 is utilised to understand various sections of the company and what their influences may be on the quality procedures as well as their influences on packhouse operations. Analysing the Ishikawa diagram, 5-Why Analysis, and the information gained during a Gemba walk and comprehensive time and motion studies, the identified root cause highlights the absence of data-driven decision-making and a systematic approach within the quality control procedures and packhouse operations. This implies that the packhouse's management lacks access to real-time data and comprehensive insights, leading to suboptimal decision-making regarding quality procedures and operational inefficiencies. Furthermore, the identified root cause highlights the absence of data-driven decision-making and a systematic approach within the quality control procedures and packhouse operations.

4 CONCEPT DESIGN

4.1 Conceptual Requirements and Decision Criteria

The following design requirements are essential to determine the DSS's conceptual design. These include but are not limited to budget limitation, simplified implementation, user-friendly interface, resource efficiency, and readiness. **Table 1** presents the decision criteria derived from the conceptual design requirements. The priority of these criteria is also determined to ensure that those with the highest importance have the most significant influence on the software selection for DSS design.

Table 1: Decision Criteria and Prioritisation

Decision Criteria	Priority	Description
User Familiarity	High	The software should be recognisable to the users at Company-X to minimise the learning curve and ensure quick adoption of the DSS.
Decision-Making Capabilities	Medium	The software should have advanced decision-making capabilities, including optimisation algorithms and analytical tools, to enhance packhouse operations.
Data Handling Capabilities	Low	The software should be capable of handling and processing large volumes of data generated during daily operations, ensuring efficient data management and analysis.
Cost-Effectiveness	High	Cost-effectiveness is crucial, and the software should have minimal to no additional costs to adhere to the budget limitations.

The seamless integration with Power BI enhances data visualisations, enabling management to gain comprehensive insights. Excel and VBA programming, accompanied by Power BI, offers a cost-effective, user-friendly, and efficient solution for Company-X's DSS needs.

The research done by Van Der Merwe et al. [5] provided valuable insights into various quality procedure concepts suitable for developing and designing Company-X's DSS. Based on the findings and considering the specific requirements of Company-X, implementing two concepts is recommended to establish the company's systematic and data-driven approach towards quality control.

4.2 Design Requirements

The design requirements for Company-X's DSS must be developed to provide a comprehensive design for the final solution. The input, output, and user interface requirements are developed to ensure seamless integration and functionality with the system's chosen software. This approach embraces Microsoft Excel [7], presenting a solution that corresponds well with the company's design requirements.

4.2.1 Input Data Requirements

The DSS will be used through daily manual input of quality and operational parameters to aid decision-makers in making informed decisions based on comprehensive insights. The DSS receives manual input data through its user interface, encompassing qualitative and quantitative attributes, as shown in **Table 2**.

Table 2: Quantitative and Qualitative Input Data Attributes

Data Category	Quantitative Attributes	Qualitative Attributes
Operational Data:	Tonnes Tipped for the day and Available Production Hours	Packhouse ID
Quality Data:	Quality Check Type and Fruit Type	Identified Deficiencies and Quality clerk ID
Packaging Data:	Count Type, Desired Weight and the Average Weight of Fruit for Specific Size	Fruit Type
SPC Data:	Tonnes Tipped and Confidence Interval	Fruit Type
Report Generation Data:	Email of Quality Report Receiver	

4.2.2 User Interface Requirements

The user interface of the DSS for Company-X's packhouse operations is a critical aspect of its effectiveness and usability. The user interface should be user-friendly and visually insightful, facilitating seamless interaction between the user and the DSS.

The User Interface consists of the following aspects:

1. **Input Section:** This section allows users to input data manually. Users should be able to update and modify the input data as needed quickly. The system's technical design will include Macros and Buttons for user input possibilities.
2. **Scenario Selection:** The users can choose specific scenarios based on changed input data, such as defects, production volumes, or changes in fruit types.
3. **Optimisation Settings:** Users can customise optimisation settings, such as labour allocation and quality confidence intervals, to align the system with Company-X's operational requirements.
4. **PowerBi Visualisation Tools:** Interactive charts, graphs, and dashboards enable users to visualise the impact of different decisions on packhouse operations, aiding in better decision-making.

The following Excel sheets, as seen in **Figure 7**, which include Macros, Buttons and User Form Generations, are applicable to the DSS design.

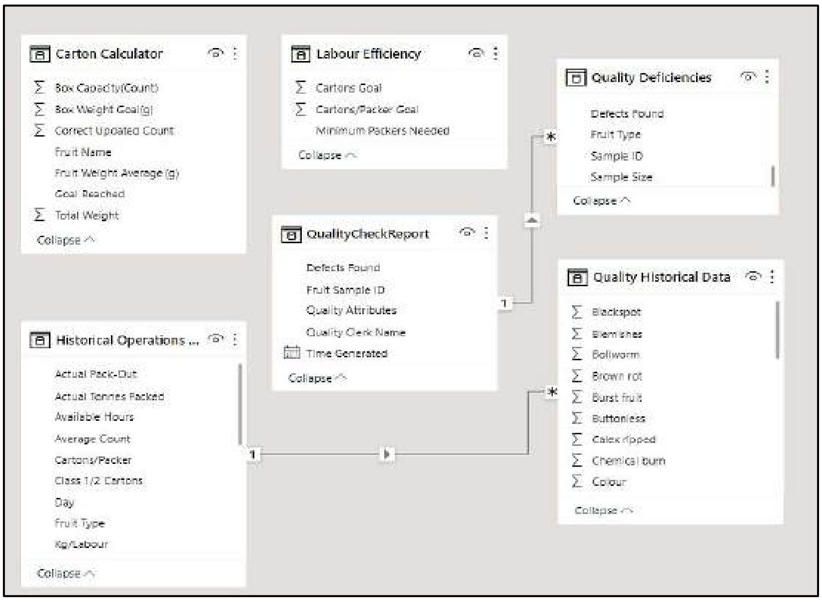


Figure 7: Data Layout of Excel Sheets

The user interface provides a clear and comprehensive overview of defect mitigation possibilities by utilising calculations created through Visual Basic Programming and interactive dashboards created in Power BI [8]. This enables decision-makers to quickly grasp the current state of operations and identify operational or quality inefficiencies that require immediate addressing. With intuitive visuals, real-time data updates, and real-time communication, the User Interface becomes a value-adding aspect, facilitating informed decision-making.

4.2.2.1 Macro Formulations

A vital aspect of the system is ensured by formulating calculations within the macros, all of which are established in predetermined data or manual inputs.

- **Resource Utilisation:** determines the minimum number of packers needed to achieve a daily packing goal, improving the utilisation of resources and providing a cost-saving solution through reduced labour costs. The suggested number of cartons a packer should be able to pack per hour is 23.
- **Sample Size Calculation:** determines the optimal sample size according to the amount of tonnage tipped in the packhouse and a Confidence Interval as selected by the packhouse managers.

A Statistical Quality Control formula determines the sample size to achieve a specific confidence level and margin of error while considering the available tonnes tipped [9]. By incorporating these calculations within the DSS, the system transforms manual input data into actionable insights, aiding decision-makers in enhancing packhouse operations and quality procedures.

4.2.3 Output Data Requirements

The deliverable's output data should be designed to be comprehensive and assist as a valuable aid to decision-makers at Company-X in their efforts to enhance the efficiency of packhouse operations and quality control procedures. Ensuring the robustness of the output data is essential, as it directly influences the credibility and reliability of the decision-making process. The output data includes the following aspects:

- **Quality Control**: The system can monitor real-time quality parameters during packing using computer vision systems and sensors. If any deviations from the quality standards are detected, the DSS will provide real-time alerts to the decision-maker.

- **Quality Insights**: The DSS can analyse past quality data and identify insights on fruit quality. It will provide insights to the decision-maker on how to take preventive actions and start mitigation strategies.
- **Performance Evaluation**: The DSS can measure the performance of each packhouse based on key performance indicators such as throughput, defect rates, and resource utilisation.
- **Quality Check Reports**: Automatically generated reports that can be emailed to relevant stakeholders, providing comprehensive real-time insights into daily operations, deficiencies, and quality performance. These reports provide detailed information about the defects identified at the quality checks.
- **Packout Potential Analysis**: Comparative analysis is provided of the potential pack out versus the actual pack out, highlighting the efficiency of the packhouse operations.
- **Optimal Quality Checks Sample Size**: Recommendations for the appropriate sample size based on the tonnage tipped and specified confidence level.
- **Data Export**: Formatted data that can be easily exported to external formats for further analysis and decision-making.

The DSS will be able to be a real-time decision-making tool, providing timely and data-driven decision-making possibilities to enhance packhouse operations and quality control procedures. The output data generated by the DSS demonstrates a robust and effective solution to address the identified root cause in **Section 3.**

4.3 Data Preparation and Analysis

Data preparation is a fundamental process that involves collecting, cleaning, and organising data from various sources to ensure its suitability for analysis and decision-making [10]. The aim is to gain valuable insights from the data that will provide an effective solution for the packhouse's operational and quality inefficiencies.

4.3.1 Historic Data Preparation

Figure 8 includes the steps followed for the historic data preparation approach.

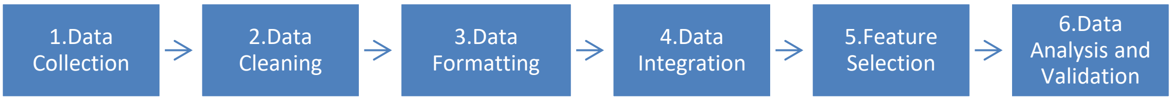


Figure 8: Data Preparation Process

The DSS consists of comprehensive and reliable data to support data-driven decision-making and improve packhouse operations and quality procedures by following this approach.

4.3.2 Input Data Validation

The input data will undergo thorough validation checks to identify potential errors or inconsistencies. If any discrepancies are detected, the system immediately generates error notifications, prompting users to correct the issues before proceeding.

To further enhance data accuracy, the User-friendly interface guides users through the data entry process, providing clear instructions and prompts. Dropdown menus, predefined options, and input constraints are employed to restrict the entry of incorrect or inappropriate data. This design approach streamlines the input process and reduces the risk of human errors.

5 THE DECISION SUPPORT SYSTEM DEVELOPMENT

5.1 Introduction to Final Design

The following section outlines the updated operations and quality procedures that the DSS will follow. **Figure 9** illustrates the Business Process Mapping Notation of the DSS's use by the users, namely packhouse management and quality controllers. This ensures a seamless integration of existing processes within the DSS [11].

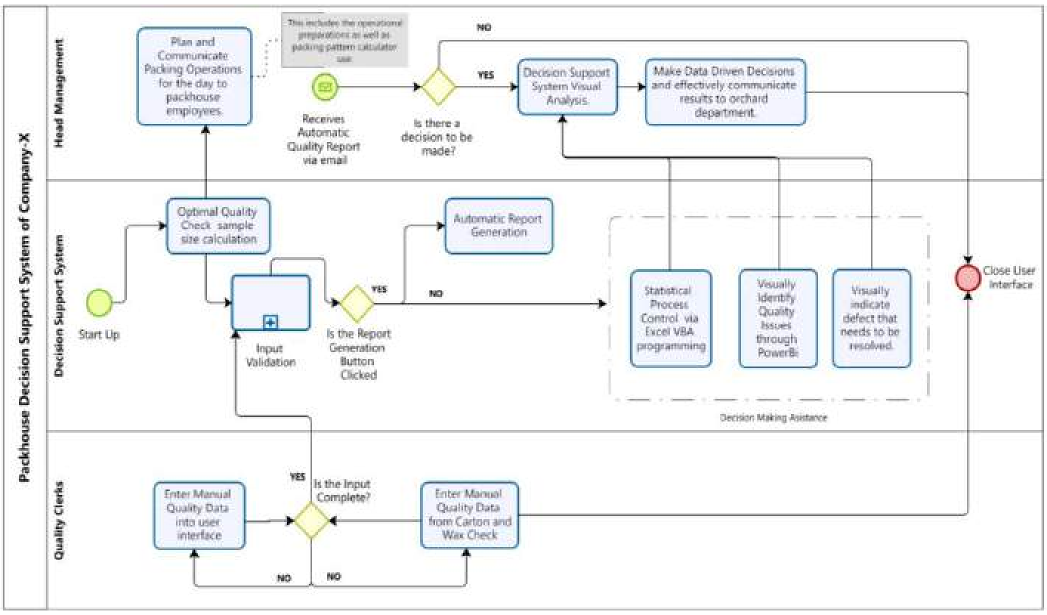
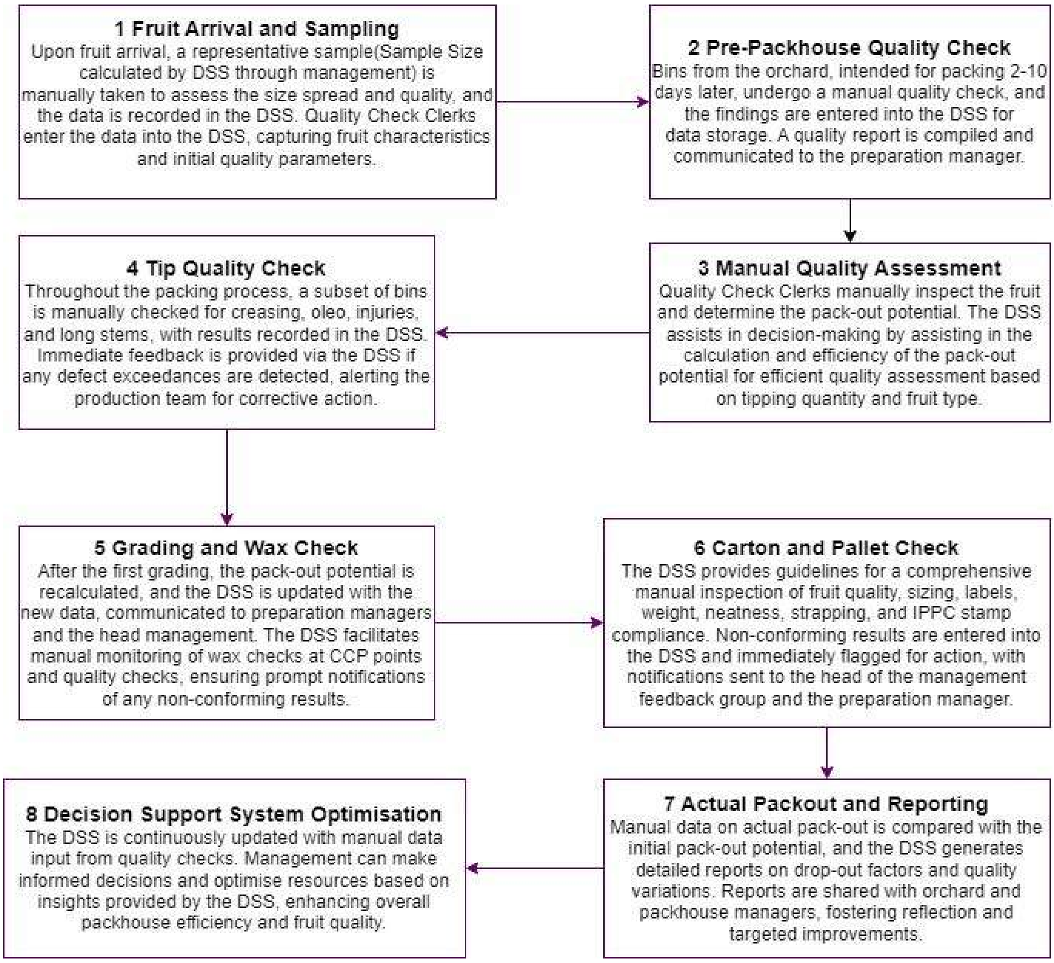


Figure 9: Business Process Mapping Notation of the added DSS.

Figure 10 illustrates the improved packhouse quality process flow with the added DSS.



1 Fruit Arrival and Sampling
Upon fruit arrival, a representative sample(Sample Size calculated by DSS through management) is manually taken to assess the size spread and quality, and the data is recorded in the DSS. Quality Check Clerks enter the data into the DSS, capturing fruit characteristics and initial quality parameters.

2 Pre-Packhouse Quality Check
Bins from the orchard, intended for packing 2-10 days later, undergo a manual quality check, and the findings are entered into the DSS for data storage. A quality report is compiled and communicated to the preparation manager.

3 Manual Quality Assessment
Quality Check Clerks manually inspect the fruit and determine the pack-out potential. The DSS assists in decision-making by assisting in the calculation and efficiency of the pack-out potential for efficient quality assessment based on tipping quantity and fruit type.

4 Tip Quality Check
Throughout the packing process, a subset of bins is manually checked for creasing, oleo, injuries, and long stems, with results recorded in the DSS. Immediate feedback is provided via the DSS if any defect exceedances are detected, alerting the production team for corrective action.

5 Grading and Wax Check
After the first grading, the pack-out potential is recalculated, and the DSS is updated with the new data, communicated to preparation managers and the head management. The DSS facilitates manual monitoring of wax checks at CCP points and quality checks, ensuring prompt notifications of any non-conforming results.

6 Carton and Pallet Check
The DSS provides guidelines for a comprehensive manual inspection of fruit quality, sizing, labels, weight, neatness, strapping, and IPPC stamp compliance. Non-conforming results are entered into the DSS and immediately flagged for action, with notifications sent to the head of the management feedback group and the preparation manager.

7 Actual Packout and Reporting
Manual data on actual pack-out is compared with the initial pack-out potential, and the DSS generates detailed reports on drop-out factors and quality variations. Reports are shared with orchard and packhouse managers, fostering reflection and targeted improvements.

8 Decision Support System Optimisation
The DSS is continuously updated with manual data input from quality checks. Management can make informed decisions and optimise resources based on insights provided by the DSS, enhancing overall packhouse efficiency and fruit quality.

Figure 10: Improved Packhouse Quality Control Process flow with the added DSS

Appendix A demonstrates the final design interphase of the DSS.

6 SYSTEM VERIFICATION AND VALIDATION

6.1 Verification of system design

The system design has been verified by evaluating it against the decision criteria and design requirements established in Section 4. The verification process forms part of the testing phase of the Waterfall Methodology project approach. This verification is confirmed in **Table 3**.

Table 3: Verification of Solution's adherence to design requirements.

Design Requirements.	Question to determine if the system adheres to the specified design requirements.	Explanation of Adherence.
The system should adhere to the budget limitations.	Does the system require additional costs for the company?	No. Leveraging Excel and Visual Basic Programming entails no additional costs for the company, as existing licenses fully support system utilisation.
The system should enable	Is the system complex enough to implement	The system is not complex to implement within the current operations and quality

simplified implementation.	within the current Packhouse Operations and Quality Procedures?	procedures. Including a user manual simplifies the implementation while using familiar software known to the Packhouse Manager further facilitates the implementation process. The additional quality procedures are easily integrated with the current Quality Checks.
The system should consist of a user-friendly interface.	Is the system complex to use?	No. The system's interface is user-friendly, offering easy use through manual input and straightforward button operations for calculations. Additionally, data input is rigorously controlled through Excel data validation and dropdown lists, minimising the potential for incorrect manual inputs.
The system should demand minimal additional resources.	Does the system demand additional resources?	No. The system requires minimal demands for additional resources. The only new software required is Power BI, which shares the exact licensing requirements as Excel. Consequently, no extra resources are needed, ensuring cost-efficiency in implementation.
Seamless integration with existing software should be ensured.	Will the system struggle to integrate with existing software in the packhouse?	No. The company's current utilisation of Excel is leveraged to ensure the smooth integration of the additional Excel-based system. Furthermore, Power BI effortlessly integrates with Excel. This compatibility reduces any operational or procedural disruptions during implementation.
The system should include future adaptation possibilities.	Will the system be challenging to adapt to future changes?	No. The system is designed with flexibility, allowing for straightforward adjustments to accommodate daily preparations and changing operational goals. Additionally, the Power BI system seamlessly adapts to the data it receives. Thus, defects encountered during the current season and future season possibilities are displayed.
The system should include manual input capabilities.	Will the users struggle to input data manually?	No. The system displays a user-friendly interface that simplifies manual input, catering to Packhouse Managers and Quality Clerks. The design streamlines the input process, improving overall usability.
The system should enable the visual interpretation of results for Packhouse Managers.	Will the system's results be unable to be visually interpreted?	No. The system's refined data collection processes seamlessly integrate with Power BI, facilitating comprehensive visual interpretations of results. These dynamic visuals empower Packhouse Managers to effectively communicate defect-related insights to Orchard Managers for targeted mitigation strategies.

The system should ensure minimal time consumption for Quality Clerks.	Is the system time-consuming for quality clerks to use?	No. The system's Quality Report Generation feature significantly reduces time consumption for Quality Clerks. With manual input capabilities and user-friendly dropdown lists, generating defect reports becomes automated. By simply pressing a button, real-time defect reports are communicated to management. This aspect improves the efficiency of quality procedures.
The system should eliminate the possibility of human errors.	Does the system increase the likelihood of human errors?	No. The system eliminates the possibility of human errors during manual input. This is achieved through the rigorous implementation of strict Excel controls integrated into the system's design, allowing only accurate data entry. Users are promptly alerted to incorrect inputs and guided to make necessary corrections, ensuring data integrity and reliability.

Company-X confirmed the above verification.

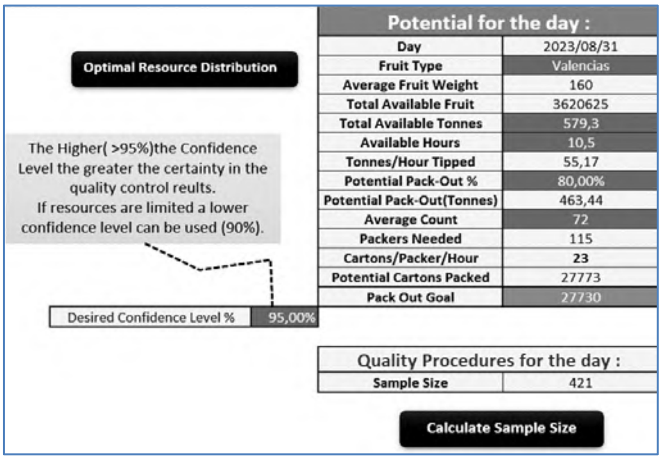
6.2 Validation of the systems packhouse preparation calculator to enhance operational efficiency and quality procedures

The Preparation Calculator significantly improves packhouse efficiency. It improves resource allocation, allowing for more carton packing with fewer packers; this can be seen in each scenario. This improvement reduces the cost of packhouse operations while improving efficiency and productivity. In **Table 4**, 579,3 Tonnes of Valencia's were tipped with an 80% pack-out potential.

Table 4: Validation Scenario 1

Production Parameter	Current State	Improved State (Potential State)	Improvement
Number of Packers	151	115	36 fewer Packers.
Cartons Packed	27730	27773	43 More Cartons Packed.
Sample Size (For every 30 Bins)	50	421(95% Confidence Level)	371 Sample Size Increases
Defect Exposure	1,67%	14,04%	12,37% more exposure to defects
Productivity	183,6424	241,5043	31,51% more efficient

This improved scenario can be seen in **Figure 11**.



The Higher(>95%)the Confidence Level the greater the certainty in the quality control reults.
If resources are limited a lower confidence level can be used (90%).

Desired Confidence Level %	95,00%

Potential for the day :	
Day	2023/08/31
Fruit Type	Valencias
Average Fruit Weight	160
Total Available Fruit	3620625
Total Available Tonnes	579,3
Available Hours	10,5
Tonnes/Hour Tipped	55,17
Potential Pack-Out %	80,00%
Potential Pack-Out(Tonnes)	463,44
Average Count	72
Packers Needed	115
Cartons/Packer/Hour	23
Potential Cartons Packed	27773
Pack Out Goal	27730

Quality Procedures for the day :	
Sample Size	421

Figure 11: Scenario 1 Improved Results

There are 10,5 available production hours. The improvement after using the system's preparation calculator shows labour cost savings of R9 608,76 for the day's labour costs. Given that the minimum loan for South Africa is R25,42 per hour [12]. A productivity calculation [13] demonstrates that the solution improves current packhouse efficiency.

$$Productivity = \frac{Output}{Input} \tag{1.1}$$

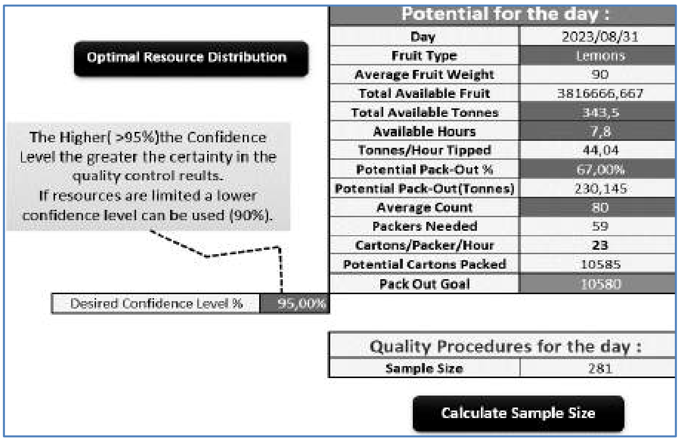
$$Productivity\ Improvement\ \% = \frac{Improved\ Productivity}{Initial\ Productivity} \times 100 \tag{1.2}$$

In **Table 5,** 343.5 Tonnes of Lemons were Tipped with a 67% pack-out potential.

Table 5: Validation Scenario 2

Production Parameter	Current State	Improved State (Potential State)	Improvement
Number of Packers	168	59	There are 109 fewer Packers.
Cartons Packed	10580	10585	5 More Cartons Packed.
Sample Size (For every 30 Bins)	50	281 (95% Confidence Level)	231 Sample Size Increases.
Defect Exposure	1,67%	8,74 %	7,07% more exposure to defects.
Productivity	62,97619	179,4068	184,88% more efficient.

This improved scenario can be seen in **Figure 12**.



The Higher(>95%)the Confidence Level the greater the certainty in the quality control reults.
If resources are limited a lower confidence level can be used (90%).

Desired Confidence Level %	95,00%

Potential for the day :	
Day	2023/08/31
Fruit Type	Lemons
Average Fruit Weight	90
Total Available Fruit	3816666,667
Total Available Tonnes	343,5
Available Hours	7,8
Tonnes/Hour Tipped	44,04
Potential Pack-Out %	67,00%
Potential Pack-Out(Tonnes)	230,145
Average Count	80
Packers Needed	59
Cartons/Packer/Hour	23
Potential Cartons Packed	10585
Pack Out Goal	10580

Quality Procedures for the day :	
Sample Size	281

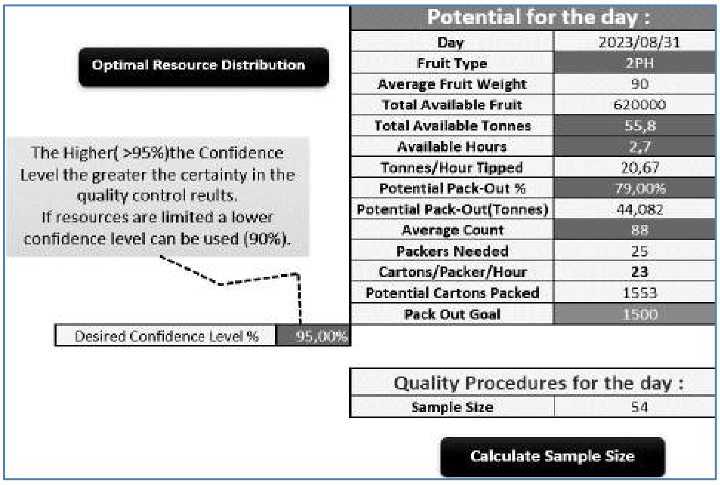
Figure 12: Scenario 2 Improved Results

There are 7,8 available production hours. The Improvement after using the system's preparation calculator shows labour cost savings of R21 612,08 for the day's labour costs. In **Table 6**, 55,8 Tonnes of Lemons-PH were Tipped with a 79% pack-out potential.

Table 6: Validation Scenario 3

Production Parameter	Current State	Improved State (Potential State)	Improvement
Number of Packers	163	25	138 fewer Packers.
Cartons Packed	1500	1553	53 More Cartons Packed.
Sample Size (For every 30 Bins)	50	54 (95% Confidence Level)	4 Sample Size Increases.
Defect Exposure	1,67%	3,6%	1,93% more exposure to defects.
Productivity	9,202454	62,12	575,01 % more efficient.

This improved scenario can be seen in **Figure 13**.



The Higher(>95%)the Confidence Level the greater the certainty in the quality control reults.
If resources are limited a lower confidence level can be used (90%).

Desired Confidence Level %	95,00%

Potential for the day :	
Day	2023/08/31
Fruit Type	2PH
Average Fruit Weight	90
Total Available Fruit	620000
Total Available Tonnes	55,8
Available Hours	2,7
Tonnes/Hour Tipped	20,67
Potential Pack-Out %	79,00%
Potential Pack-Out(Tonnes)	44,082
Average Count	88
Packers Needed	25
Cartons/Packer/Hour	23
Potential Cartons Packed	1553
Pack Out Goal	1500

Quality Procedures for the day :	
Sample Size	54

Figure 13: Scenario 3 Improved Results

There are 2,7 Available Production hours. The Improvement after using the system's preparation calculator shows labour cost savings of R9 471,49 for the day's labour costs. This is because 138 fewer packers are needed to reach the pack-out goal. The scenarios demonstrate how the sample size is associated with the total tonnes tipped into the packhouse and the set confidence interval. Simultaneously, the number of packers necessary aligns with the management's pack-out goal.

7 CONCLUSIONS AND FUTURE RECOMMENDATIONS

In conclusion, the developed DSS enhances the quality procedures and operational efficiency of Company-X. It also comprises the capacity to improve other Citrus Packhouses. The following inefficiencies are successfully addressed: fruit quality, labour resource allocation, packing patterns and time to identify defects. The root cause of these inefficiencies, as determined in Section 2, which was the absence of data-driven decision-making and a structured approach to quality control procedures and packhouse operations, is subsequently addressed through the project's successful completion. The study's success and practical contribution additionally lie in providing packhouse management with real-time data and comprehensive insights to ensure informed decision-making. The DSS solves the operational and quality inefficiencies and positions the packhouse for sustained continual success and excellence in the citrus industry. If Company-X's budget limitation is excluded, it can be recommended that Company-X invest in tablet devices for quality controllers. Adding this feature would significantly improve their mobility and the efficiency of data collecting and reporting during the quality checks.

Future research opportunities may focus on further integrating DBMS systems and rigorous quality control principles within packhouse operations. This integration can further enhance decision-making capabilities, operational efficiency, and quality procedures. Future Research could examine the effectiveness of these approaches and address potential implementation challenges, offering valuable insights for agricultural industry practitioners and researchers. Establishing continuous improvement possibilities for this DSS could ensure that defects are accurately identified and addressed in various agricultural industries. They are additionally improving the standards of agricultural products in South Africa. This project's successful completion showcases its potential to improve quality procedures and operational efficiency. This information can be a foundation for future research and continuous enhancements in agricultural packhouse operations and quality procedures.

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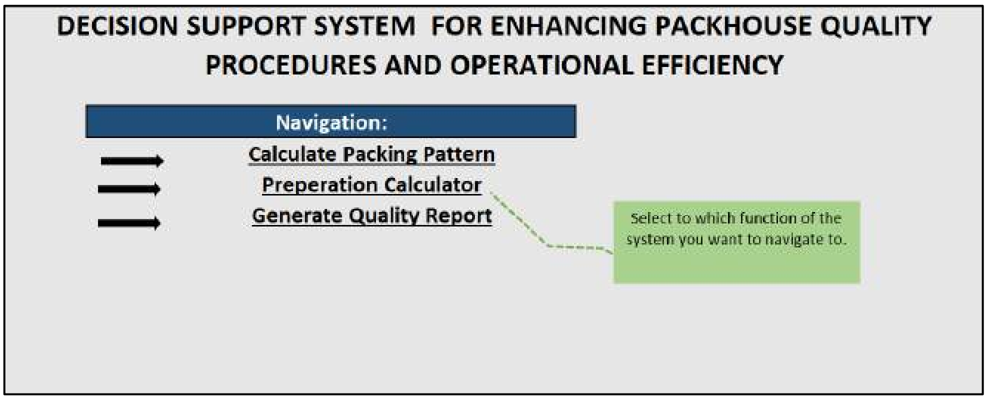
9 APPENDIX A

9.1 Final Design Interface of Decision Support System

The following section represents the final design of the DSS's user interface, how the system improves Company-X's operational and quality procedures and its capacity for decision-making capabilities. **Figure 14** demonstrates the System Navigation Page, a critical component that improves both Packhouse Quality Procedures and Operational Efficiency.



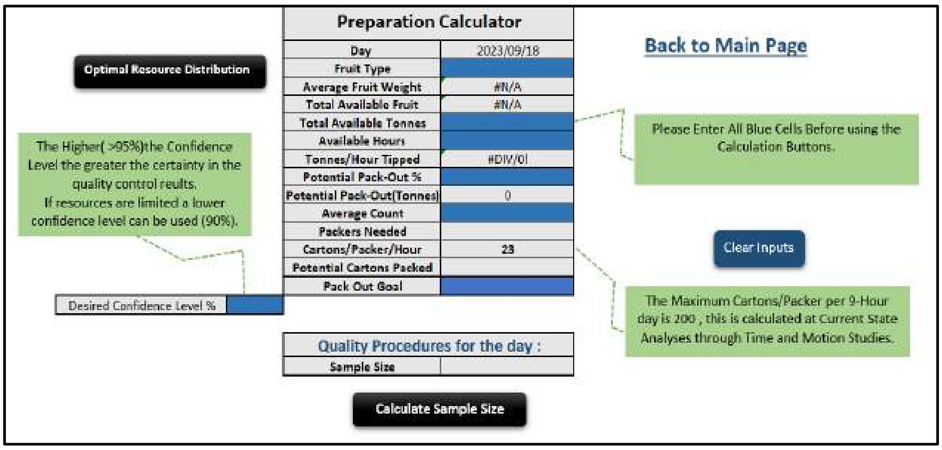
DECISION SUPPORT SYSTEM FOR ENHANCING PACKHOUSE QUALITY PROCEDURES AND OPERATIONAL EFFICIENCY

Select to which function of the system you want to navigate to.

Figure 14: DSS Navigation Page

This page functions as the main portal for users, allowing them to easily access numerous system aspects such as the Packing Pattern Calculator, Packhouse Preparation Calculator, and Real-Time Report Generation for Quality Reports and Defect Data. The Navigation Page has been designed to offer a user-friendly interface that ensures seamless, simple navigation. When users select the specific component they want to use, the system effectively transmits them to their desired page of the DSS, offering a simple but effective user experience. The green annotation on each page provides the steps to follow to use the system efficiently.

9.1.1 The Packhouse Preparation Calculator aspect of the system design.



Preparation Calculator	
Day	2023/09/18
Fruit Type	
Average Fruit Weight	#N/A
Total Available Fruit	#N/A
Total Available Tonnes	
Available Hours	
Tonnes/Hour Tipped	#DIV/0!
Potential Pack-Out %	
Potential Pack-Out(Tonnes)	0
Average Count	
Packers Needed	
Cartons/Packer/Hour	23
Potential Cartons Packed	
Pack Out Goal	

Desired Confidence Level %	

Quality Procedures for the day :	
Sample Size	

The Higher(>95%)the Confidence Level the greater the certainty in the quality control reults.
If resources are limited a lower confidence level can be used (90%).

Please Enter All Blue Cells Before using the Calculation Buttons.

The Maximum Cartons/Packer per 9-Hour day is 200 , this is calculated at Current State Analyses through Time and Motion Studies.

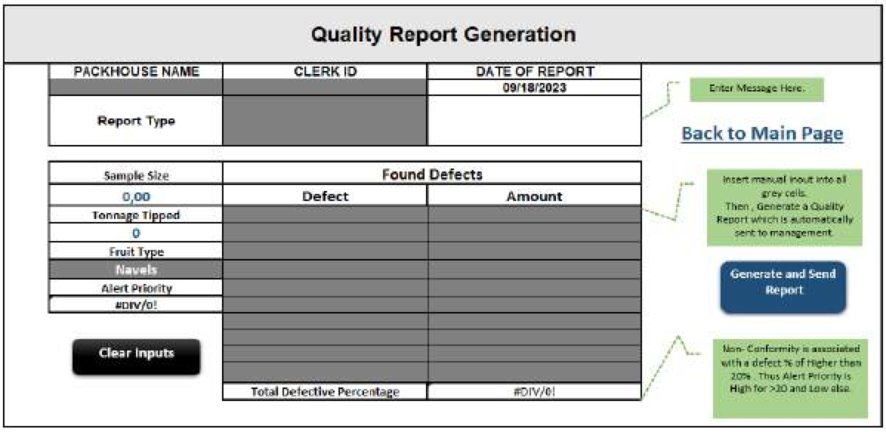
Figure 15: System's Preparation Calculator for Packhouse Management Use.

Figure 15 illustrates the DSS Preparation Calculator Page. This calculator is essential in supporting packhouse managers with decision-making, as well as improving overall efficiency, productivity, and resource utilisation throughout daily packhouse operations. It accomplishes this by estimating the minimum number of packers required to meet the day's pack-out goal efficiently. This estimate is based on time and motion study findings, which revealed an average packing rate of 23 cartons per hour per packer. While this value can be changed based on packhouse manager preferences, the anticipated rate of 23 cartons per packer per hour achieves ideal productivity.

To use this calculator effectively, the Packhouse Manager must fill in all values within the indicated blue blocks. After providing these parameters, the user can proceed by clicking the "Optimal Resource Allocation" button. Following that, the user can enter their preferred confidence interval before selecting the "Calculate Sample Size" button.

It is noted that a larger confidence interval improves the dependability of quality check results, allowing users more confidence that the results truly represent the defects present in the current tipping. It defines the sample quantity required for efficient quality control on the specified day. This computation is based on an established confidence interval and the total tipped tonnage for the day. The obtained sample size is the number of fruits that should be quality checked for every 30 bins, which corresponds to approximately every 3000 fruits. This defect identification can then be subjected to additional analysis to ensure that the correct defects are being addressed.

9.1.2 Real-Time Defect Communication through Report Generation.



Quality Report Generation

PACKHOUSE NAME	CLERK ID	DATE OF REPORT
		09/18/2023
Report Type		

Sample Size	Found Defects	
0,00	Defect	Amount
Tonnage Tipped		
0		
Fruit Type		
Navels		
Alert Priority		
#DIV/0!		
	Total Defective Percentage	#DIV/0!

Enter Message Here.

Insert manual input into all grey cells.
Then , Generate a Quality Report which is automatically sent to management.

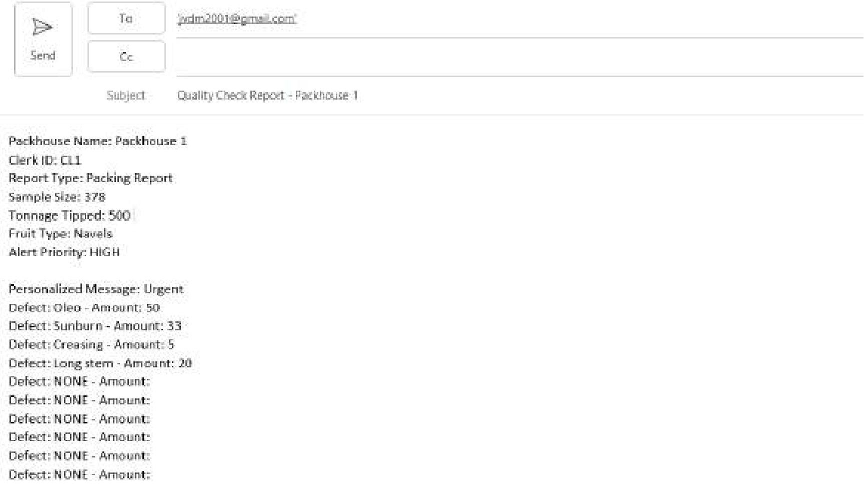
Non- Conformity is associated with a defect % of Higher then 20% . Thus Alert Priority is High for >20 and Low else.

Figure 16: System's Quality Report Generation Page for Quality Controller use.

Figure 16 illustrates the Quality Report Generation Page, which Quality Controllers use efficiently during the quality check process. This simplifies the creation of automated quality reports, increasing reporting efficiency. To create a report, users must fill out the information in the dark grey input areas. Once all the necessary information has been provided, simply clicking on the "Generate and Send Report" button initiates the automatic configuration and sending of the report to a designated recipient in email format.

To further improve operations, it can be beneficial that the company establish a designated email address exclusively for receiving these quality reports. This will reduce email redundancy and ensure that the reports reach the intended recipients promptly.

To reduce the possibility of human errors, the DSS includes input data validation controls and drop lists. Notably, the sample size and tonnage tipped are automatically updated daily depending on Packhouse Management's estimates in the Packhouse Preparation Calculator. An essential feature is the system's ability to identify instances where the Total Defective Percentage exceeds 20%, indicating these as non-conformities and high-priority alerts for Packhouse Decision Makers. A "Clear Inputs" option is included to ensure that additional reports may be promptly produced and dispatched.



To: 'jvdm2001@gmail.com'
Subject: Quality Check Report - Packhouse 1

Packhouse Name: Packhouse 1
Clerk ID: CL1
Report Type: Packing Report
Sample Size: 378
Tonnage Tipped: 500
Fruit Type: Navels
Alert Priority: HIGH

Personalized Message: Urgent
Defect: Oleo - Amount: 50
Defect: Sunburn - Amount: 33
Defect: Creasing - Amount: 5
Defect: Long stem - Amount: 20
Defect: NONE - Amount:
Defect: NONE - Amount:
Defect: NONE - Amount:
Defect: NONE - Amount:
Defect: NONE - Amount:
Defect: NONE - Amount:

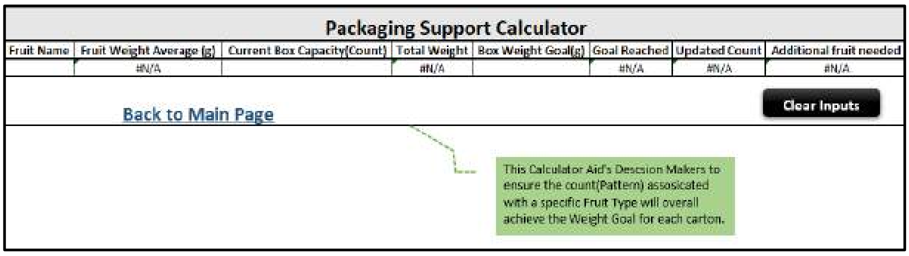
Figure 17: Automated Email that is sent after the Report Generation Button is clicked.

Figure 17 illustrates an automated email sent by the system to a specified email address. This email serves as an important source of real-time communication, sending critical information regarding discovered quality defects to Packhouse Management.

The email's content offers details about the quality control checks, offering insights into the fruit's quality. It includes details such as the date and time of the quality check, the particular quality controller and the type and amount of defects discovered. Furthermore, the email includes a personalised note, giving Quality Controllers the option to contribute additional context or insights.

By employing this automated email system, the packhouse ensures that critical defect data is communicated efficiently to decision-makers. This immediate communication allows for timely responses and informed decision-making, contributing to the overall quality of procedures' effectiveness and efficiency.

9.1.3 The Packaging Support Calculator.



Packaging Support Calculator

Fruit Name	Fruit Weight Average (g)	Current Box Capacity(Count)	Total Weight	Box Weight Goal(g)	Goal Reached	Updated Count	Additional fruit needed
	#N/A		#N/A		#N/A	#N/A	#N/A

This Calculator Aid's Descsion Makers to ensure the count(Pattern) assosicated with a specific Fruit Type will overall achieve the Weight Goal for each carton.

Figure 18: Packaging Support Calculator for Packhouse Management Use.

Figure 18 illustrates the Packaging Support Calculator, a tool accessible to both Quality Controllers and Packhouse Management. Its purpose is to ensure that each final product meets the specified weight requirement. This is particularly critical for the export market, where compliance with weight standards is essential.

Firstly, the user should specify the fruit type for which the carton count pattern is being configured. After that, the current box capacity, which is user-defined based on the carton type currently in use, should be entered. The required weight for the carton should then be set. This is the maximum weight that each carton should attain. The calculator then calculates the overall weight of the carton by multiplying the average fruit weight by the box capacity selected. The system determines if the computed total carton weight is within the set weight range. If it is not, the calculator provides a modified count estimate as well as the additional amount of fruit required to achieve the weight goal. Users can then make informed decisions by picking the count that is nearest to the recommended adjustment.

The Packaging Support Calculator simplifies the process of verifying that cartons fulfil weight requirements consistently during quality checks. It removes the need for repetitive packing and weighing of cartons, making weight compliance more efficient and practical.

9.2 The System Integration with Power BI for result visualisation capabilities.

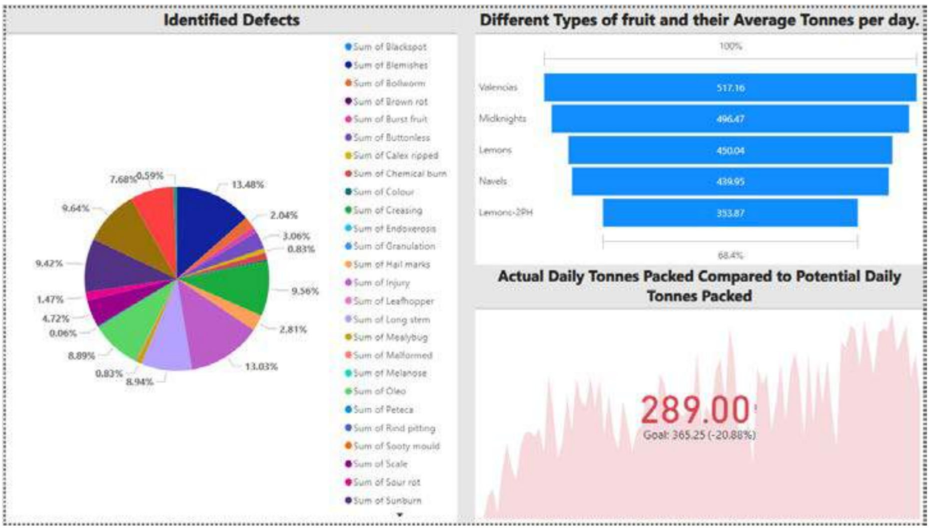


Figure 19: Power BI Dashboard for data visualisation.

Figure 19 illustrates the Power BI dashboard, a tool that decision-makers can use to improve their understanding of the packhouse's quality performance and its influence on daily packing efficiency. This interactive dashboard has been developed to aid with data-driven decision-making and includes the following sections:

1. **Identified Defects:** This component uses a pie chart to illustrate discovered defects visually. Decision-makers can then promptly determine which defects are more significant.
2. **Fruit types and their average tonnes tipped per day:** The dashboard displays the numerous fruit varieties that were packed, along with their average daily tonnage. This data assists decision-makers in evaluating the performance of various fruit kinds in the packhouse.
3. **Actual vs Potential Daily Tonnes Packed:** This critical component compares actual daily tonnes packed to potential daily tonnes packed. Decision-makers can assess the effectiveness of daily operations by identifying any inconsistencies between actual production and the potential production of the packhouse.

The Power BI dashboard provides decision-makers with real-time insights on packhouse performance through a simple and information-packed interface. It allows them to make more informed decisions and prioritise defects that need to be addressed.

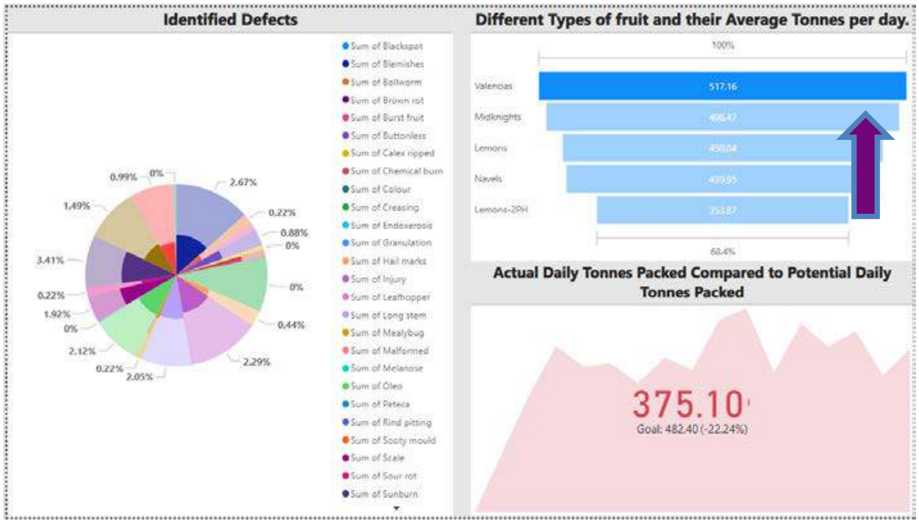


Figure 20: Power Bi Fruit Type Interaction.

Figure 20 demonstrates the interactive features of the Power BI dashboard, allowing Packhouse Managers to gain insights into the relationship between fruit types, defects, and their influence on daily tonnage loss. This visualisation enables Packhouse Managers to make informed data-driven decisions based on an accurate understanding of the influencing defects.

The dashboard provides an interactive interface that allows Packhouse Managers to examine how different fruit types are linked to certain defects; as seen in **Figure 20** by the purple arrow, a specific fruit is chosen. They can then identify which fruit types are more prone to specific defects by engaging with different combinations. The dashboard additionally demonstrates which fruit types are the most responsible for tonnage loss due to defects. This data is beneficial for strategic defect mitigation planning.

As a result, the Power BI dashboard is a valuable tool for Packhouse Managers to interactively investigate and fully understand the relationship between fruit types, defects, and their influence on daily tonnage packed. This insight enables managers to mitigate defects and improve the overall packhouse efficiency and final product quality, thus achieving the aim of the project as stated in Section 1.

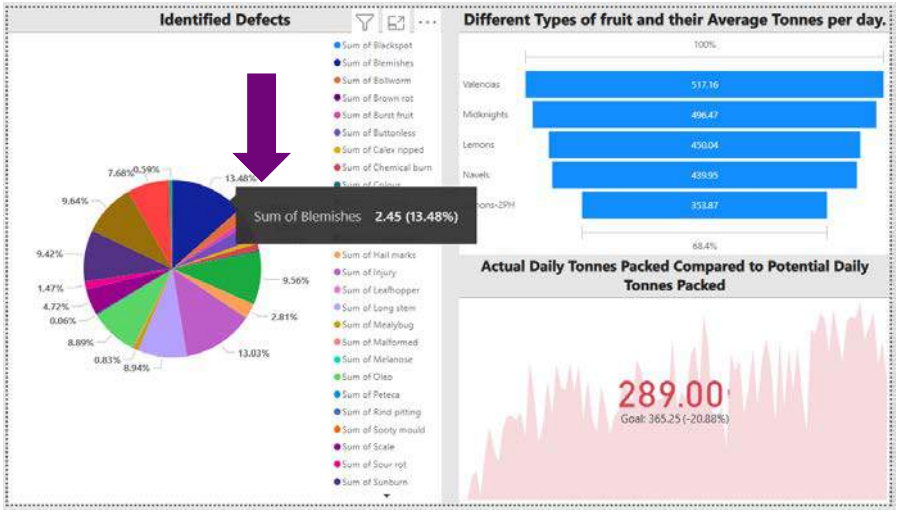


Figure 21: Power BI Defect Identification and Mitigation.

Figure 21 further illustrates the interactive features of the Power BI dashboard, providing Packhouse Managers with a more in-depth understanding of the impact of defects on pack-out losses.

Packhouse managers can pinpoint defects' influence on pack-out losses by simply clicking on them. This precision allows for accurate defect identification and mitigation. The dashboard illustrates the defects that have the greatest influence on pack-out losses based on the data given. Blemishes (13.48%), Injury (13.03%), Long Stems (8.94%), and Sunburn (9.42%) are examples from the current data used. Packhouse Managers may make informed decisions and prioritise which defects to address using this information. For example, resolving concerns like injuries and long stems may necessitate improved picking techniques, whereas minimising sunburn and blemishes may require the installation of extra netting in orchards.

Packhouse Managers are now able to collaborate with Orchard Managers to address specific defects and improve fruit quality, benefiting the overall packhouse operations. This is done by identifying and addressing high-impact defects. In addition, the citrus packhouse quality procedures and operational efficiency are enhanced.

Figure 22: Power Bi Defect Identification according to defect categories and fruit types.

Figure 22 illustrates an additional Power BI dashboard that offers a detailed overview of identifying defects by categorisation. This feature enables decision-makers to gain insights into where and how defects are distributed throughout different fruit types and their related categories, as established in Section 3.

The dashboard divides defects into categories, allowing decision-makers to differentiate between a variety of defects. This classification improves the accuracy of identifying defects. Decision-makers can investigate which fruit types are more prone to specific defect categories. The dashboard, for example, shows at the indicated purple arrow that Valencia's has the most severe instances of sunburn. This knowledge guides decisions on where to focus defect mitigation efforts. Decision-makers can now use this data to make data-driven decisions about how to address the defects. Based on the high incidence of sunburn in Valencia, for example, they can increase the amount of netting in Valencia's orchards as an immediate response. This systematic strategy guarantees that efforts are focused where they will have the most impact.

The Power BI dashboard provides decision-makers with a clear and structured overview of defects across different fruit types and defect categories. These data-driven insights allow for more informed decisions and more efficient use of resources, ultimately resulting in higher fruit quality and operational efficiency.

AN INDUSTRIAL ENGINEERING LIGHTHOUSE MODEL FOR TRANSDISCIPLINARY PROBLEM SOLVING AND SUSTAINABLE DEVELOPMENT IN SOUTH AFRICA

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ABSTRACT

The Industrial Engineering profession is a prevalent multidisciplinary profession capable of yielding operational gains for organisations in almost any sector. However, it is unclear how the characteristics of this profession can be used to meet the sustainable needs and complex problems in South Africa. This research presents an Industrial Engineering lighthouse model for strategic foresight in transdisciplinary problem solving in relation to the United Nations Sustainable Development Goals. This discussion paper reflects on existing literature as a basis for this novel artefact. Using the components that belong to this lighthouse, researchers and practitioners can identify future contributions Industrial Engineers can make in developing countries such as South Africa.

Keywords: Industrial Engineering, Foresight model, Sustainable Development Goals, Transdisciplinary research, South Africa

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1 INTRODUCTION

1.1 Background

Much like all engineering disciplines, engineers can produce value through innovative solutions that benefit society and communities at large. This notion cannot be more accurate for the industrial engineering discipline. The industrial engineering profession has emerged as an influencing engineering discipline that can yield productivity gains in various industries using a blend of mathematics, statistics, operations research, human factors engineering, phycology, management systems, economics, accounting and manufacturing systems engineering [1].

The multidisciplinary nature of the profession underscores the contribution it can make in solving the vast and rather complex array of challenges South Africa faces. According to Schutte, et al. [2], industrial engineering is responsive to technology trends and societal trends. This is also further supported by Mangaroo-Pillay and Roopa [3], believing that the profession will start to embark on new problem-solving ventures that belong to social sciences and environmental studies. South Africa is bombarded with several issues which relate to other developing countries.

In South Africa, problems are ever-present, and challenging and lead to excessive resource allocations with growing concern. According to Smith [4] and Legotlo [5], South Africa is confronted with issues concerning widespread poverty, inequality, unemployment, landlessness, homelessness, lack of basic services, lack of adequate healthcare, food insecurity, constrained resources, corruption, poor education systems and high levels of crime and violence.

Authors have provided innovative descriptions of problems that we face. One such example is to describe problems as “wicked”. Wicked problems are seen as complex, contested and unique social and socio-ecological issues that relate to various stakeholders with changing requirements [6, 7]. There exists no “silver bullet” to resolve wicked problems [8]. Another categorisation of problems is housed in what we now see as a VUCA world. VUCA is viewed as a world or environment where problems possess volatility, uncertainty, complexity and ambiguity [9]. According to Dhillon and Nguyen [10], we are all agents in a VUCA environment. Problems are sporadic, systemic, ever-changing and ill-defined with hairball structure ultimately resulting in vague perceptions and no clear nexus.

Problems in society often relate to the challenge of sustainable development. All developing countries have a more complicated path to sustainable development; hence South Africa is not alone in the pursuit for transformative changes in society [11]. The nature of problems that pertain to sustainable development require a multidisciplinary approach [12]. The industrial engineering profession may be the beacon of light that can solve these complex problems since it inherently is multidisciplinary and harnesses solutions from a vast array of theory domains that produce integrated knowledge. The industrial engineering profession can illuminate and uncover new root causes behind problems, employ systems thinking, and project new solutions to produce sustained change in society.

1.2 Research problem

South Africa is confronted with complex problems and challenges which includes sustainable development.

1.3 Research opportunity

Industrial engineering can solve complex problems and sustainable development issues using transdisciplinarity.

1.4 Research aim

The aim of this research is to develop an artefact that will facilitate transdisciplinary problem-solving and sustainable development in South Africa.

This research paper is structured with the literature review in section 2, methods presented in section 3 and the artefact design and presentation in section 4. Conclusions and recommendations constitute section 5.

2 LITERATURE REVIEW

2.1 Transdisciplinarity

Industrial engineering is argued to be multidisciplinary in nature. This deliberate configuration allows it to build on a vast array of knowledge domains to produce creative solutions to complex problems. Recently, academic scholars and practitioners have become more fixated on the notion of transdisciplinary knowledge and transdisciplinary solutions. To appreciate the evolution of transdisciplinary research, one must first contextualise its antecedents, namely disciplinary, multidisciplinary and interdisciplinary research. Research has also tried to define the differences between multi-,inter- and transdisciplinary sustainability research by a framework which found this often has blurred understanding [13]. According to Tress, et al. [14], disciplinarity is siloed between disciplines whereas multidisciplinary has loose cooperation between various disciplines during the knowledge exchange and theory development. In contrast, transdisciplinary type research has various goals that involve academic and non-academic knowledge bodies. This is best explained and imagined using Figure 1.

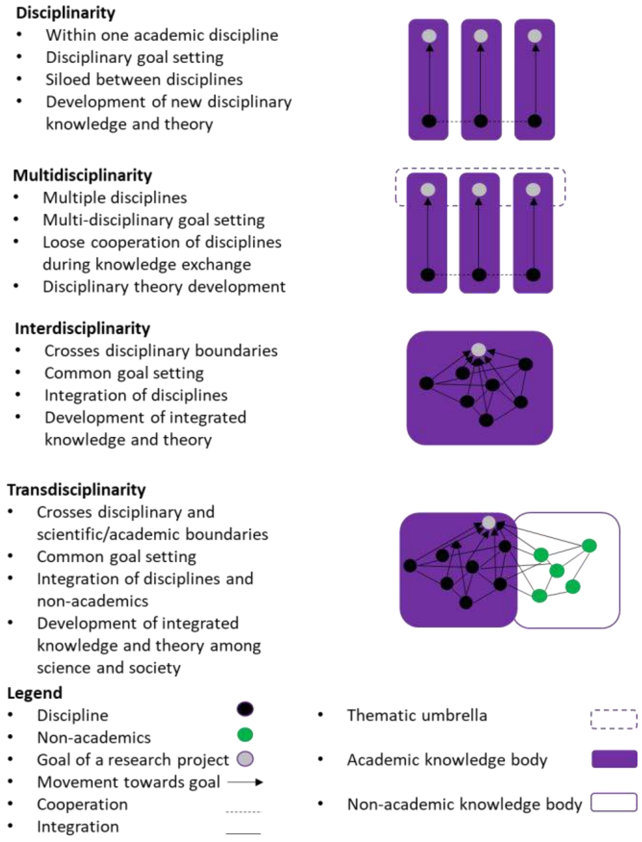

Figure 1: Transdisciplinary, interdisciplinary, multidisciplinary and disciplinary illustration redrawn from Tress, et al. [14]

Dalton, et al. [15] believe that in collaborative research that forms part of a multidisciplinary system, individual researchers provide concise but fragmentary solutions embedded within loosely designed and dynamic meta-problem superstructures. A year later, the same researchers explored interdisciplinary research. The researchers forge this as a system comprised of researchers assembled through false formation and morphing into a central organising principle that combines intention by unifying aims and methodologies [16].

For South African challenges, transdisciplinary approaches are the way forward. Dhansay, et al. [17] mention the Global Change Program highlighting the importance of transdisciplinary solutions to address the multifaceted issues in South Africa. In a transdisciplinary project, the venture undergoes three distinct stages, problem framing, problem analysis and exploring impact [18]. According to Pohl, et al. [19], a transdisciplinary project connects the realm of science, rigor and understanding with the realm of practice, relevance and design. This journey co-produces knowledge through learning and integration as a multidimensional interactive process involving many stakeholders. The gains from transdisciplinary research have maintained a positive impact on society which drives other forms of transdisciplinary research. Several transdisciplinary knowledge domains have emerged. One close to industrial engineering is that of industrial ecology. Industrial ecology strives to seek a balance between industrial metabolism (productivity gains) and ecological metabolism (preservation of nature) by viewing industrial and natural systems with interaction [20].

This research paper argues that Industrial engineering can perpetuate transdisciplinary knowledge due to its high multidisciplinary nature, industry relevance and systems thinking that gives a holistic perspective as masters of integration. This argument is also supported by Peruzzini, et al. [21], those who believe that Industrial Engineering is becoming increasingly viewed as a transdisciplinary field with particular reference to Industry 4.0. Sperotto [22] even recommends that academic institutions prescribe methods for the industrial engineering profession to lead rapid changes in the social and industrial environment for the needs of industry, the human-machine relationship and cultural aspects of society. It is therefore also befitting that transdisciplinary knowledge be explored since it considers academics and learned practitioners. There are however a myriad of challenges faced by transdisciplinary research, namely [23]:

- Diverse definitions and understandings of transdisciplinarity
- Complex and unclear relationships between methods, process phrases and knowledge types
- A gap exists between best practices and real-world projects
- Scarcity of high-level engagement
- Difficulty in evaluating the impact of the research

2.2 Future cones and strategic foresight

Society has long studied the effects of the past and imagining, preparing, and embracing what lies ahead. This fixation presents itself in various concepts concerning future thinking, future studies and predicting the future. Future studies can visualise the possibilities of many futures since it is most believed that the future is many. This visualisation is carefully crafted using future cones and the cone of possibilities.

The concept of future cones has been adapted, refined and improved upon over many years. An early, and widely accepted proposition is the version of the cone of uncertainty. Bauman [24] presents a cone that argues that as time progresses, the level of uncertainty diminishes as less likely outcomes and possible futures become non-probable. Since then, this idea has been contested and argued that time progression increases the likelihood of more futures. Research efforts by Gall, et al. [25] uncover and report on variations of the future cone. Their outcome is to consolidate the versions using the characteristics that have been composed over many years. This revised future cone is depicted in Figure 2.

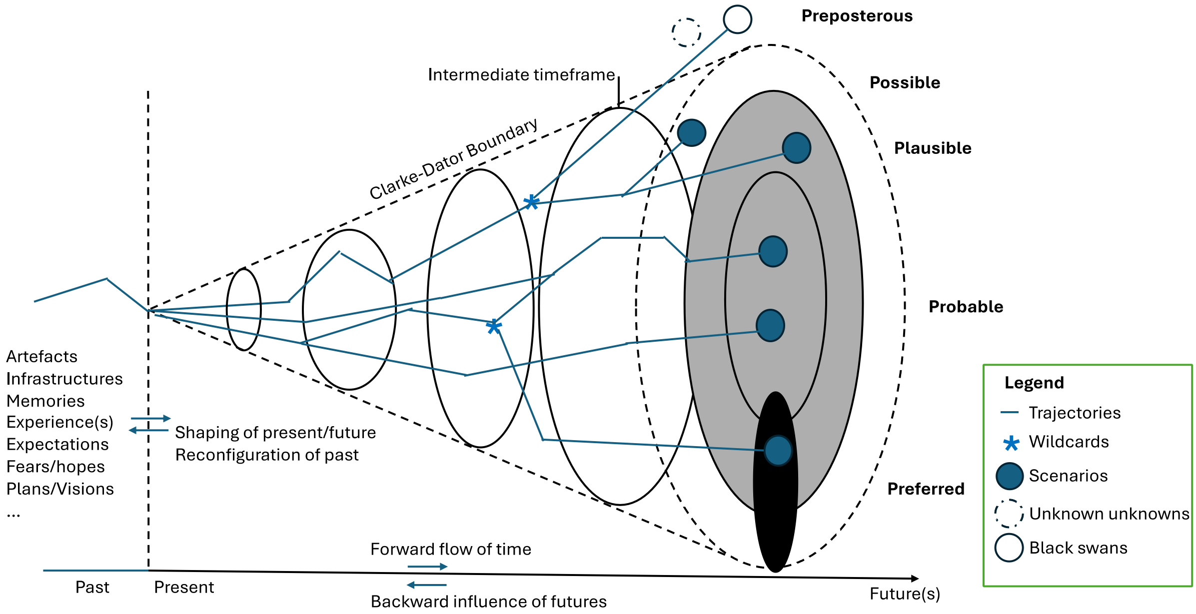

Figure 2: Revised future cone redrawn from Gall, et al. [25]

This revised model combines the concepts from 14 future cones using consistent characteristics. Each time element is subjected to a scenario that is dictated by the forward flow of time and the backward influence of futures with backcasting [26]. The model also accounts for linear temporality implying that time only flows in one direction. There also exists a widening range of possibilities with events creating distinctions between probabilities that yield new trajectories that can be multiple and non-linear in nature. The future also plays host to wildcards, which are deemed as high-impact, high-uncertainty events that can alter these trajectories [27]. Future cones form a crucial part of the foresight process.

Strategic foresight enables an enterprise to conceptualise strategies that allow entities to detect weak signals and wildcards by embracing environmental scanning methods and reflecting on strengths and internal capabilities [28]. One segment of any business is the technological advances that may follow. A technological foresight model by Güemes-Castorena, et al. [29] uses foresight to identify business opportunities using change drivers, Delphi, scenario planning and a technology roadmap. This combination demonstrates the application of foresight welcoming a diverse set of tools that can complement the endeavour an organisation or society pursues.

For the industrial engineer, the ability to apply foresight and future thinking would prove valuable to their diverse set of problem-solving skills. Not only will the prediction, planning and response to future outcomes make organisations more resilient, but this would also empower society to embrace more dynamic changes with more scenarios accounted for and understood. It also cultivates an environment eager for change. This could indirectly increase buy-in for the very creative solutions needed to solve the complex problems that dominate our world.

2.3 Sustainable Development Goals

For any country to make a meaningful impression on society and reap sustained value for the future, the sustainable development goals are pivotal. The 17 Sustainable development goals (SDGs) were introduced in 2015 as part of the UN 2030 Agenda for a sustainable society which accounts for social, environmental and economic pillars [30]. The 17 SDGs are [31]:

- SDG 1: No poverty
- SDG 2 - Zero hunger

- SDG 3 - Good health and wellbeing
- SDG 4 - Quality education
- SDG 5 - Gender equality
- SDG 6 - Clean water and sanitation
- SDG 7 - Affordable and clean energy
- SDG 8 - Decent work and economic growth
- SDG 9 - Industry, Innovation and infrastructure
- SDG 10 - Reduced inequalities
- SDG 11 - Sustainable cities and communities
- SDG 12 - Responsible consumption and production
- SDG 13 - Climate action
- SDG 14 - Life below water
- SDG 15 - Life on land
- SDG 16 - Peace, justice and strong institutions
- SDG 17 - Partnerships and goals

These are broad-reaching and address the shortcomings of the Millennium Development Goals (MDGs) [32, 33]. The SDGs form part of orientation knowledge which formulates and justifies the goals and objectives for a social change process [23]. These goals aspire to lead a transformational process which begins with incremental change, moving on to accelerated radical change (increasingly seen as inevitable) and finally leading to a system change as an end transformational state [34].

The SDGs lay the groundwork for sustainable transformations together with sustainable development. Voulvoulis, et al. [34] advise that systems thinking is needed for sustainability transformations. Fortuitously, the industrial engineering profession prides itself on its systems view and systems thinking approach which complement the execution of SDGs, and so it becomes the industrial engineer who can aid in the roll-out and strategic planning needed for the SDGs to take effect.

3 METHODOLOGY

The nature of this research is explorative since it takes on a constructivist paradigm. To achieve the aim of the research, a new methodology is proposed. This methodology is coined as the ACD methodology which can be used for high-level abstraction for theory development as part of problem-orientated research similar to Gregor, et al. [35]. The stages for this methodology are illustrated in Figure 3.

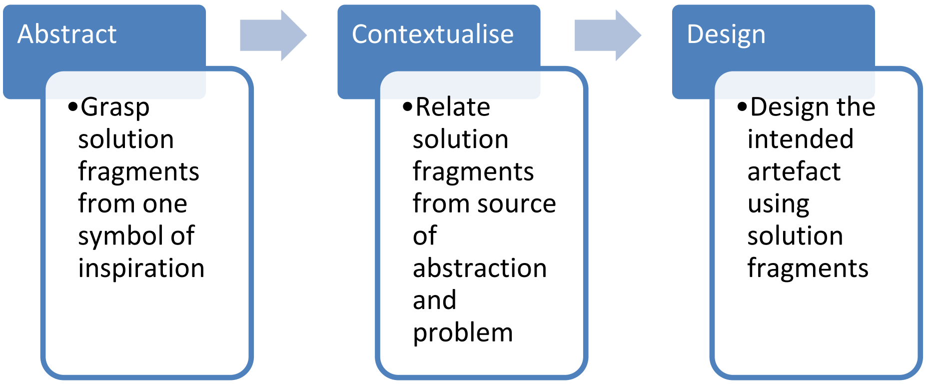

Figure 3: ACD methodology

During the first phase, the researcher identifies a symbol that either mimics or serves as a metaphor for the improvement initiative. As soon as this symbol, icon, artefact or analogy is obtained, the functions are exposed, critiqued and used to brainstorm solution fragments that will be used later on. The use of abstraction is able to simplify complex relationships that my exist, but also guide design decisions [36].

The Contextaulise phase welcomes case specific circumstances, characteristics and methods of application in the same geographical region or subject matter orientated around the problem. Two aspects can be contextualised, the problem or the assortment of solution fragments.

In the Design phase, the fragments in the abstraction and contextaulisation phase are pieced together to create the intended artefact. The solution fragments must become inherent subcomponents or features that belong to the symbol, icon or artefact identified in the abstraction phase.

In this research the data collection with aid in developing a literature-based lighthouse model that leverages Industrial Engineering knowledge. In the contextualise phase, the data will thus require pertinent literature on artefacts that can support sustainable development in South Africa. They will be summarised in table format so as to inform the design phase. These findings are now presented in section 4.

4 INDUSTRIAL ENGINEERING FORESIGHT MODEL

4.1 Lighthouse abstraction

This research takes inspiration from a lighthouse since it is a symbol of clarity, direction, and measurement as monitoring mechanisms. It gives strategists a sense of alignment as to where they currently are, where they are going and how far away, they are from the shore or their intended destination. A lighthouse simply illuminates the way forward.

This research is not the first to explore the concept of a lighthouse for design inspiration. Furthermore, it is also not the first to consider a lighthouse with regard to sustainability. The research by Holmberg and Larsson [37] produce an innovative sustainability lighthouse that guides sustainability transitions in socio-technical systems. This model is encapsulated in Figure 4.

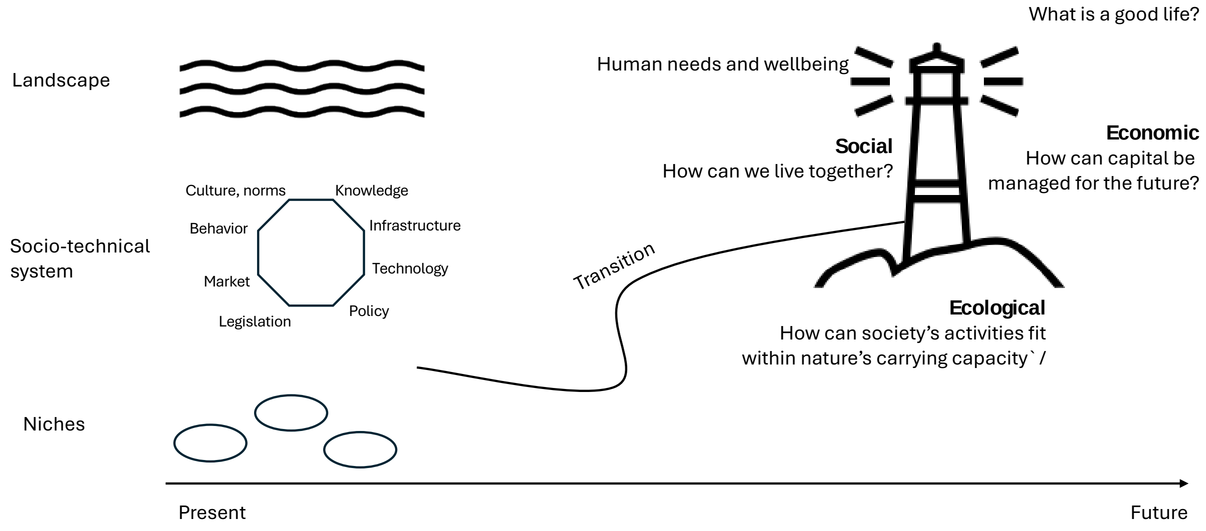

Figure 4: Sustainability lighthouse guiding socio-technical systems redrawn from Holmberg and Larsson [37]

This model guides sustainability by bridging the issue of sustainability transitions, forming part of a backcasting process and appeals to modes of transdisciplinary research and its relevant actors [37]. This also validates the selection of a lighthouse according to the purpose of this research seeing that this focuses on sustainable development, demonstrates foresight components and speaks to transdisciplinarity. This model highlights leadership processes that must consider social, economic and ecological aspects and eight core socio-technical system components.

In South Africa, research into socio-technical transitions is also presented in the literature. Asiimwe and De Kock [38] perform a bibliometric analysis on the interconnectedness and degree to which Industry 4.0 can be used in sustainability or socio-technical transitions. It was found that systems engineering, innovation, industrial production, technology adoption and digitalization are among many core components.

The clockwork and exact mechanisms that execute the function of a lighthouse are worth abstracting. The functionality is derived from the lens, turntable, base and clock mechanism that is supported by a weight. This is demonstrated in Figure 5.

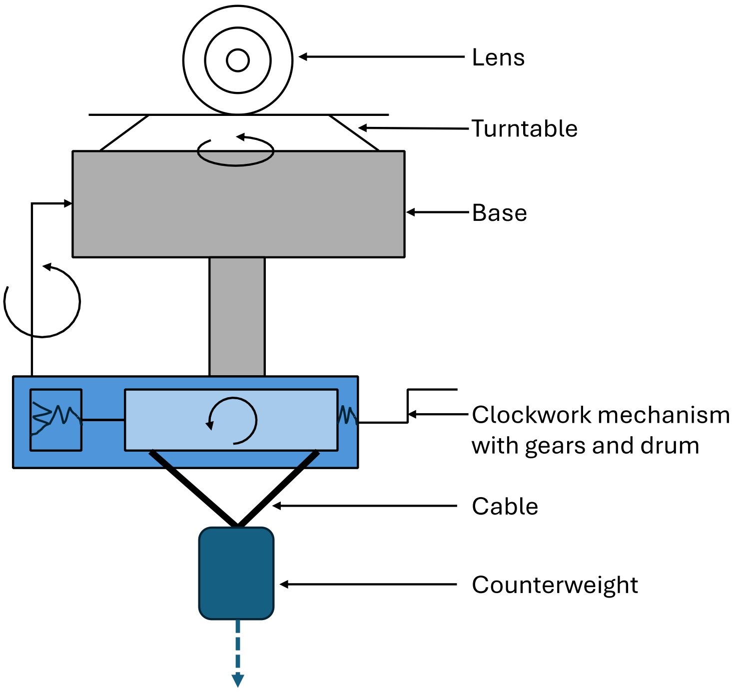

Figure 5: Lighthouse mechanisms redrawn from the Sheringham Point Lighthouse Preservation Society [21]

The visibility of the lighthouse is made possible by a 360-degree rotating turntable that ensures the light is visible in all directions. This alludes to any specific solution needing multiple perspectives. A counterweight drops a cable that rotates the clockwork drum mechanism to help drive the rotation throughout the entire light mechanism. This grounding symbolises relevance and being in tune with your surroundings. It now becomes more important that each idea or solution must have relevance or contextualisation, but also complement and appeal to the circumstances for the intended solution.

Every lighthouse in a specific region in the world has a unique signature. The composition of this signature uses a specific flash pattern which entails a colour of light shone with a certain light emission duration and spacing thereof [39]. The most prominent light colour across South African shorelines is white, hence hues of black and white will be used in the model.

4.2 Contextualisation

To contextualise the solution with the intent to be relevant and add value in South Africa, the research conducted in the country must be included. In order to succinctly present some of the relevant research in the field, Table 1 categories artefacts predominantly developed in the South African Industrial Engineering domain that can be used for transdisciplinary problem-solving and sustainable development. The table provides the title of the research paper, the authors, the specific artefact, rationale for its selection and the design consideration that will be used in the design and visualisation of the artefact for this research.

Table 1: Summary of Industrial Engineering work relevant to this research

Title	Authors	Artefact and description	Rationale for selection	Design consideration
The industrial engineering identity: From historic skills to modern values, duties and roles	Darwish and Van Dyk [40]	Industrial engineering identify tree model on the identity and role of IE	Focused on the industrial engineering discipline	Balance, industrial and systems thinking, design, engineering, management and proactiveness
An engineering approach to an integrated value proposition design framework	Alessandro, et al. [41]	A value proposition design framework that caters for new value proposition launches using Kano, Blue Ocean strategy and Generalised Bass model for a more customer-centric view	South Africa is a service economy and competitiveness is crucial for economic prosperity	Value creation must have functional, economic, psychological and creative value
A Lean implementation framework encompassing South African Ubuntu	Mangaroo-Pillay [42]	A South African Lean-Ubuntu analogy of the management principles	The framework prescribes execution across three execution levels in organisations	Collectivism should also take preference, considering problem-solving, processes, people and philosophy
Rapidly arriving futures: future readiness for Industry 4.0	Botha [43]	Industry 4.0 Readiness assessment using aspects from future thinking	Future thinking, scenario planning and wildcards used	Some form of impact assessment is important with future thinking
Towards a customized foresight model on "disaster risk management" in developing countries	Sayah Mofazali and Jahangiri [44]	Preparedness approaches and methods to disaster risk management are proposed	The findings relate to South Africa as a developing country	Preparedness features as the core aspect for risk management

Title	**Authors**	**Artefact and description**	**Rationale for selection**	**Design consideration**
Exploring the disconnect between bodies of literature pertaining to socio-technical transitions and technology assessment (Part 2): Linkage analysis	De Kock and Brent [45]	Insights on socio-technical and technology management literature revealed using a bibliometric and linkage analysis	Various keyword and theme occurrences relate to sustainable development	Innovation, economics, multi-level perspective and appropriate research methodologies are key occurrences
Learning to frame complex sustainability challenges in place: Explorations into a transdisciplinary “Challenge Lab” curriculum	McCrory, et al. [46]	A method for framing problems using four principles	Framing sustainability challenges in trandisciplinary is an initial stage in the problem-solving approach	Four principles for backcasting proposed as a slope
Towards a framework for systemic creativity in engineering organisations	Bam and Vlok [47]	Seven core elements for systemic creativity proposed	Creativity and systemic solutions resolve complex problems	Person, process, place, product, influence of leadership, persuasion and potential are seven elements for consideration

These solution fragments from the rightmost column of Table 1 are design considerations transferred into the design phase to address transdisciplinarity and sustainable development in South Africa.

4.3 Design logic and visualisation

Due to the medium to high level of abstraction required to embody Industrial Engineering traits that support transdisciplinary problem-solving and sustainable development, the design logic draws on the mechanisms of a lighthouse and the theory previously discussed. These are the attributes extracted from the solution fragments:

- Stakeholder engagement, co-creation, collaboration, problem analysis and impact assessment from transdisciplinarity
- Multiple perspectives, relevance, a strong foundation and black and white shades in the design from lighthouse abstraction
- Relevance, grounding in theory and contextualism from clockwork mechanism abstraction
- Backcasting was also deemed a suitable approach for realising the SDGs and African Union’s Agenda 2030 Goals [37].
- Backcasting, risk evaluation and scenario planning from future cones and foresight
- Technology management, collaboration and systemic change derived from the SDGs
- Systems thinking, design, engineering and management from Darwish and Van Dyk [40]

- Solution fragments related to the knowledge domains from Salvendy [1] that translate into operations management, engineering economics, human factors engineering, technology management and operations research as underlying industrial engineering knowledge domains for the lighthouse base
- Openness, people-centred processes, culture from Mangaroo-Pillay [42] adapted to people and culture
- Value creation from Alessandro, et al. [41]
- Innovation, economics, multi-level perspective and appropriate research methodologies from De Kock and Brent [45] used to create cascading levels in the lighthouse
- Culture, knowledge and technology from Holmberg and Larsson [37] are factored into the design
- Innovation and systems thinking from Asiimwe and De Kock [38] that ensure sustainable transitions
- Impact assessment from Botha [43]
- Four backcasting steps from McCrory, et al. [46] redirected as the slope from the lighthouse to the shore
- Seven elements for systemic creativity from Bam and Vlok [47] where process, leadership and potential are used in the lighthouse

All of the aforementioned solution fragments have been contextualised and morphed into a total of 28 solution fragments that are depicted in the lighthouse model in Figure 6.

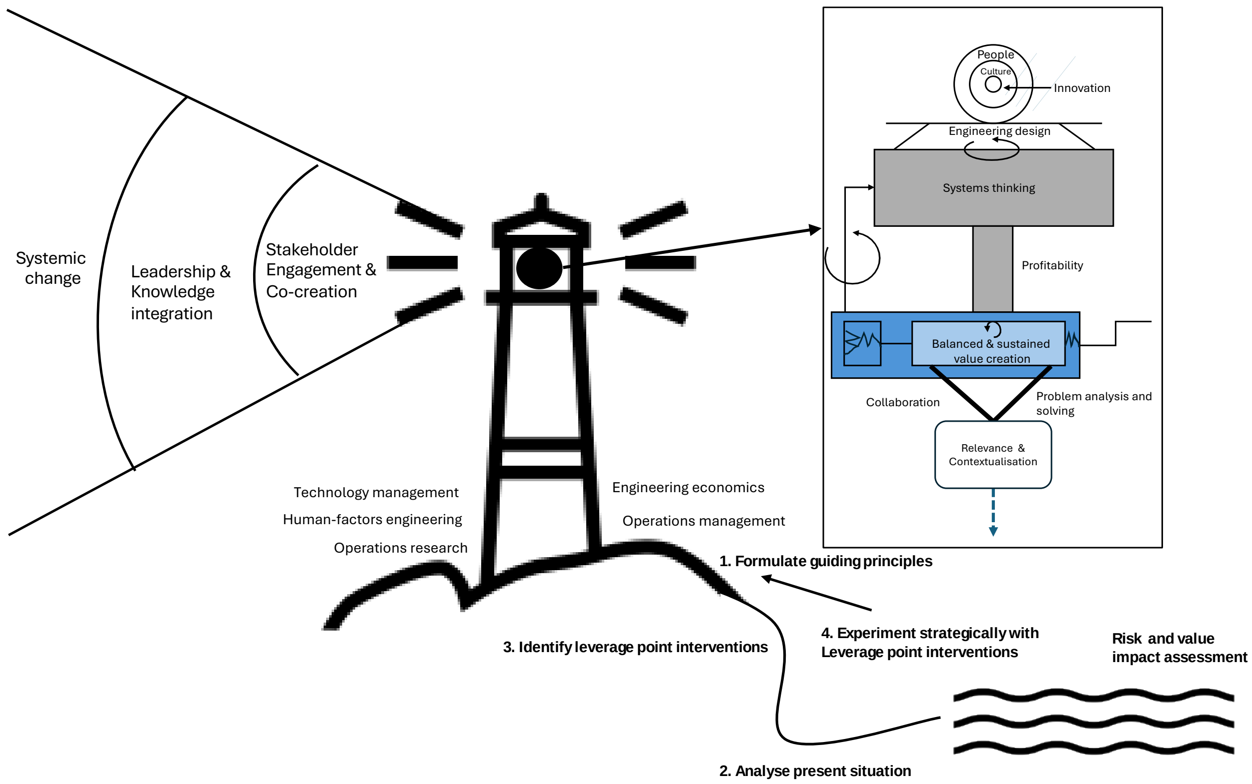

Figure 6: Industrial Engineering foresight model for transdisciplinary problem solving and sustainable development

4.4 Application and implications

The abstraction and subsequent visualisation coalesces this as a lighthouse model that harnesses and builds on the work from other South African Industrial Engineering artefacts. It demonstrates multiple perspectives using the skeleton 3D visualisation and five-sided theoretical base that represents the industrial engineering knowledge domains deemed most relevant to the research aim. The model walks towards the lighthouse through the backcasting process, builds up using the pertinent industrial engineering knowledge domains, leverages on the core clock and light mechanisms before projecting far-reaching attributes for its success.

Rittel and Webber [48] mention that for wicked problems, a range of possible solutions is the best resolve. Hence, this model should guide its user in producing a generic or case specific solution. The backcasting is applied at the bottom of the model, where the risk and value impact assessment lies in deep waters containing further complexities. The clockwork mechanisms embody the core aspects which were most recursive in the contextualisation stage of the research. The lens is comprised of people centredness and innovation at its core. Finally, the light begins with stages, ultimately leading to systemic change.

The model serves as a method to creating transdisciplinary solutions by providing the skeleton structure and crucial solution fragments that can foster systemic change through integrated knowledge and leadership that respects all stakeholders through co-creation. The implication of this model is that although holistic and generic, it demonstrates the valuable contribution industrial engineers can make when tackling complex solutions that exist in South Africa and other developing countries.

5 CONCLUSIONS AND RECOMENDATIONS

This research presents an industrial engineering foresight model for transdisciplinary problem-solving and sustainable development in South Africa. Not only does this strive to solve convoluted problems, but it also gives direction towards a problem-solving approach that the industrial engineer can lead irrespective of their industry.

Despite the advances this research makes, much like any research, there are of course shortcomings. One of the clear limitations is that this is unspecific to a sector or industry in South Africa. Therefore, this model can be repackaged to better suit set industries. Another drawback is that this has placed focus on South Africa, and while this could still easily apply to other developing countries, this is yet to be determined. Adaptations of this can look at modifications in other parts of the world.

Although this research is built on the icon or symbol of a lighthouse, alternative studies can explore other symbols for abstractions, but also, apply a lighthouse to contextualise and solve pressing issues.

The interest in the African Union’s Agenda 2063 goals is gaining much traction in academia. These 19 goals envisage a means of boosting economic growth and development through transformation on the continent. Even though the SDG’s have been factored into the design of the lighthouse model, to make this model more relevant to Africa, these goals could be considered and used for modifications.

Efforts can be made to have the findings from this research cascade further down the knowledge supply chain or into the quadruple helix. In this way, the components that belong to the lighthouse model may add more technical value to industry, academia, government and civil society.

A relevant and popular quote from the Harry Potter franchise belongs to Professor Albus Dumbeldore. In this fantasy novel series by Rowling [49], he said :

> *"Happiness can be found, even in the darkest of times, if one only remembers to turn on the light."*

This symbolises that the switch could resemble Industrial Engineering know-how, instincts, or traits that we embody. For us to "turn on the light" and find happiness in our solution, we must be vigilant of our impact on society in terms of sustainable development as we embark on new challenges, reach new horizons and sail in white water. As industrial engineers, we can solve the complex issues we face through collaboration, integrated knowledge, creative problem-solving, systems thinking and foresight.

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INCORPORATING BUSINESS INTELLIGENCE MANAGEMENT INTO THE ENGINEERING STEEL INDUSTRY TO ENHANCE ITS ECONOMIC RESILIENCE

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ABSTRACT

This study investigates the potential of using Business Intelligence Management to bolster the economic resilience of the South African engineering steel industry. The industry has faced recent challenges due to load-shedding and COVID-19, highlighting the need for improved adaptability and survivability. The study identifies external factors affecting resilience through consultations with industry experts and evaluates the potential benefits and challenges of implementing a BI model. A system dynamics-based BIM model was constructed using qualitative data from semi-structured interviews. This developed model highlights the importance of data-driven decision-making for enhancing economic resilience and identifies the bottlenecks from the TOC, which then derives the final model, proving the possibility of enhancing economic resilience once deployed. Further research is recommended to investigate the full-scale adoption of this model and its effectiveness in improving the economic resilience of organisations within the industry.

Keywords: economic resilience, business intelligence management, engineering steel industry, data-driven decision-making, system dynamics

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1 INTRODUCTION: BACKGROUND AND PURPOSE OF RESEARCH

The South African steel engineering industry has navigated a period of significant economic volatility in recent years. This instability has been compounded by unforeseen challenges, most notably the recent COVID pandemic, which factors have had a considerable negative impact on various industry players. Such unforeseen challenges continue to prevail but can be mitigated through effective resilience enhancement, which incorporates BIM into the industry [1]. Business Intelligence Management (BIM), which is related to the effective utilisation of data-driven decision-making, is a suitable risk mitigation support system [2][3], which, when implemented successfully in an organisation, may lead to enhanced economic resilience, which is the core focus of this study.

This research investigates the development and implementation of a System Dynamics-based BIM model designed to augment the economic resilience of the South African engineering steel industry. The model aims to mitigate risks and challenges faced by companies within this sector [2][3]. The study initiated a comprehensive literature review, examining the prevalent challenges encountered within South Africa's engineering steel industry while evaluating existing systems and frameworks. A scoping literature review was used to explore the domain thoroughly, pinpoint research gaps, and address key research questions.

The system dynamics model's (SDM) requisite data was gathered through a qualitative multiple-case study approach using semi-structured interviews. The study analysed variables, their interdependence, and desired model outcomes. The model was then iteratively refined and developed through semi-structured interviews with industry experts. Finally, the Theory of Constraints (TOC) was applied to the model to expose systemic bottlenecks and devise strategies for their resolution [4]. Following this, an examination of the solution's potential advantages and implementation challenges was conducted.

The following research questions were derived in line with the aim and objectives of the study:

1. Will the engineering steel industry benefit from implementing BIM to enhance economic resilience?
2. What are the best practices for BIM implementation to enhance economic resilience?
3. Will the ongoing management of the implemented BIM tool yield measurable performance outcomes in terms of economic resilience?

The following sections start with a literature review that is divided into two sections. The first is a general review, followed by a scoping review. The general literature review provides background to the study, while the scoping review was used to develop a preliminary conceptual model. This is followed by an iterative process of refining the model through interviews. The methodology is explained in Section 4, and the results are presented in Section 5. The progression of the model is discussed in Section 6, and the study's conclusions are given in Section 7.

2 LITERATURE REVIEW

The literature review consisted of a general literature review exploring typical Business Intelligence (BI) applications and challenges, followed by a Scoping Literature Review to address knowledge gaps specific to the engineering steel industry. The scoping literature review systematically identified research gaps, laid out the field of study and addressed the study's research questions.

The literature review commenced by defining the primary themes:

- Resilience is a system's capacity to endure disturbances while preserving its core structure and function [5]. This study examined resilience as a critical outcome of implementing BIM within the South African engineering steel industry.

- Risk involves exposure to danger, which may introduce unwanted consequences to a system or entity [6].
- Risk Management is the early warning approach to identify, manage and mitigate risk before it can harm the system or organisation [5].
- Data-driven decision-making involves making decisions based on analysing adequate, valuable data and not purely on intuition [7].
- BI is a data-driven digital support system combining data gathering, data storage and knowledge management with analysis to enable better data-driven decisions [8].
- BIM involves the management of BI technology (tools), processes, and human resources [2][9].
- System Dynamics is used to evaluate the complex, non-linear behaviour of a system(s) over time. It involves qualitative data (causal (feedback) loops) and quantitative data (stock-flow diagrams) [10].

2.1 General Literature Review

2.1.1 Prelude to Business Intelligence

Legacy systems within modern companies often represent significant investments of time and resources. However, these systems may require improved structure and usability for complex managerial decision-making [11]. While existing enterprise applications like Enterprise Resource Planning (ERP), Customer Relationship Management (CRM), and Warehouse Management Systems (WMS) provide operational reports, they offer limited analytical power for strategic needs [12]. Data Warehousing (DW) and Online Analytical Processing (OLAP) may address this by extracting and consolidating operational data, enabling multi-source analysis. This approach constitutes low-level BIM, providing insights for enhanced decision-making [13].

2.1.2 Data Silos and Data Warehousing

Functional silos within organisations often lead to isolated data stores focused on departmental metrics. This fragmentation hinders cross-functional insights and collaboration. While data warehousing aims to consolidate these data sources, it faces challenges, including cost, technical complexity, specialised skill requirements, and potentially less user-friendly analysis tools. Additionally, the data consolidation process can introduce delays, reducing the real-time data availability for decision-making [13].

Many industries contend with unstructured or poorly organised datasets, emphasising the need for preprocessing to make the data usable. Raw data alone offers limited decision-making value; algorithms and analytical structures are essential to extract insights. The sheer volume and complexity of data, even when centralised in a warehouse, can impede the swift, informed decision-making that executives require [13].

2.1.3 Business Intelligence and Management

Raw data processing can be time-consuming, hindering real-time reporting with traditional methods. BI addresses this challenge by enhancing data processing speed and quality, ultimately leading to improved decision-making and presentation[14]. BI revolutionises data management by transforming collection, storage, selection, analysis, and presentation processes. Notably, BI fosters the creation of new knowledge and understanding from raw information [14].

BIM encompasses two key components: human capital and technological infrastructure [15]. Human capital refers to the individuals who generate, utilise, and govern data transformation processes. In contrast, technological infrastructure includes the various BI tools and systems necessary for effective data management within an organisation. Successful BIM fosters a symbiotic relationship between these elements [15].

2.1.4 SDM and TOC

- System dynamics, originating from feedback control theory, decision theory, simulation, and computer applications, offer a valuable framework for analysis and simulation in BIM [16]. Its emphasis on systematic reasoning, learning, and investigation aligns with the goals of effective BIM [16]. Hence, system dynamics provides tools to study variables and relationships in complex systems [17].
- Causal loop diagrams (CLDs) are core components of system dynamics, visually representing variables and their causal relationships. CLDs support qualitative analysis, while stock-flow diagrams incorporate quantitative data to model rates of change. It is necessary to decompose the issue into influential factors and variables, followed by a rigorous causal analysis [18] to address complex problems such as economic resilience in the engineering steel industry. CLDs utilise positive and negative causal loops, as shown in Figure 1, where negative (balancing) loops maintain system stability, while positive (reinforcing) loops drive self-sustaining growth or escalate deviations [18][19]. Time lags can be incorporated to model delayed effects within feedback loops [20].

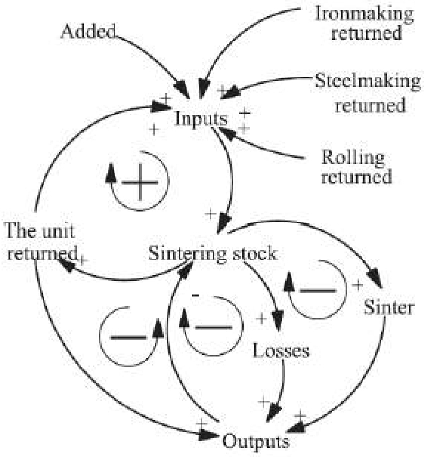

Figure 1 Causal Loop Diagram Example[16]

- System dynamics models can be taken further from CLDs (qualitative) by including rates of change and quantitative data [17], as this modelling approach is valuable for assessing dynamic resilience over time. In economic contexts, system dynamics aid decision-making in restoring a system to its pre-disturbed state [21]. The resilience principles (anticipation, monitoring, readiness, and learning) provide a framework for utilising system dynamics to mitigate risk and inform strategic decision-making for BIM [22].
- Goldratt's TOC offers a framework to augment BIM by identifying and addressing bottlenecks that hinder BI effectiveness. Constraints within BI systems can be systematically targeted for improvement or elimination through TOC implementation [4]. A robust BI Framework can mitigate these constraints, but its success requires a structured data collection, analysis, and decision-making approach. This approach is aligned with the long-term objective of BIM: ensuring optimal use of techniques, tools, and personnel.
- Real-time information access is paramount, maximising the value extracted from a well-implemented BI Framework [15].

CLDs aim to conceptually model dynamic systems, while BIM systems aim to measure the inputs and outputs of systems in real-time. Thus, it should be useful to develop a CLD and refine it before implementing a BIM system. This paper aims to develop this CLD that can potentially be further developed in a BIM application.

2.2 Scoping Literature Review

This study employed a scoping literature review developed by [23] to explore the knowledge base on BIM and its potential applications within the engineering steel industry.

The review adhered to the framework outlined by [24], involving the following key steps:

1. Defining Research Questions: Research questions were refined to address BIM's potential benefits, implementation best practices, and measurable resilience outcomes within the engineering steel industry.
2. Search Strategy Development: Search terms for Google Scholar were formulated and refined with the aid of AI tools (e.g., ChatGPT, Google Bard/Gemini) to ensure comprehensive coverage of relevant literature.
3. Data Extraction and Synthesis: Approximately 70 literature sources were analysed with Atlas.ti's AI-powered summarisation and coding tools.
4. Research Gap confirmed: The scoping review validated a notable gap in the literature explicitly relating to BIM while highlighting abundant resources on BI tools and implementation techniques.
5. Refined Research Focus: The identified gap informs the direction of this research, which seeks to address the management of BI systems and processes within the engineering steel industry to enhance economic resilience.

2.2.1 Research Question One

BI offers a competitive edge for the South African metals manufacturing industry. By integrating BI with frameworks like the TOC, companies can overcome data silos and enhance decision-making based on timely, integrated information [25][13]. BI tools facilitate data management for cost accounting, pricing strategies, and operational efficiency in the context of fluctuating steel prices [14]. Key advantages include [26][27]:

- **Improved decision-making:** Real-time access to accurate data enhances decision-making across various business functions.
- **Enhanced operational efficiency:** BI optimises processes, identifies inefficiencies, and aids in resource allocation through integrated data analysis (TOC integration).
- **Accurate performance measurement:** KPIs facilitate effective performance tracking across operations.
- **Proactive risk management:** Analysing historical and real-time data aids in mitigating supply chain disruptions, quality issues, and market volatility.
- **Enhanced customer insights:** BI offers a deeper understanding of customer behaviour and preferences.
- **Competitive advantage:** Companies gain a competitive edge through data-driven market trend analysis and business strategy optimisation.
- **Data-driven culture:** BI fosters evidence-based decision-making throughout the organisation.

A crucial aspect of BIM for the engineering steel industry is the ability to forecast steel prices, which directly impact economic resilience. Incorporating statistical methods, machine learning, technical analysis, and models like Long Short-Term Memory (LSTM), Gated

Recurrent Unit (GRU), and AutoRegressive Integrated Moving Average (ARIMA) into BI frameworks offers promising possibilities for accurate price prediction [28][29]. Due to their volatility and dependence on external factors, predicting steel prices may be complex. Accuracy metrics like Root Mean Square Error (RMSE), sensitivity, specificity, and correlation coefficients guide the evaluation of forecasting models [28]. Here's a summary of standard techniques [30]:

- **Multivariate Regression:** Analyses relationships between multiple variables and steel price.
- **Logistic Regression:** For classification tasks, potentially predicting upward or downward price trends.
- **Artificial Neural Networks (ANNs):** Inspired by biological neural systems, ANNs learn patterns from data to make predictions.
- **Decision Trees:** Rule-based models with potential advantages in steel price forecasting.
- **Random Forest:** Builds multiple decision trees for more robust predictions, particularly for classification.
- **Support Vector Machines (SVM):** Useful for both classification and regression problems.

Techniques from sales forecasting in the vehicle industry offer potential insights for steel price prediction [31]:

- **Moving Average (MA):** Forecasts based on recent historical trends.
- **Exponential Smoothing:** Uses weighted averages for more refined predictions.
- **Linear Regression:** Identifies linear relationships between variables.
- **Adaptive Neuro-Fuzzy Inference System (ANFIS):** Combines ANNs with fuzzy rule sets for enhanced learning and refined forecasting.
- **Data Normalisation:** Research suggests normalised and denormalised data can yield similar forecasting efficiency for neural networks [32].

Investigating Random Forest classification models within a BIM framework offers a promising avenue for enhancing economic resilience through more accurate price forecasting. Recent research demonstrates the promise of sophisticated techniques for price prediction:

- **Gaussian Process Regression (GPR):** Shows high accuracy in forecasting steel prices in the Chinese market [29].
- **Geometric Brownian Motion (GBM):** Predicts iron ore prices based on historical analysis [33].
- **Vector AutoRegressive Moving Average (VARMA):** Reveal unidirectional relationships between global oil and steel prices, highlighting external factors influencing steel [34].
- **Laspeyres Method:** Successfully models steel price indices in China for market stabilisation [35].

While mathematical models offer value, they can be enhanced by integrating real-time data using BI and machine learning. Understanding macroeconomic influences (i.e., consumer prices, exchange rates, inflation) is crucial, given their impact on metal and steel prices [36][37]. Combining techniques like Multivariate Empirical Mode Decomposition (MEMD), Particle Swarm Optimisation (PSO), Least Squares Support Vector Regression (LSSVR), and the GARCH model offers promising accuracy in forecasting steel price indices. Successful BIM is critical for gathering the vast historical and real-time data required for these models [38].

Based on the above research, the engineering steel industry stands to gain economic resilience from BIM. Accurate steel price forecasting, powered by BI's real-time data management capabilities, is the cornerstone of this advantage.

2.2.2 Research Question Two

From the research, external factors that directly influence the steel price and pose challenges for BI implementation include:

- **Rand-dollar exchange rate:** Fluctuations significantly impact import/export costs.
- **Inflation:** Impacts production costs and overall economic stability.
- **Repo and prime lending rate:** Affect investment and financing decisions.
- **Volatile demand:** Makes forecasting and resource management difficult.
- **Socio-political factors:** Strikes, regulations, and policy changes can disrupt operations.
- **Global Steel Price Index:** Influences the pricing of domestically produced steel.

Employing foresight within BI through data mining, information mining, and predictive modelling is vital as these were crucial for accurate steel price forecasting [39]. With these factors understood, Balanced scorecards in Business Performance Management can be used to help ensure plan execution [40]. Once external factors, tools, and a comprehensive plan are in place, a structured roadmap can guide successful BI system implementation and management.

2.2.3 Research Question Three

BIM aims to mitigate business disruptions, fostering resilience - the ability to recover quickly from adverse events [13][5] in the way inter-operational stability and proactive risk management are crucial for resilience [13]. The research shows that combining risk assessment with data-driven decision-making is a vital component of a robust BIM strategy for enhanced economic resilience.

2.2.4 Scoping Literature Review Findings

Research Gap: BIM

Extensive literature exists on BI tools, implementation, and utilisation. However, this study aimed to develop a conceptual model tailored to the engineering steel industry. Existing literature focuses on BI tools and processes, but dedicated management platforms require further exploration [41].

Potential for System Dynamics Integration

System Dynamics (SD) offers a valuable framework bridging BIM and complex system analysis. While the literature on SD and CLDs is readily available, research specifically combining BIM with SD is limited. Understanding the overlaps between these fields could yield innovative approaches for data-driven decision-making and problem-solving.

Future Research Directions:

- **Quantifying Performance Improvements:** Studies are needed to quantify performance gains from BIM implementation.
- **Innovative BI Applications:** Research should explore how BIM can facilitate early warning systems to enhance economic resilience and competitive advantages [6].
- **Maturity Assessment:** Enterprise BI Maturity models can assess the capabilities of a fully implemented BIM system in the engineering steel industry [42].

3 CONCEPTUAL MODEL

The proposed conceptual model forms the core of this research, integrating literature findings within a theoretical framework. Existing BI models primarily focus on tools and implementation. This model extends those by incorporating BI models, frameworks, and tools alongside human capital and processes, with effective management of this triad essential for achieving the desired outcomes. The model drew upon existing tools and techniques for forecasting and data analysis. TOC is incorporated into the model, emphasising the importance of identifying and addressing the most significant constraints inhibiting a company's resilience and competitiveness [25][4]. The model aims to streamline and enhance existing forecasting approaches used in various industries. By leveraging BIM and AI alongside mathematical models, the goal was to develop more accurate and efficient steel price forecasting/early warning for the engineering steel industry. A foundational SDM in the form of a CLD was developed to manage the inherent complexity of a full BIM model. This CLD served as a framework for:

- **Identifying Model Inputs:** Defining variables and factors impacting the system.
- **Determining Dependencies:** Clarifying the relationships between model variables.
- **Defining Model Outputs:** Outlining the model's intended results.
- **Assessing Advantages:** Understanding potential benefits of model implementation.
- **Exploring BI Integration:** Considering pathways for incorporating the model within a comprehensive BIM framework.

The conceptual model, depicted in Figure 2, provided a structured basis for qualitative data gathering, clarifying complex system interactions and identifying bottlenecks. This model established a foundation for further refinement.

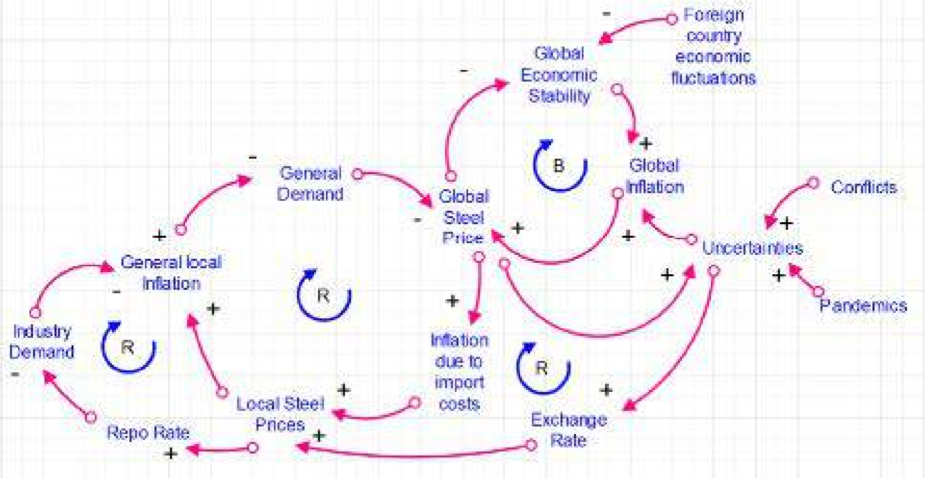

Figure 2 Theoretical Conceptual Model

The identified causal loops illustrate the complex interplay of factors affecting the steel price and economic resilience. These loops are characterised as:

- **Reinforcing Loops (as per Figure 2):**
  - **Loop 1, 2, 3 (from left to right):** Highlight the cyclical nature of steel price fluctuations, inflation, demand, and economic uncertainty.
- **Balancing Loop (as per Figure 2):**
  - **Loop 4:** Demonstrates the counterbalancing effect of global economic instability on steel prices.

The conceptual model aims to test the following propositions regarding BI implementation's potential impact:

- Proposition 1: BI implementation can lead to improved Decision-Making.

- Proposition 2: BI implementation can lead to the identification and management of risks.
- Proposition 3: BI implementation can lead to better data utilisation.

The proposed model was designed to achieve the research objectives by:

- **Addressing Economic Challenges:** Investigating the specific economic hurdles engineering steel companies face.
- **Enhancing Economic Resilience:** Developing a BIM model to bolster the resilience of companies in response to external factors.

4 METHODOLOGY

4.1 Research design

This study employed a qualitative multiple-case study approach, gathering primary data through semi-structured interviews with an action research approach selected due to the industry's awareness of existing challenges and the need for an innovative solution. This approach allowed the solution to be developed collaboratively during interviews, drawing upon industry knowledge and expertise to address the identified problems.

4.2 Data and Sampling

The research setting was the four main types of steel engineering companies in South Africa: a steel merchant, a steel processor, a steel profiler and a machine builder. The process was fulfilled as follows:

- Semi-structured interviews.
- Participants were purposely selected to represent the diverse South African engineering steel industry sectors.
- The conceptual model served as a foundation for the action research process. Through iterative discussions, the author and interviewees collaborated to identify critical inputs, variables, interdependencies, desired outcomes, potential benefits, deployment challenges, and considerations.
- The intermediate SDM was shared with industry players for evaluation and feedback, which informed the development of the final model.

5 RESULTS

5.1 Semi-structured interviews

Semi-structured interviews provided qualitative insights that informed the further developed SDM CLD (Figure 3) from the model shown in Figure 2 and its subsequent refinement (Figure 4). Informants were selected based on their industry expertise and granted anonymity. A thematic analysis approach was employed, comprising the following steps[43]:

1. **Data Preparation:** Organisation and transcription of interview recordings.
2. **Familiarisation:** Initial review of data corpus to identify potential gaps.
3. **Memoing:** Capturing emergent understandings of the data.
4. **Coding**: Descriptive coding, identification of themes, and concept grouping.
5. **Categorisation:** Development of themes aligning with research questions and analytical goals.
6. **Transparency**: Mapping the analysis process for research quality.

The interview process prioritised addressing the primary research questions, with a secondary focus on enhancing the CLD and potential integration into a future BIM model.

1. Will the engineering steel industry benefit, and in what way, from the advantages of implementing BIM to enhance its economic resilience?

   It is identified that BIM can significantly benefit organisations facing substantial uncertainty across political, operational, and economic domains. By systematically mapping these factors and leveraging existing data, companies can develop early warning mechanisms to mitigate risks associated with unforeseen events. This approach aligns with fundamental BIM principles, promoting data-driven decision-making and maximising the value of existing information resources.

2. What are the best and most optimal practices for BIM Implementation in the engineering steel industry to enhance its economic resilience in selecting the right tool, change management and staff training to utilise this practice?

   Informants were unable to directly address this research question due to the novelty of the topic within the South African engineering steel industry. However, interviews revealed strong interest in piloting the proposed BIM approach. Participating industries possess the financial resources and IT infrastructure necessary for such a project. Implementing this initiative would necessitate extensive staff training and aligns well with action research and change management methodologies.

3. Will the ongoing management of the implemented BI tool in this industry yield measurable performance outcomes in terms of economic resilience?

   Informant responses to the proposed SDM-based BIM approach and CLD visualisation indicate strong support for further development. The potential value is recognised, and transitioning the model into a quantitative stock-flow format will enable measurable performance outcomes. This method aligns with the informants' shared desire to enhance economic resilience within the engineering steel industry.

5.2 Initial SDM

The primary objectives of qualitative data coding were to identify:

1. **Inputs and Variables**: Specific factors influencing the system under study.
2. **Relational Dynamics**: How inputs and variables interact within the model.
3. **Desired Outcomes**: The intended results and benefits informants anticipate from the model.
4. **BIM Integration**: The potential for incorporating the model into a broader BIM framework.

The variables are shown in the output model (Figure 3).

5.3 Causal Relationships for both Initial and Final Models

Referring to Figure 3 (Left to Right):

Reinforcing Loop 1 logic flow:

1. Local economic steel stability
2. Rising local steel prices contribute to inflation.
3. Inflationary pressures lead to increased repo rates.
4. Higher repo rates influence the supply-demand ratio, favouring increased availability of steel and other goods.
5. Inflation subsequently decreases in the medium term, leading to a potential reduction in local steel prices.
6. This loop represents a self-perpetuating cycle with both rising and falling phases.

Balancing Loop 1 logic flow:

1. Global economic stability
2. Increased global steel prices discourage imports, favouring local production.
3. Higher demand for local steel drives up prices.
4. Rising prices create the potential for increased profit margins.
5. Potential profit growth stimulates investment and employment.
6. Increased economic activity contributes to more excellent global stability.
7. Stabilised market conditions may moderate steel prices but could also lead to long-term increases due to overall rising demand.
8. This loop demonstrates a self-regulating mechanism seeking equilibrium within the global market.

Reinforcing Loop 2 logic flow:

1. Chinese steel market dynamics
2. Elevated global steel prices increase competitiveness for Chinese steel.
3. Higher Chinese steel prices stimulate the Chinese economy.
4. A strengthened Chinese economy further elevates Chinese steel prices.
5. Increased Chinese steel prices contribute to rising global steel price indices.
6. This loop depicts a self-reinforcing cycle within the Chinese steel market and its impact on global prices.

Figure 4:

Additional Causal Loops after sending the model back to industry:

Reinforcing Loop 3 logic flow:

1. Chinese competitiveness and global impact
2. Elevated Chinese steel prices make local South African steel more expensive to maintain competitiveness with imports.
3. Higher prices create the potential for increased profit margins (for select companies).
4. Potential profit growth stimulates investment and employment.
5. Increased economic activity contributes to greater global production capacity.
6. Enhanced global stability and affordability may further elevate global steel prices, including Chinese prices.
7. This loop represents the influence of Chinese market dynamics on South African steel pricing and the broader global economy.

Balancing Loop 2 logic flow:

1. Data-driven decision-making (BIM) aims to reduce the likelihood and impact of conflicts and pandemics.
2. Mitigated uncertainties contribute to fewer fluctuations within foreign country economies.
3. Enhanced global economic stability promotes adopting data-driven decision-making (BIM).
4. This loop emphasises the potential of BIM to mitigate risk, reduce bottlenecks in the system, and promote global economic resilience.

5.4 Output

Industry players anticipate comprehensively analysing identified variables, inputs, and their causal relationships. This analysis should culminate in a complete CLD that accurately reflects the qualitative data and depicts the complex system under study. A key goal is to visualise system bottlenecks, enabling mitigation or elimination in accordance with the TOC [4]. The desired output should offer a unified view of political, economic, and operational factors, highlighting how improved data utilisation within these domains can enhance the economic resilience of the industry.

5.5 Model Visualisation

Guided by the principles established in the Literature Review, the variables and inputs were converted into Causal relationships, refined into reinforcing and balancing loops and developed into a CLD, as shown in Figure 3.

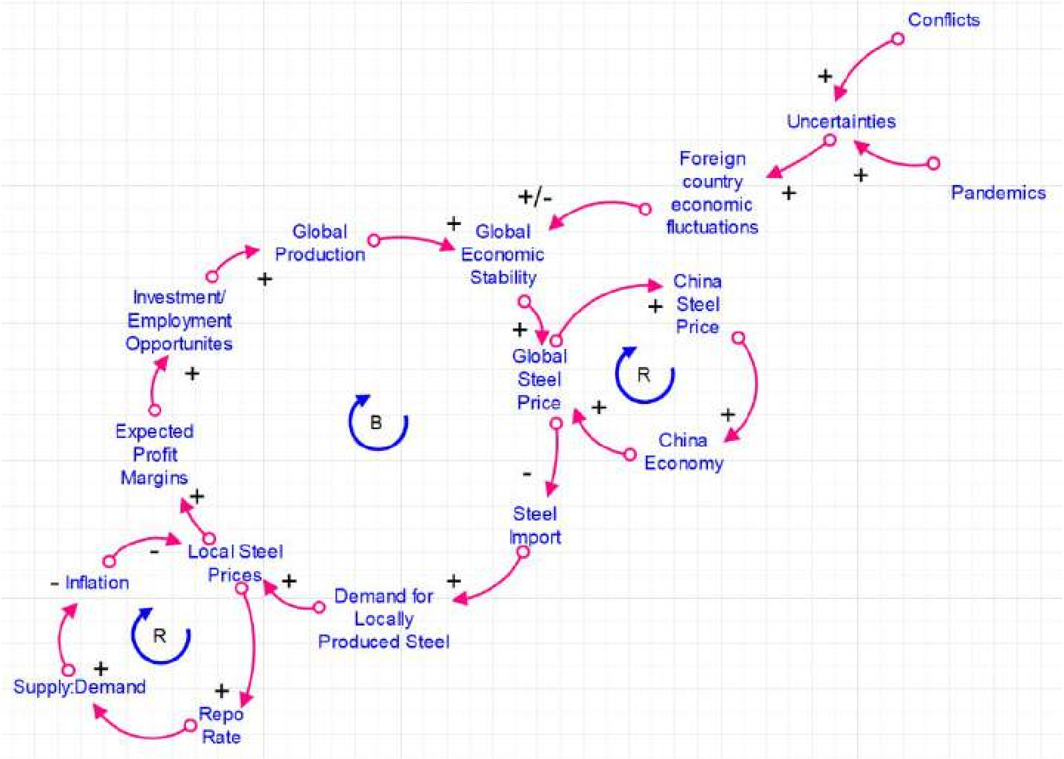

Figure 3 Initially Developed CLD from interview data.

5.6 Final SDM

Industry players reviewed the model and provided feedback. Based on their suggestions, revisions were made to the model, resulting in the updated version depicted in Figure 4. The TOC was applied to identify the system bottleneck, as seen in the Global Economic Stability section below. With these resolved and eliminated, BIM did the rest and ensured stability, as discussed in this study.

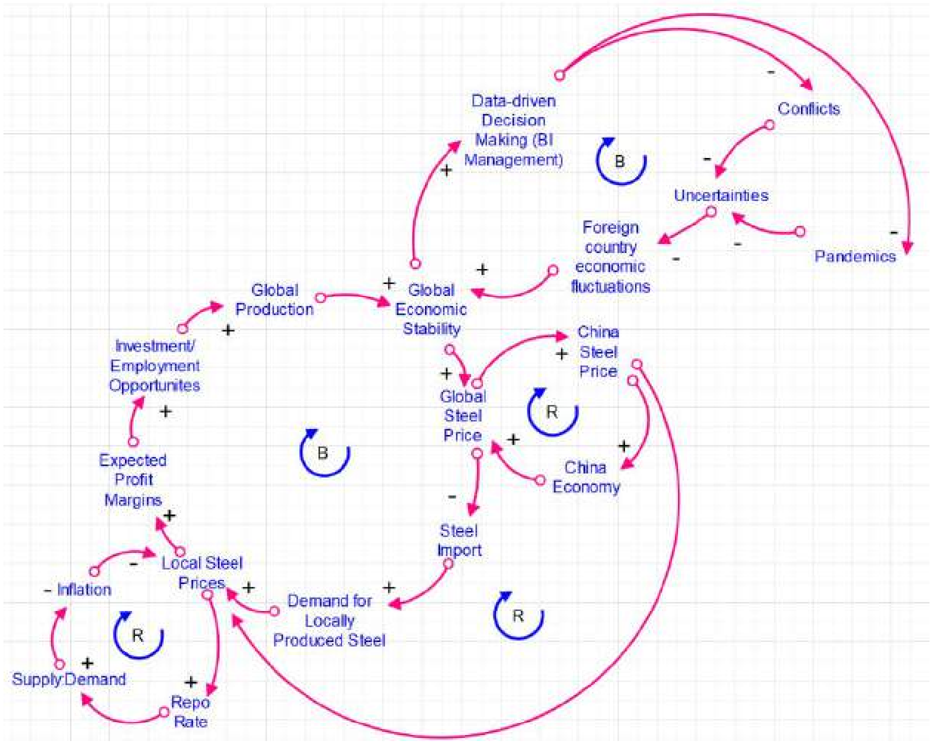

Figure 4 Final CLD developed from further industry response

5.7 Advantages

Qualitative data gathered from semi-structured interviews and subsequent feedback revealed the following potential advantages of the proposed system:

- Improved Data-Driven Decision-Making
- Enhanced Resource Planning and Acquisition
- Strengthened Risk Mitigation
- Market and Economic Surveillance
- Early Warning Capabilities

6 DISCUSSION

The Initially Developed CLD (Figure 3) was developed based on industry interviews exploring challenges and potential solutions within BIM. Qualitative insights from industry feedback developed the Final CLD model (Figure 4), which will serve as the basis for future research to enhance data-driven decision-making within the South African engineering steel industry.

The significance of the relationship loops (reinforcing and balancing) introduced in the preceding section, as well as correlations between loops and their implications for the South African engineering steel industry, are now analysed:

Figure 5 illustrates five primary loops within the Final SDM CLD:

1. Reinforcing Loop 1 (blue): Represents the dynamics of local South African economic factors and their influence on consumer goods prices, including steel.
2. Balancing Loop 1 (red): Depicts the interaction between global and local economic factors.
3. Reinforcing Loop 2 (gold): Shows internal economic relationships within China.
4. Reinforcing Loop 3 (yellow): Illustrates how Chinese economic factors affect global and South African markets.

5. Balancing Loop 2 (black): Demonstrates the potential of BIM to mitigate global uncertainties within foreign countries.

Balancing Loop 2 functions as such only with the integration of BIM; otherwise, this loop would reinforce negative price impacts due to pandemics and conflicts. Mitigating this bottleneck through BIM and the TOC is crucial for enhancing economic resilience. Improved resilience within foreign economies could subsequently stabilise steel prices, promoting overall economic stability and gradual price increases within the sector. This result is natural when economies flourish, and the local and global industries are making economic gains.

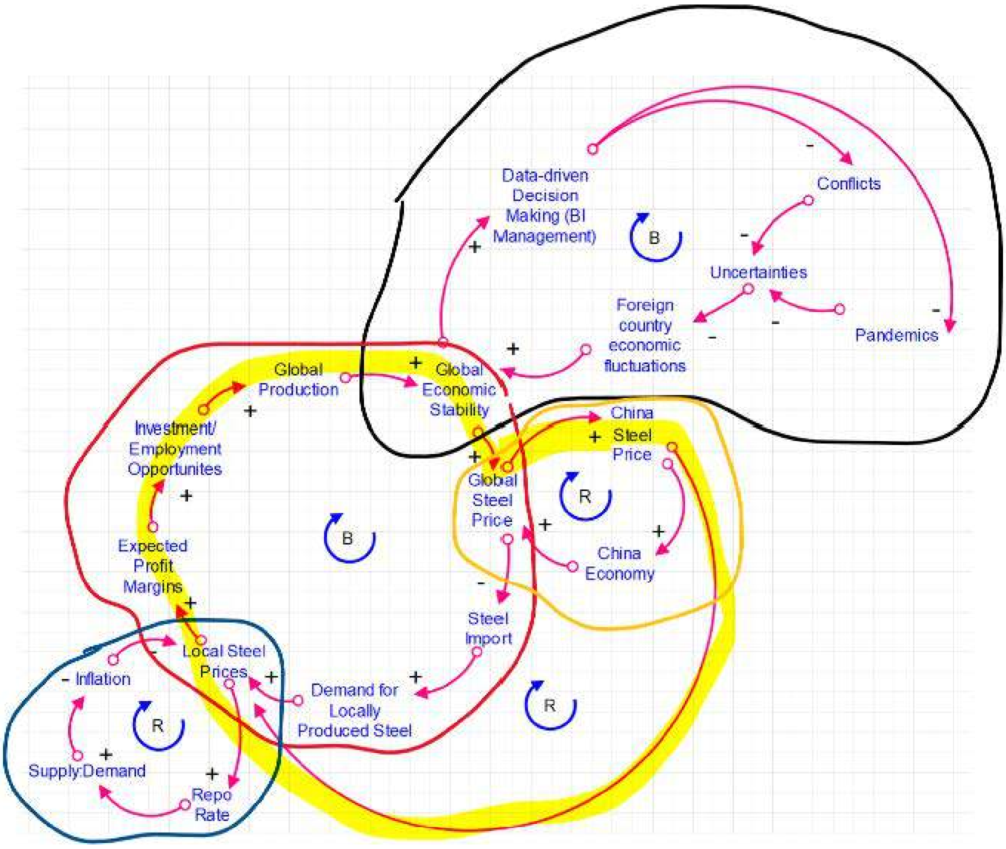

Figure 5 Analysed Final CLD

Figure 6 illustrates the iterative development process of the conceptual model. It begins with the initial CLD. This initial CLD is then refined based on input from industry players. The subsequent iteration incorporates the effects of BIM as a potential solution to enhance the economic resilience of companies within the steel engineering sector. This final model can be integrated into the broader framework of BIM, transforming it into a BI-centric model. This BI-centric model can then be further developed and deployed within a BIM system for testing and application in companies and large organisations throughout the steel engineering industry.

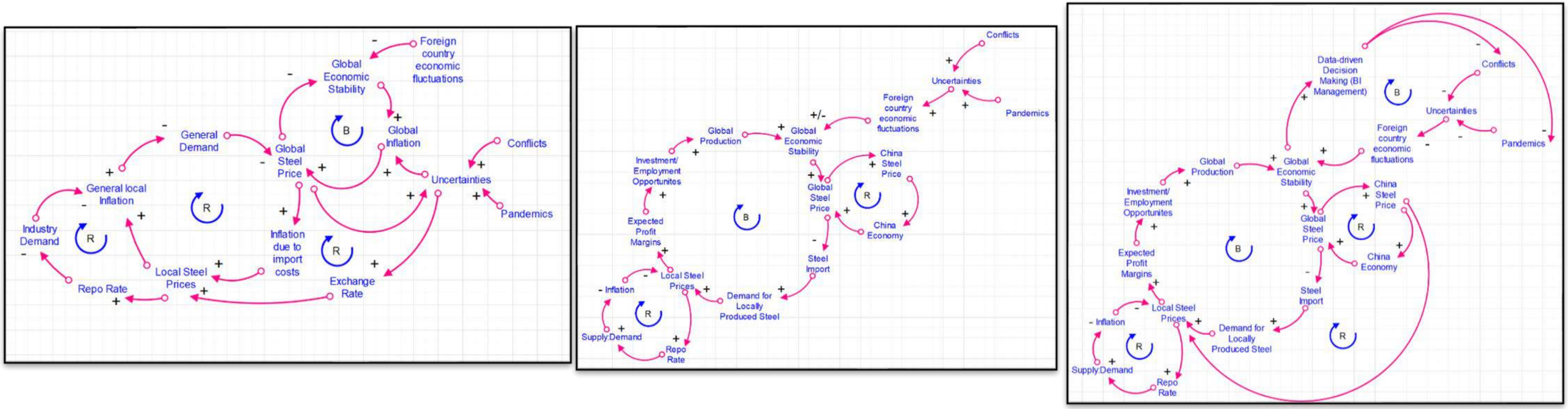

Figure 6 Development Process of CLD Model

7 CONCLUSIONS

This conclusion synthesises the research findings related to the study's three propositions and three research questions.

7.1 Proposition Conclusions:

Proposition One

The data obtained was analysed and extracted to identify risks, bottlenecks, and critical drivers to enhance economic resilience. By managing this model, it allows a continuous process to improve decisions in routine and unstable circumstances. Through sufficient early warning and data, necessary decisions are made to minimise the company's susceptibility to disturbances such as threats, demonstrating enhanced resilience.

Proposition Two

Implementation leads to proactive risk management and mitigation. The enhanced awareness and encouragement of better data utilisation for better data-driven decision-making will assist businesses in identifying and mitigating risks such as threats, making better economic decisions, minimising economic disruptions, and thus enhancing their economic resilience.

Proposition Three

The research shows that enhanced economic resilience is being implemented via data-driven decision-making. This results in improved data utilisation and benefits such as better risk identification, mitigation and management. This finding suggests an infinite loop is created; thus, Business Intelligence implementation leads to better data utilisation.

7.2 Research Questions Conclusions

Research Question One

The study found that the engineering steel industry could benefit from continuous analysis and early warnings of global uncertainties and external factors. Having this early warning knowledge enhances economic resilience, which allows companies to adapt to these disruptions, mitigate risks better, and minimise adverse economic impacts.

Research Question Two

A full BIM model is complex as established due to the mentioned constraints and limitations. In contrast, the System Dynamics-based BIM model can be developed and deployed far quicker to address resource constraints. The study indicates that the SDM can be used to assess complex systems to help companies manage uncertainty for enhanced economic resilience.

Research Question Three

The industry players believe the developed BI-based tool will be able to add an economic buffer against price fluctuations and unexpected events, improve data-driven decision-making, and provide more predictable operations.

7.3 The SDM

An SDM was developed to facilitate the dissection and comprehension of economic resilience within the South African steel engineering industry. The qualitative analysis, mainly the CLD developed, revealed critical interdependencies and potential bottlenecks, utilising the TOC within the derived system model, which set the foundation for future research efforts. These efforts can further this study by integrating this model with a dedicated BIM model and system.

The resulting model framework can enhance economic resilience by utilising the advantages gained from the data-driven decision-making processes encapsulated within this approach.

8 RECOMMENDATIONS AND FUTURE RESEARCH

Considering the complexity of BIM systems, particularly where SDM is integrated, full deployment within the engineering steel industry is essential for further development and quantitative analysis. Future research could develop and deploy this study's System Dynamics-based BIM model. Further research may refine the Casual Loop Diagram into a quantitative Stock-Flow Diagram based on differential equations. Real-time data acquisition would then make it possible to comprehensively measure and realise this study's original intended long-term outcomes.

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EVALUATION OF THE SOUTH AFRICAN SAWMILL INDUSTRY'S NATIONAL COMPETITIVE ADVANTAGE USING PORTER'S DIAMOND MODEL

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ABSTRACT

Wood is a renewable resource that can be transformed into many different products and stores carbon in products in service. The wood-based industry in South Africa is one of the industries that contribute to the country's economic development. Most wood-based products are used locally, and some are exported. The study evaluated the export competitiveness of the South African wood-based industry. The analysis of the Revealed Comparative Advantage (RCA) index for different wooden products over time mainly showed a decline in the RCA index value for the different wood-based products. Porter's diamond model was used as a framework for analysing the South African sawmill industry, which revealed the factors affecting South Africa's competitive advantages on a global scale. Future studies should look at ways individual sawmills can create national advantages to drive the competitiveness of the sawmill industry to increase local usage and export using prediction models and other economic indexes.

Keywords: National competitiveness, Revealed comparative advantage, Wood products, Renewable resource, Sawmill industry

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1 INTRODUCTION

Sawmillers in South Africa are under growing pressure to boost their competitiveness on a national and international level [1],[2]. Many countries highly value the forest products industry because it offers revenue and employment in rural areas [3]. Commercial forests are being developed and preserved to meet the increasing demand for timber-based goods in the global market [4]. Sawn timber is significant in climate change mitigation and can replace alternative raw materials with larger carbon footprints [5]. Trees act as a sink for carbon while growing and play a significant role in the earth's carbon cycle through carbon sequestration [4]. In the current global market, firms must compete with national rivals and international firms [6]. Hosseini [7] emphasised that most sawmills worldwide have inefficient operations with high raw material waste. Regarding competition in the sawmill industry, Sasatani and Zhang [8] observed that more extensive facilities were less likely to close. In contrast, mills owned by corporations with many mills were much more likely to close. Several sawmills have invested in innovative production technologies reliant on automated sawing systems to increase their productivity, frequently focused on enhancing some constrained features, such as economic profits obtained from new sawmilling machinery, and ignoring the reality that different factors must be addressed to meet increasingly complex market needs leveraging limited and fluctuating raw material supplies [7] [9]. For this reason, it is essential to ensure that the sawmill industry in South Africa strives to be competitive on the world stage. The concept of competitiveness is argued to vary based on the measure, structure, and objective of its use [10]. Competitiveness could be founded on the comparative edge concept, which is based on economic concepts, or competitive advantage, which is founded on political and business notions [11]. This study uses Porter's diamond model framework to evaluate the South African sawmill industry’s national advantage. Secondary data on competitive indicators was also used to form the basis for discussion.

2 LITERATURE REVIEW

2.1 Porter’s Diamond model

The theory of competitiveness was introduced by Micheal Porter, who introduced the diamond model to explain national competitiveness [12]. Porter's diamond model denotes a framework for evaluating why specific economic industries inside a country are competitive worldwide and arguments for why they are not [13], [14]. The diamond model can analyse internal and external factors significantly influencing an industry [13], [15]. Porter's Diamond model determinants are categorised into six major categories, as shown in Figure 1, and have become an essential instrument for competitiveness analysis. Demand conditions, Factor conditions, Related and supporting industries, and the Firm's strategy, structure, and rivalry considerations are all significant determinants of competitiveness. The model's other two components are governance and chance/opportunity. To attain a national competitive edge, the government positively influences each component. A chance event or occurrence is any event or incident beyond a company's control [16]. Some authors argue that the model in itself only focuses on national competitiveness and might exclude other key aspects [17]. Davis and Ellis [18] highlighted that many globally renowned business sectors do not have these strong determinants in their nations, and inbound foreign direct investment does not indicate low national productivity or a lack of competitiveness. Due to these shortcomings, certain authors have amended the model to accommodate other aspects, such as the size of the country or innovation activities in the country [19]. For this study, Porter’s diamond model was used without amendments as it covered aspects the study aimed to assess.

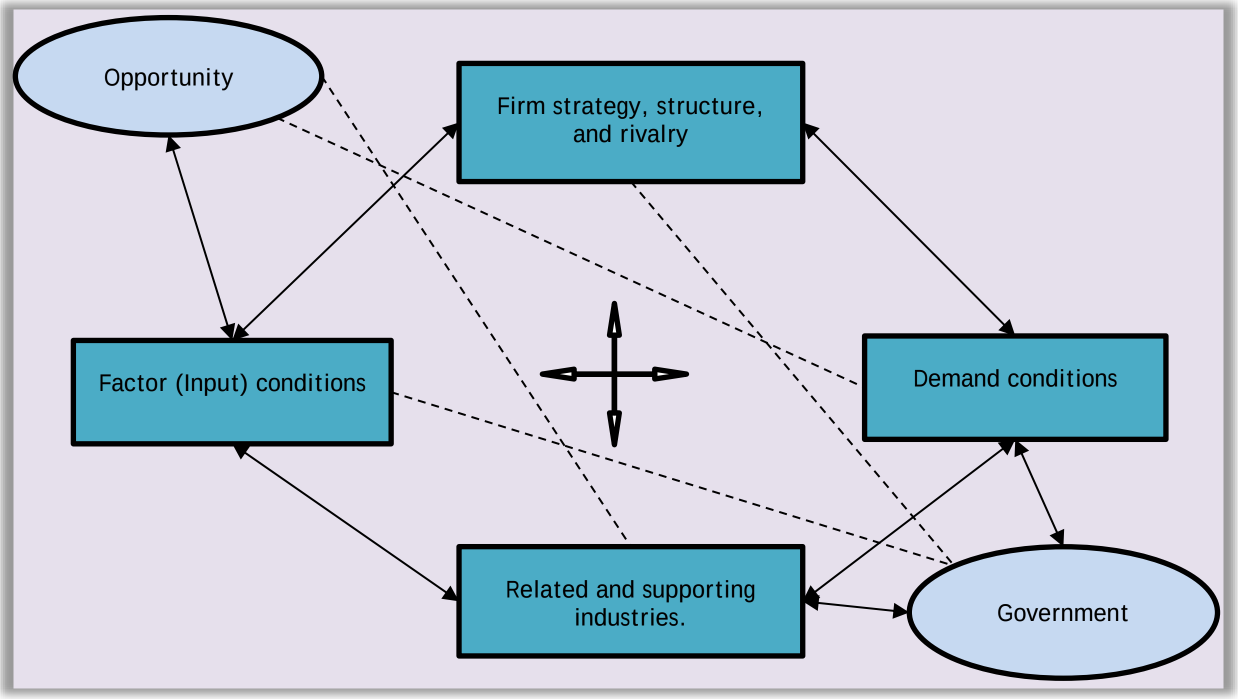

Figure 1: Porter Diamond Model source. Redrawn from [16]

2.1.1 Factor conditions.

Factor conditions are values of a firm that influence competition and are crucial in ensuring involvement in the rivalry of a specific industry [20][21]. They include skilled labour, the knowledge base, capital, infrastructure, technology, etc. [20], [22], [16]. These attributes frequently provide initial benefits, which are expanded upon [23]. Factors associated with an industry's needs imply an ongoing significant investment [24]. Porter [16] mentioned that advancements in technology and rivalry have diminished many of the traditional functions of location as a determinant because supplies, capital, advances in technology, and numerous other components can be efficiently supplied in global marketplaces and, as a result, it is no longer required to locate near big markets to serve them.

2.1.2 Demand condition.

Demand conditions determine the rate and trajectory of breakthrough ideas and product establishment [23]. The extent, rate, and nature of demand for items or services offered by the local market and the estimation of local demand for overseas markets are referred to as demand conditions [19]. Demand conditions include factors such as the magnitude of home demand, the number of independent buyers, demand portion structure, complex and demanding buyers, pre-emptive buyer requirements, early saturation, local demand growth rate, early home demand, portable or international regional buyers, and foreign buyer influences [10]. Countries gain an edge in industries when domestic demand gives enterprises a better understanding of customer demands than overseas competitors [20].

2.1.3 Firm strategy, structure, and rivalry.

According to Michael Porter, firm strategy, structure, and rivalry pertain to the national framework in which enterprises operate and how varied management methods can foster innovation and competitiveness [25], [22]. There is variability in configurations and tactics among firms, and some will work better than others [26]. Previous research on numerous industries found that the likelihood of firm survival/closure is positively associated with the firm's size due to economies of scale [8]. National rivalry ensures international competitiveness by pushing firms to develop economically effective and sustainable business strategies. On the other hand, domestic rivalry or competition is inefficient as it replicates efforts without cause and threatens scale economies [24]. Local company rivalry and the pursuit of competitive advantage within a country can offer foundations for firms to achieve such an advantage internationally [23]. Public ownership and licensing rules, antitrust laws, and trade and foreign investment policies influence regional rivalry [25].

2.1.4 Related and Supporting Industries.

Related and supporting industries primarily represent sectors closely linked to the industry, particularly the upstream and downstream value chains [10]. Suitable related and supporting industries provide firms with additional competitive advantages and prospects to utilise their goods or services [26]. When regional supporting industries are competitive and robust global competitors, firms appreciate more cost-effective and groundbreaking inputs from the supporting industries in the value chain [23]. This is because firms in related and supporting industries influence their suppliers' innovation efforts [24]. Savić et al. [26] say that more sophisticated products and post-purchase support can be provided through a well-established value chain network inside a certain country or region. The significance of related and supporting industries stimulates the propensity to cluster [27]. Porter [16] says that the industry's quality significantly shapes the sophistication of how firms compete in a region.

2.1.5 Government.

Countries' competitive advantage and regions' competitiveness have emerged as critical issues in economic policy [28]. The government can affect competitiveness by intervening in political matters, the economy, and society and enacting policies that affect the industry [20]. Policies employed without regard for the effects of the factors affecting competitiveness tend to deteriorate national competitiveness [11]. The government positively influences the four determinants to achieve national competitive advantage [13], [26]. The government of a nation could increase or reduce the national competitiveness [11]. According to Porter [25], governments have significant roles in creating a setting to assist in growing productivity.

2.1.6 Opportunity (chance).

Chance or opportunity refers to occurrences outside of the firms' and generally the nation's government's control, such as innovations, technological developments, external political pressures, large swings in overseas demand, and so on [20], [13]. Opportunities can cause interruptions that could change or reorganise the industrial structure, resulting in new possibilities for business entities to replace past opportunities [11]. Chance or opportunity significantly shifts the competitive advantage in many industries [20]. Although not a main determinant, opportunity influences the four main determinants [29].

2.2 Measurement of export competitiveness

An industry's ability to compete internationally is gauged using Balassa's Revealed Comparative Advantage (RCA) approach [30]. Several authors have used the RCA index to study the export competitiveness of products in various industries [31],[32],[33]. The ratio of a nation's export of a given good to its overall export value to the export share of that good in global trade is known as revealed comparative advantage. The method to calculate the RCA is shown in equation 1 and was explained in the context of measuring the RCA in the wood-based products industry.

$$[RCA_{ij}] = \left[\frac{\frac{x_{ij}}{x_{it}}}{\frac{x_{wj}}{x_{wt}}}\right] \qquad (1)$$

$\frac{X_{ij}}{X_{it}}$ selects the ratio of South Africa’s wood-based product export trade to South Africa’s total export trade and $\frac{X_{wj}}{X_{wt}}$ selects the proportion of the world's wood-based merchandise exports to the entire export. The values for RCA are measured using the categories in Table 1 [34]. The table shows that if the RCA value is smaller than 0,8, then the competitiveness level is weaker, and for an RCA value larger than 2,5, the export competitiveness level is higher.

Table 1: The scale of the RCA index and its associated competitiveness [34]

Competitiveness level	RCA index size
Weaker	RCA < 0,8
Moderate	0,8 < RCA < 1,25
Stronger	1,25 < RCA < 2,5
Very strong	RCA > 2,5

3 METHODOLOGY

The study used a desktop study approach to gather data to evaluate the South African Sawmill industry's national advantage through Porter’s diamond model framework. Past studies conducted in the forestry and sawmill industry in South Africa were identified, and their results were used in the model. The study also used time series secondary trade data obtained from Unctadstat [35]. The data was used to plot charts to understand South Africa’s export competitiveness of wood-based products produced in South Africa.

4 RESULTS AND DISCUSSIONS

4.1 Revealed Comparative Advantage analysis.

The data from Unctadstat [35] was used to plot the annual Revealed Comparative Advantage (RCA) index values for different wood and wood residue products. The data shows the trade indicators for wood-based products manufactured in South Africa. The N.E.S. (Not Elsewhere Specified) establishes the right export control classification number [36]. The product grouping that was selected was:

- Wood manufacture, N.E.S.
- Veneers, plywood, and other wood worked, N.E.S.
- Wood in chips or particles and wood waste.
- Wood in the rough or roughly squared.
- Fuel wood (excluding wood waste) and wood charcoal.
- Paper and paperboard.

The plots in Figures 2 to 7 were plotted to include the graph showing the threshold for weaker RCA value, which is at 0,8, as discussed above. The revealed comparative advantage index values for *wood manufacturing N.E.S.* show a decline since 2006, as shown in Figure 2. The chart shows South Africa's export competitiveness level is declining as it is now below the 0,8 threshold.

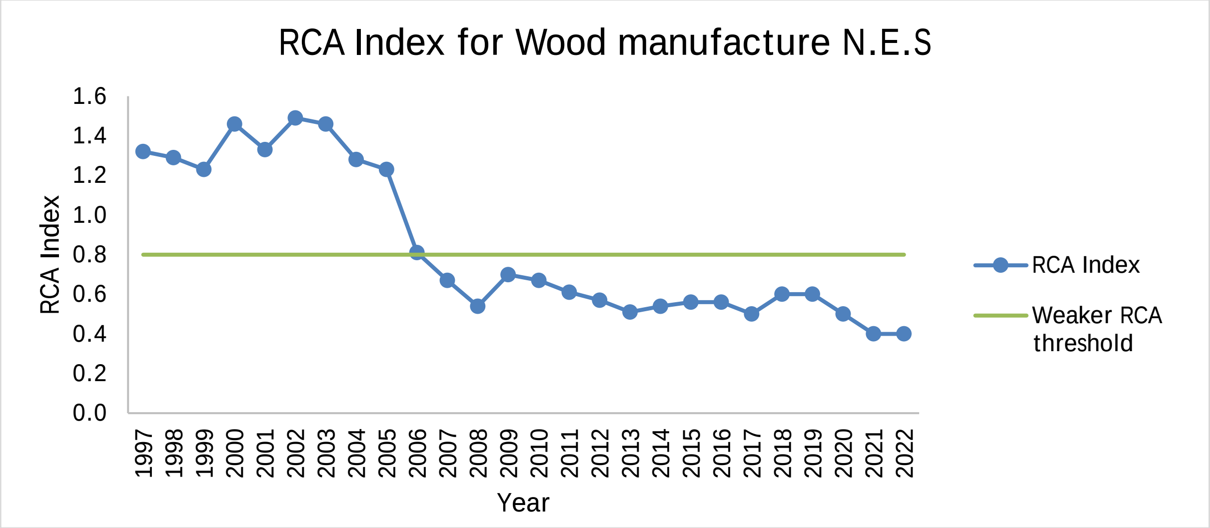

Figure 2: Chart displaying the revealed comparative advantage index values for wood manufacturing N.E.S. over the years

The revealed comparative advantage index values for *Veneers, plywood, and other wood, worked, N.E.S*. has been below the 0.8 threshold over the studied period, as shown in Figure 3. This implies that the export competitiveness of *Veneers, plywood, and other wood, worked, N.E.S*. from South Africa is not globally competitive.

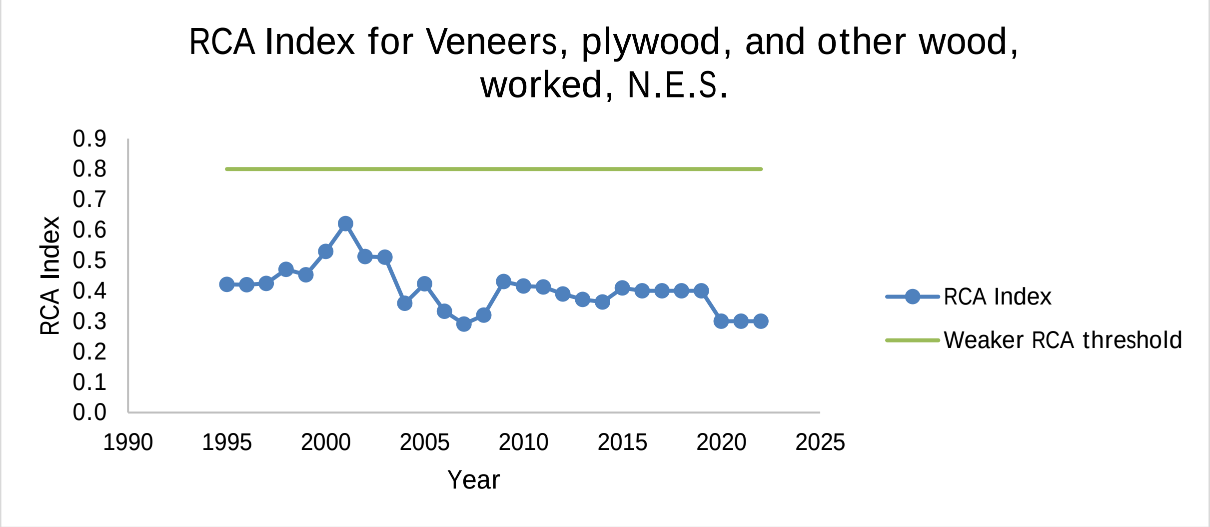

Figure 3: Chart displaying the revealed comparative index values for Veneers, plywood, and other wood, worked, N.E.S., over the years

The revealed comparative index values for *wood in chips or particles and wood waste* show a decline over the years, as shown in Figure 4. The RCA index is above the competitiveness threshold, which indicates that South Africa exports *Wood in chips or particles and wood waste* competitively.

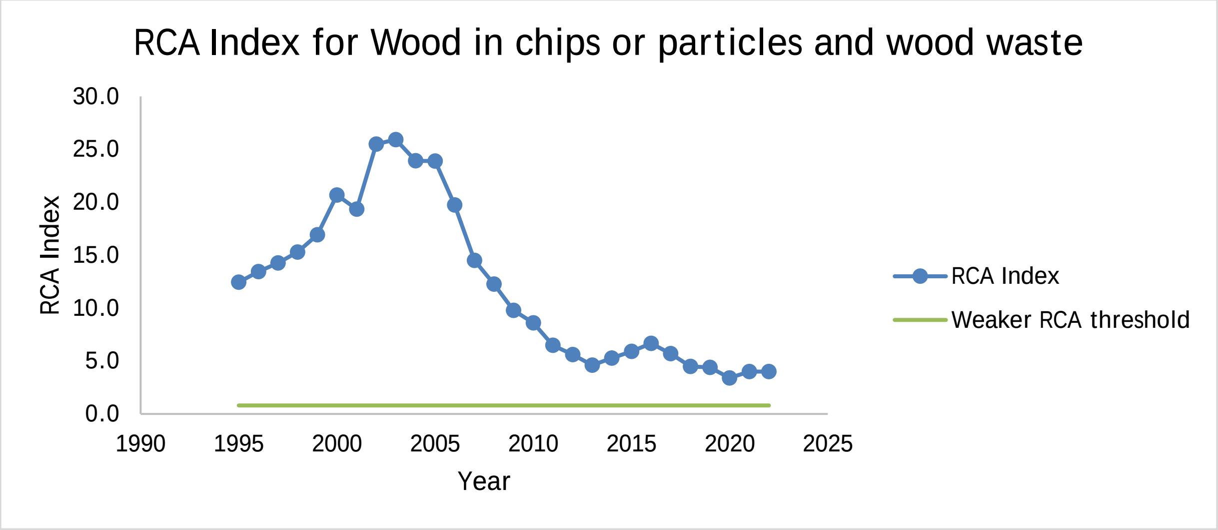

Figure 4: Chart displaying the revealed comparative index values for Wood in chips or particles and wood waste over the years

The revealed comparative advantage index values for *Wood in the rough or roughly squared* show a decline below the export competitiveness threshold between the years 2003 and 2017, as shown in Figure 5. South Africa's export competitiveness level has been increasing since 2018, with an RCA index above 0.8.

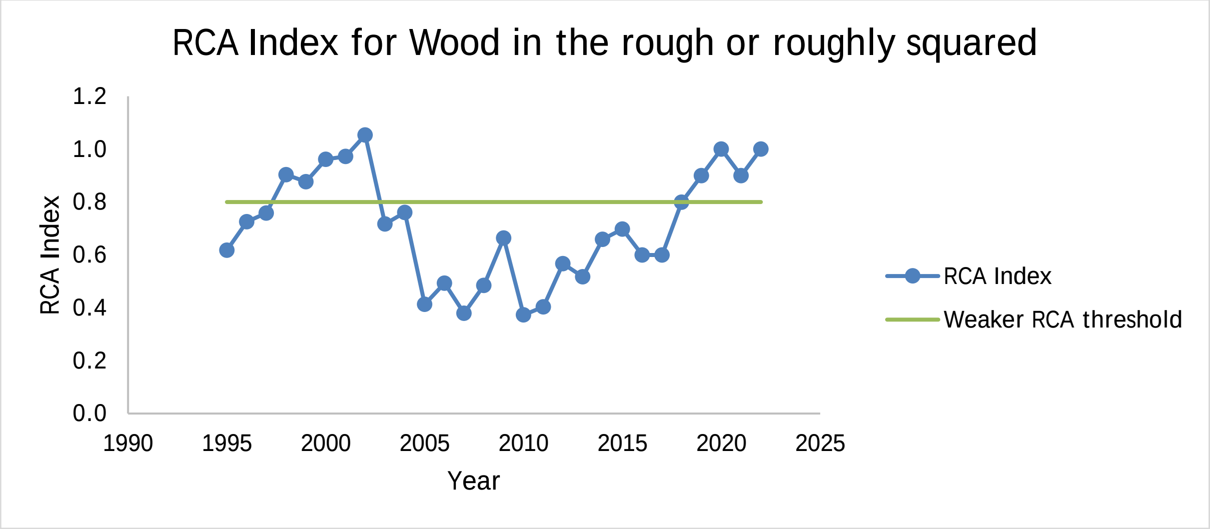

Figure 5: Chart displaying the revealed comparative index values for Wood in the rough or roughly squared over the years

The revealed comparative index values for *Fuel wood (excluding wood waste) and wood charcoal* are above the competitiveness threshold, as shown in Figure 6. The chart indicates that South Africa is a competitive exporter of *Fuel wood (excluding wood waste) and wood charcoal*.

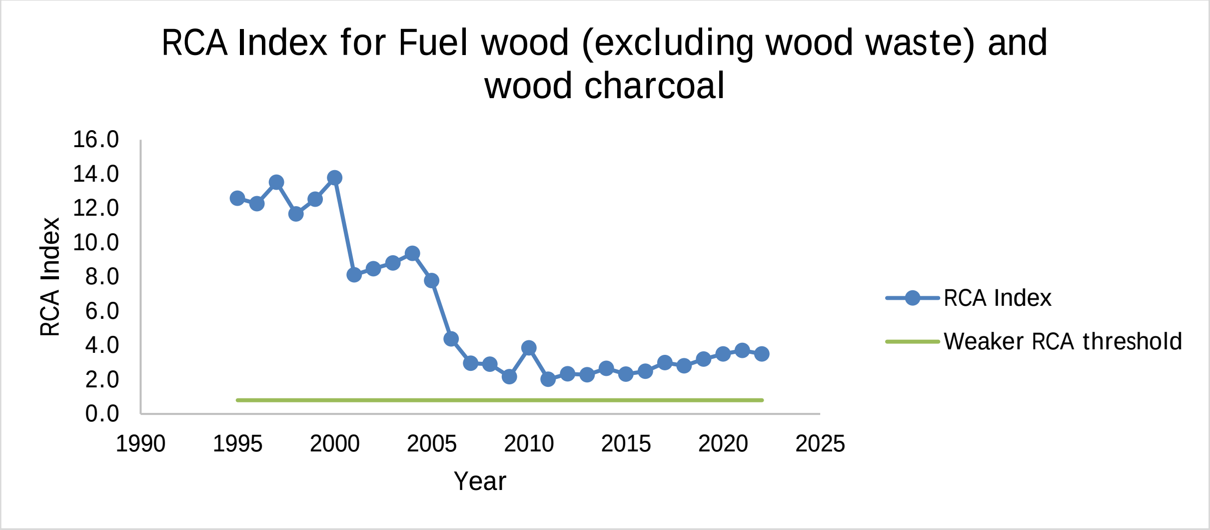

Figure 6: Chart displaying the revealed comparative index values for Fuel wood (excluding wood waste) and wood charcoal over the years

The revealed comparative advantage index values for *Paper and paperboard* show a decline below the threshold from 2011, as shown in Figure 7. The chart indicates South Africa's export competitiveness level for *paper and paperboard products* has declined.

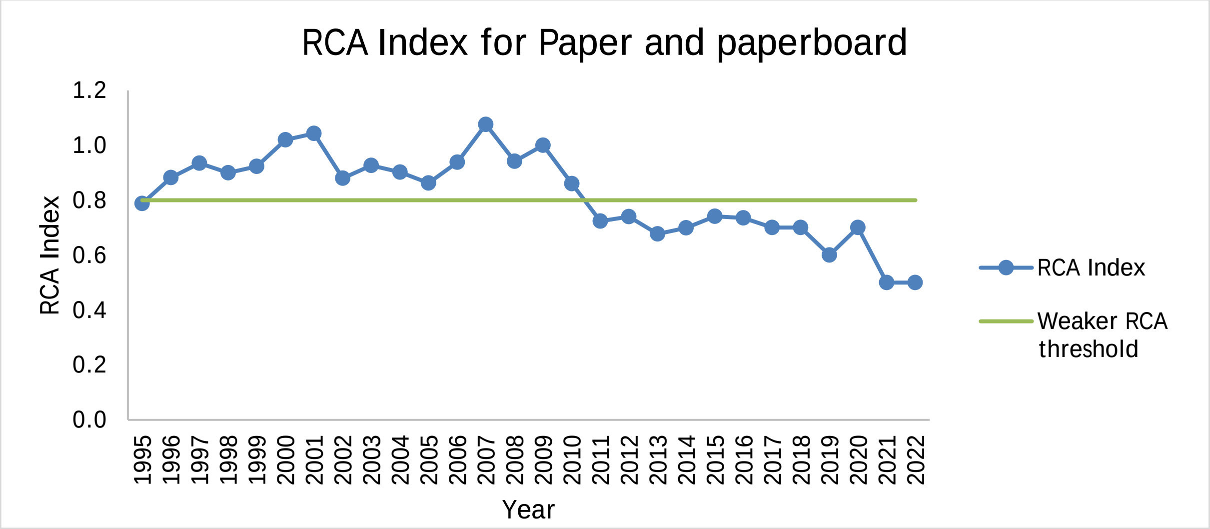

Figure 7: Chart displaying the revealed comparative index values for Paper and paperboard over the years

The RCA data shows a decrease in the comparative advantage over the years for *Wood manufacture N.E.S.*; *Veneers, plywood, and other wood worked, N.E.S.*; *Wood in chips or particles and wood waste*; *Fuel wood (excluding wood waste) and wood charcoal* and *Paper and paperboard*. The RCA index value for *Wood in the rough or roughly squared* was the only one that increased. *Wood in chips or particles and wood waste*, and *Fuel wood (excluding wood waste), and wood* charcoal were the superior products with a competitiveness level that is very strong as their RCA values were mostly above 2.5 over the years. The plots show that most South African wood-based products are not competitive globally, as demonstrated by their RCA values. This led us to identify the reasons behind the low RCA index using Porter's diamond model determinants. The next section describes the factors that explain why the measured RCA could be low for certain wood-based products based on the data gathered from studies conducted in South Africa.

4.2 Porter's diamond model analysis

The discussion below will evaluate the South African sawmill industry's national competitive advantage using Porter's diamond model as a framework for analysis. The study results are presented according to the different Porter's Diamond Model determinants discussed in Figure 1 above. Table 2 below highlights the aspects under each determinant that influence the industry's national competitiveness derived from South African literature sources. This summary is based on factors directly affecting the South African sawmill industry, as discussed below.

Table 2: Summary of the factors affecting the South African sawmill industry's national competitive advantage using Porter's diamond model Porter diamond model

Chance	Factor conditions	Demand conditions	Related and supporting industries	Firm strategy, structure, and rivalry	Government
Pests and diseases	Land claims	Population growth	Wine	Global markets	Forestry master plan
Forest fires	Exchange rate	Construction industry volatility	Construction and Building	Number of sawmills	National forestry act
Innovative products	Wage determinations	Low afforested areas	Furniture Manufacturing	Strategic, tactical, and operational strategies	
Timber theft and other crimes	Suitable land for new afforestation	Decline in print media /digitisation.	Woodworking and carpentry	Sawmill location	
Natural disaster	Environmental considerations	Energy security and climate change	Paper and packaging	Sawmill capacity	
	Employment	Number of sawmills	Engineered Wood Products		
	Cost of raw materials		Musical Instruments		
	Level of automation		Bioenergy		
	Target markets		Packaging and pallets		

	Operational costs	Agricultural and Horticultural
		Academic institutions

4.2.1 Factor conditions affecting the sawmill industry in South Africa.

The ability of producers to effectively address the unique crucial success factors prevalent in each market segment determines whether or not they can meet buyers' needs [37]. In their study, [38] highlighted that the future of South African forestry as an alternative source of energy and raw material could be affected by factors such as disputes over land, exchange rate, a spiraling oil price, pay estimations, and a lack of appropriate land for new forest regeneration. Aspects determining the nature of established plantations comprise the kind and makeup of the plantation owner; variations in consumer demand for varied and novel wood products; concerns regarding the environment such as the utilisation of biomass for energy and carbon sequestration and trading; bio-network facilities and supplementary offerings; and forest management low-impact certification [4]. In their study focusing on the historical events in the South African forest industry, Louw [38] mentioned that approximately 100,000 ha of valuable plantation forestry in South Africa will be removed through State Forest restructuring, water law, environmental preservation, and buffer zone demarcation.

Employment in the forestry and related services industry (2017-2020) has been decreasing, with the number of employees decreasing from 34 287 in 2017, 31 054 in 2019, and 28 736 in 2020 [39]. In their study, [8] discovered that product type influenced sawmill survival, arguing that profitability varies across market segments. The competitiveness of sawmills is impacted by various variables such as the cost of raw materials, level of automation, target markets, operational costs, by-products marketability, and conversion effectiveness [40].

Wood and wood products, Paper, publishing, and printing account for around 10% of all manufacturing in South Africa. Sawmilling contributed about 0,87% while other wood products contributed 0,88% [41]. Total production from manufacturing was noted to have dipped by 0.3% in 2022 versus 2021, with the majority of the decrease coming from chemical products, petroleum, plastic, and rubber goods (-2,5% and responsible for -0,5 of a percentage point) and wood-related goods, paper, publishing and printing (-2,8% and adding -0,3 of a percentage point) [41]. In their South African Furniture Industry study, Kaplinsky et al. [37] found that overseas purchasers do not appear to immediately impact the agricultural industry's upstream operations and associated services.

4.2.2 Demand conditions in the sawmill industry in South Africa.

The world's population growth impacts how different countries see the value systems that govern their societies. More resources, particularly forests, are needed to accommodate more people [4]. Because sawn wood is primarily used in construction, the sawmill business is vulnerable to significant recurrent variations in demand and pricing, affecting its financial performance and competitiveness [42]. In their study, Louw [38] outlined that the South African sawmilling industry was facing an extreme risk in the availability of raw timber supply caused by poor afforestation areas, high demand, significant fires, and a shift in production aims from saw timber to pulp wood. According to Statistics South Africa [39], Sales of products can be associated with the demand. Total forestry, logging, and associated services industry sales of timber and raw goods in 2020 (R16,3 billion) presented a decrease of 8,5% (or -R1,5 billion) over the total sales reported in the corresponding survey of 2019 (R17,9 billion). The main factors driving the worldwide demand for forest products were outlined by McEwan et al. [4]: an increase in living standards; a substantial drop in print media and business forms, causing significant business restructuring; and energy supply needs and climate change, which are fueling the need for biomass-derived bioenergy and products. A considerable part of satisfying niche market demand is fulfilled by the about 300 unofficial sawmills in South Africa, sometimes known as "bushmills" [37]. McEwan [4] highlighted that new technologies and technological advancements impact the supply and demand for forest-based goods as the world advances technologically.

4.2.3 Related and supporting industries in South Africa.

The forestry industry is directly linked to several other sectors. These industries include industries such as:

- Wine production, where the wine barrels they use for storage, aroma, and flavour are made from timber [43] processed in the sawmill.
- Agriculture and horticulture, where timber posts and stakes support crops [44], while fencing materials are used to manage animals.
- Construction, where engineered wood products and structural timber are used for framing, interior design, and roof trusses [45], [46], [47].
- Paper and packaging, where wood chips are sometimes produced at a sawmill or paper mills, are used [48].
- Musical instruments, where musical instruments are made from different woods [49], [50].
- Furniture still primarily uses solid wood or wood composites in furniture making [51],[52].

Although South Africa has nine provinces, commercial forestry is concentrated in five provinces [53]. Sasatani and Zhang [8] mention that the geographic clustering of enterprises in the same industry attracts a bigger workforce pool, leading to decreased labour and other raw material costs and increased demand for associated by-products within the cluster. To secure the success of the overall forest business, a concentration on every aspect of the supply chain is essential [38]. The competition in the wooden furniture industry is rising as more and more manufacturers penetrate the international markets. Consequently, global prices are falling [37]. In terms of bioenergy, McEwan et al. [4] mentioned that green energy production and use have risen due to rising fossil fuel costs, enhanced replenishable technologies, government regulations, and expanding global energy needs. As a result, the usage of woody biomass for energy generation is projected to rise. According to Visser [54], regarding biomass power plants, South Africa's Levelized Cost of Electricity is somewhat in line with that of the US compared to other countries. However, South Africa's levelized cost of electricity cannot be compared to Canada's (too cheap) or Europe's (too costly). South Africa charges a comparable sales tariff to China and, to some degree, the United States.

According to Tewari [55], Pulp, paper, wood chips, and raw materials are mainly exported. In contrast, wood is used domestically to make furniture, poles for telephone and electricity distribution, and home construction materials. In South Africa, sawn timber is used mainly in the building sector for roof trusses [40]. Over 70% of all sawn wood processed at South African sawmills is utilised in construction, primarily in roof frames [56]. A report by Statistics South Africa [57] mentioned that the total worth of documented building plans passed reported for residential properties and expansions and changes increased by 3.9% from January to April 2022 relative to January to April 2021. Growing awareness of how buildings affect the environment has led to a sharp increase in the green building industry, with the South African market having a rapid global rate of growth [58].

4.2.4 Firm strategy, structure, and rivalry in the South African sawmill industry.

4.2.4.1 Business strategy.

The commercial forestry sector in South Africa is undergoing rapid transformation, with new companies and groups joining the ranks of industry stakeholders. This has increased pressure for institutional and policy changes within the sector [55]. Small producers' afforestation of additional land in rural regions is one of the primary strategies for increasing productivity [38]. Landowners decide management intentions and precedence, usually driven by financial returns [4]. According to Grobbelaar and Visser [57], sawmills that use a value-adding approach are more likely to survive economic downturns and thrive during seasons of economic prosperity. The decision-making processes in the forest industry may include different aspects of wood flow and delivery, namely strategic, tactical, and operational [7]. In their study, Hosseini [7] identified potential opportunities for implementing automated decision-making systems in the wood production process, such as economic profits, technical achievements, environmental incentives, and penalty avoidance. Louw [38] said that mindset changes and addressing issues between contractors and growers would be crucial for future growth as the relationship between the two is vital for success. They also highlighted the importance of a comprehensive supply chain and strategic approach to vendor and outsourcing management.

4.2.4.2 Industry structure.

The South African sawmill industry consists of firms with sawmills in different locations. Sasatani and Zhang [8] outlined that firms with multiple sawmills, instead of single mill firms, can increase their competitiveness by lowering transportation costs, improving efficiency, and decreasing vulnerability to location-specific threats through product or service broadening and knowledge transfer across firms. Singer and Donoso [59] mentioned that understanding the firm's internal capabilities is necessary to plan supply, production, and inventory accordingly. In their study, Penfield et al. [60] discovered that high-performing supply networks are more efficient, possibly more efficient, and profitable.

Forest management is a worldwide endeavour with shifting ownership patterns [4]. Crickmay and Associates reported a significant shift in the sawmilling environment, where 188 formal sawmills were reduced to 45 softwood and two hardwood mills in South Africa between 1994 and 2002. Although there was a significant decline in the number of mills, the remaining mills continuously improved productivity, costs, and profits, with recovery from gate to gate improving to 47,6% [61]. This decline in sawmills was also observed in developed countries, leaving larger mills dominating the softwood industry [8]. Sasatani and Zhang [8] highlighted that Such substantial changes in the industry's structure attract the interest of forest landowners and policymakers because they frequently bring social and economic adversity to rural areas and limit financially viable management alternatives for small timber growers.

4.2.4.3 Local rivalry

Firms within a cluster are not necessarily homogeneous [8], as sawmills battle for similar resources, technology, and customers; therefore, they must stay competitive to thrive in this climate [40]. In their study of the Finish sawmill industry, Kallio [3] showed that the consequence of various competition patterns on market actors' performance is not reliant on projections but on firm-capacity layout, yield market cycle, and timber supply flexibilities due to sub-market connectivity. Sasatani and Zhang [8] mentioned that each sawmill is presumed to benefit from its location; however, organisationally similar mills also compete for scarce resources, which leads to an increase in sawmill closures.

4.2.5 South African Government's influence on the sawmill industry.

In their study of the South African forestry industry, Louw [38] outlined that the government increasingly appears to be realising the value of forestry in terms of economic growth and development, mainly in rural parts of the country, and that the forest industry seems to have a bright future in the coming years, assuming the numerous projects and efforts that the various significant players envision can come to pass. Crafford et al. [58] mentioned that during the 2011 COP17 climate change conference in South Africa, the South African government committed to decreasing emissions of greenhouse gases through the implementation of environmentally friendly technology and systems like environmentally friendly constructions, and the South African government backed the compulsory SANS 10400-XA:2011 in the National Building Regulations to offer guidance on the planning and constructing of environmentally friendly structures. Although there are many initiatives the government is doing in terms of forestry, Louw [38] outlined that from the private forestry business, the government continues to over-regulate the industry, hindering its expansion. Policies encompassing carbon sequestration payments and those striving to minimise the loss of forest lands to alternative land uses may impact the forest sector [4]. The South African government has approved the Forestry Master Plan, which deals with seven focus areas: 1. Increased forestry resource and protection/maintenance; 2. Transformation; 3. Wood processing; 4. Illegal logging and criminal activity; 5. Development of research, development, innovation, and skills; 6. Crucial inhibitors; 7. Institutional development as an initiative to improve the competitiveness of the forestry sector [62]. The Forestry master plan outlines commitments for industry stakeholders such as Businesses (Sawmills and supporting industries), the Department of Forestry, fisheries and the Environment, The Department of Trade, Industry and Competition, other government agencies (Industrial Development Corporation and Land Claims Commission), Department of Labour and other community small growers. Porter and Kramer [63] said regulations should be crafted to support shared value rather than hinder it. This is because the new shift in economic development is that economic expansion is a collaborative method connecting government at numerous levels, firms, academic institutions, and the private sector [64].

4.2.6 Chances/ opportunities in the South African sawmill industry.

The forest sector has a significant potential to contribute to improving forest supply chain management. However, chances may be missed if choices focus on improving upstream without considering downstream benefits [7]. Grobbelaar and Visser [2] highlighted that South Africa could enhance the intensity of sawn timber utilisation per capita compared to other developed and developing countries. While there is currently little use of wood in construction, this is anticipated to change due to pressure from global players, commitments to mitigate climate change, and growing public awareness of the advantages of using wood as a construction material [58]. Innovative wood-based products are developing, and some traditional wood-based goods are being phased out [4]. Although there are several positive opportunities facing the industry, there are also instances that suddenly affect the forestry industry. Statistics South Africa [39] reported that in the forestry, timber harvesting, and related industries, enterprises experienced losses as a result of criminality, diseases, pests, and extreme weather and that for the year 2020, the highest losses were from forest fires, timber theft, equipment theft, pest and diseases, other crime, drought, hail, other loses, black frost and other natural disasters in this order. The growing frequency of these instances shows that diseases and pests are becoming more prevalent and are thought to be among the industry's primary concerns. It is evident that crime and timber theft have a significant influence, but it is still impossible to estimate their combined effects [38]. These events occur outside firms' control and should be considered when evaluating activities that occur by chance.

5 CONCLUSIONS

The process of globalisation is depicted by the eradication of hurdles to the cross-border transit of people, ideas, products, information, and technology, which also allows firms to trade on the global market. This, however, opens the door for more competition from other industry players both locally and internationally. The annual Revealed Comparative Advantage Index analysis for different products made from wood and wood residues revealed that most South African wood-based products were not competitive globally, as their annual RCA values were less than 0.8 and showed a continuous decline over the years. Using Porter's framework as the basis for analysis in this study allowed us to explore the effect of demand conditions, factor conditions, firm strategy, structure and rivalry, related and supporting industries, government, and opportunity on the national competitiveness of the South African sawmill industry. It was revealed from the study that different factors, as outlined in Table 2, will always affect the industry, which in turn affects the need for wood-based goods in the industry. The study also revealed that although many supporting and related industries are linked to the sawmill industry, chance events significantly affect whether or not the industry can satisfy the demand for wood merchandise, even though demand for wood products might be high. The government influences sawmill industries and their competitiveness as the policies set out by the governments of each country subsequently affect how businesses operate within the country and internationally. This is supported by Michael Porter, who pointed out that proper government regulation can incentivise firms to pursue mutually beneficial objectives. This study will add knowledge to the South African sawmill industry, highlighting the influence of different competitiveness determinants on national competitiveness.

6 LIMITATIONS

The study relied on published data from research done in South Africa to map out the results so that the determinants of Porter's Diamond model are all addressed. More studies are needed to address some of these determinants in a South African context.

7 RECOMMENDATIONS

Future research should focus on the global economic position of the South African sawmill industry by critically looking at other economic indicators and using the data to develop prediction models. More studies involving other business strategy models are necessary to complement the results of this study and critically look at the competitiveness of the South African sawmill industry. This can include using the Quadruple Helix Innovation Systems to investigate further the link between government, society, academic research and businesses. The sawmill industry can look at the results of this study, identify the less competitive products, and see if there are opportunities for increasing their local utilisation and exports. The industry should also focus on the identified factors affecting the South African sawmill industry's national competitive advantage and engage different industry stakeholders in ways to improve the industry's competitiveness.

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THE DEVELOPMENT OF A DDDM IMPLEMENTATION FRAMEWORK FOR THE SOUTH AFRICAN MINING INDUSTRY

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ABSTRACT

The advancement of Industry 4.0 over the past decades has made it increasingly easier for organisations to collect and store vast amounts of data. The availability of quality data is one of the enablers of data-driven decision-making (DDDM). However, the mining industry has struggled with implementing new technologies over the years. DDDM requires an organisation to not only have the required technology but also several capabilities that build the overall DDDM capability of an organisation. These capabilities are linked to a business's technological, analytical and managerial aspects. This paper focussed on the South African mining industry. It used in-person interviews to identify the different DDDM tools currently used, the observed benefits of DDDM, the key enablers for DDDM, and the lessons learned from previous implementations. The paper aims to assist South African mining organisations in developing a DDDM implementation framework.

Keywords: data-driven decision-making, industry 4.0, mining, South Africa

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1 INTRODUCTION

This paper intends to build upon the findings of previous work [1] by contextualising it to the South African mining industry. According to both Antin [2] and Sishi and Telukdarie [3], the South African mining industry is one of the largest mining industries in the world and is a critical part of the South African economy, contributing to both socioeconomic and human development. However, Antin [2] describes the South African mining industry as having "severe productivity issues". South Africa holds some of the largest resource deposits globally but often produces less raw material than countries with much smaller resource deposits [2].

According to Sishi and Telukdarie [3], the mining industry's management decision-making can be improved by providing decision-makers with real-time data from all business areas. A combination of Enterprise Resource Planning (ERP) and Industry 4.0 (I4.0) technologies can be used to provide management with the tools required to perform Data Driven Decision Making (DDDM) [3].

In a 2011 study, Brynjolfsson et al. [4] analysed a large sample of publicly listed firms to evaluate if firms that emphasise making data-driven decisions perform better than those that do not. This study concluded that DDDM is associated with higher productivity and market value of firms, with those that practice DDDM showing a 5-6% increase in output and productivity [4].

Better information can be obtained through better data collection, reduced statistical noise within the information, improved data analytics, and better data visualisation [4]. Brynjolfsson et al. [4] explain that although investment in Information Technology (IT) drives improved productivity, some studies have suggested that using IT is also important besides the investment itself. In essence, the capability to use and interpret information from DDDM tools are as important as the tools themselves.

Implementing any new technology comes with challenges, as has been the case within the mining industry, where the implementation of new technologies is still behind compared to other industries like manufacturing [3]. Sishi and Telukdarie [3] explain that the mining industry has not yet made the best use of new information and business integration technologies and still operates in disjointed systems.

1.1 DDDM Process

Jia et al. [5] describe DDDM as the process of analysing and using data to support efficient and effective decision-making instead of relying on intuition. DDDM results in smarter, more efficient business with improved productivity [4], [5]. Troisi et al. [6] define DDDM as "The adoption of a real orientation to manage big data throughout the entire decision-making cycle".

Jia et al. [5] provide a comprehensive DDDM process by combining information obtained from various literature sources. The process shows DDDM as a continuous process comprising multiple steps that focus on data gathering, data analysis or processing, information visualisation, decision making, implementation, evaluation, and feedback. The process provided by Jia et al. [5] also shows that DDDM is not an isolated process but is interlinked with the organisation's decision-making resources and culture, integration into their supply chain and the organisation's external environment.

1.2 Data-driven decision-making tools

IT-based tools can be used in different parts of the DDDM process introduced by Jia et al. [5]. Brynjolfsson et al. [4] mention the following technology groups that can contribute to DDDM:

- Enterprise information technology.

- Data analytics technologies.
- Data-generating technologies.

Davenport et al. [7] describe the technology that enables DDDM as being in one of two groups:

- Transaction systems.
- Analytical technologies.

Davenport et al. [7] explain that transaction systems tend to be relatively generic and do not require in-depth organisational knowledge to implement. It is also possible to automate many of the functions within transaction systems [7]. In contrast, analytical technologies are more complicated, requiring a better understanding of the organisation to be implemented [7].

Van Der Horn and Mahadevan [8] state that Digital Twins (DT) and simulation models can also provide insights to decision-makers. They [8] define a DT as "a virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and the virtual system". According to Van Der Horn and Mahadevan [8], the main difference between a DT and a simulation model is that a DT is used to track a system's current and past state, while a simulation model is used to predict future states of the same system.

Coelho et al. [9] propose that the definition of a DT should reference it as a decision support system.

1.3 Data-driven decision-making capabilities

Jia et al. [5] performed a study to identify the capabilities required for an organisation to perform DDDM. They found that past literature focused more on the benefits of DDDM without sufficiently covering DDDM capabilities and how to build these capabilities. Subsequently, they proposed a DDDM capabilities framework consisting of the following five capabilities:

- Data governance capability: Data collection, integration, quality control, and access control.
- Data analytics capability: This includes elements such as decision time (the time frame within which analytics are performed, such as real-time, hourly, daily, or weekly), analytics (visualisation, exploration, explanatory, and predictive), and techniques (the analytics or models such as statistics, machine learning, computation, and simulations that an organisation has).
- Insight exploitation capability: The ability to use insights gained from data analytics in decision-making across core business processes such as manufacturing/operations activities, marketing activities, customer service activities, enhancing supplier linkages, sales activities, and financial management and budgeting.
- Performance management capability: This is the process of monitoring the processes and outcomes of decision-making and, specifically, the business performance so that managerial actions can be guided accordingly.
- Integration capability: Refers to an organisation's ability to combine different assets, structures, systems, and people within a firm into a unified whole. Integration can be divided into IT infrastructure integration, process integration and people integration.

1.4 Objectives

This study aimed to evaluate the opportunities and challenges related to the implementation of DDDM in the South African mining industry by answering the following questions.

1. To what extent does the South African mining industry use DDDM, and which tools do they use to perform DDDM?

2. What benefits have the South African mining industry observed due to DDDM?
3. What key enablers are required for South African mine organisations to perform DDDM successfully?
4. What lessons can be learnt from existing implementations of DDDM in the South African mining industry?

2 LITERATURE REVIEW

A scoping literature review was performed to investigate the use and implementation of DDDM within mining industries worldwide [1]. The scoping literature review considered an initial pool of 7 132 documents, which was reduced to only 40 relevant documents through various screening methods [1]. Bisschoff and Grobbelaar [1] provided answers to the following research questions:

1. Which DDDM tools are currently being used in the mining sector?
2. What are the potential benefits of DDDM in the mining sector?
3. What are the key enablers of DDDM in the mining sector?
4. What are the main lessons learnt from implementors of DDDM in the mining sector?

The research questions answered by Bisschoff and Grobbelaar [1] are similar to those posed in section 1.4, but focus on mining industries worldwide instead of only the South African mining industry. This section summarises specific findings from the scoping literature review related to these research questions [1].

2.1 What DDDM tools are used in the mining industry?

The scoping literature review performed by Bisschoff and Grobbelaar [1] found various tools that contribute to the process of DDDM. These tools can be grouped into the following types:

- Enterprise information technologies/Transaction systems.
- Data analytics technologies.
- Data gathering technologies.
- Simulation/DT technologies.

2.2 What are the benefits of DDDM?

According to Provost and Fawcett [10], the benefits seen by companies who use data to make decisions include higher productivity and more favourable returns on assets and market value.

The scoping literature review performed by Bisschoff and Grobbelaar [1] found the following DDDM benefits that have been observed in the mining industry.

- Increased production.
- What-if analysis.
- Improved safety.
- Decreased energy usage.
- Prolonged equipment life.
- Faster decision-making.
- Improved maintenance.

2.3 What are the key enablers of DDDM?

The scoping literature review performed by Bisschoff and Grobbelaar [1] found the following enablers that are critical to the success of DDDM in the mining industry.

- Availability of real-time data.
- Availability of sensor data.

- Availability of integrated data.
- Data visualisation.
- Data processing/analytics.

2.4 What lessons can be learnt from DDDM implementations in the mining industry?

The scoping literature review performed by Bisschoff and Grobbelaar [1] found several references to actual instances where DDDM or tools related to DDDM were implemented. Below are some of the specific lessons that can be learned from these instances:

- The implementation and integration of advanced technologies at different levels of the mining business are not as simple as often promised
- The mining industry often implements technologies in silos requiring manual data transfer and reporting between systems.
- Quality data is required for DDDM.
- Implementing complex models can often be limited due to limited access to the required data.
- Implementation of DDDM is not only technology-dependent but is also dependent on organisational effort.
- Data that is not integrated between systems is often unavailable to decision-makers.
- Information is only usable if the stakeholders and users buy into DDDM.

3 CONCEPTUAL METHOD

Conceptual models serve as abstract, psychological representations of how processes could interact with each other. Thus, a DDDM conceptual model would aim to illustrate how processes interact with each other to reach specific objectives. For this conceptual model, it is assumed that the final objective is to achieve benefits from the implementation of DDDM. As previously illustrated [1], these benefits may include increased production, what-if analysis, improved safety, decreased energy usage, prolonged equipment life, faster decision-making, improved maintenance, etc.

Jia et al. [5] describe DDDM as a process of analysing and using data to support efficient and effective decision-making. Thus, it can be assumed that if one wants to realise the benefits of DDDM, it is imperative to have an effective DDDM process.

The presence of an organisational data-driven strategy, as described by Davenport et al. [7] is assumed to be critical for the successful implementation of DDDM. However, a data-driven strategy is not believed to be an absolute requirement for a DDDM process

DDDM capabilities are discussed by both Jia et al. [5] and Davenport et al. [7]. These capabilities include both DDDM technology and DDDM enablers. There is an overlap between DDDM technologies and DDDM enablers. Certain technologies are enablers of DDDM, such as technology used for data capturing and data storage. Other technologies, such as data analysis tools, are meaningless without having the skills (enablers) required to use them. Thus, DDDM capabilities are considered to have a direct effect on the DDDM process.

Considering the above, it can be assumed that an appropriate DDDM conceptual model should consider the following:

1. DDDM benefits as a final outcome
2. DDDM process as a combination of:
    a. Organisational data driven strategy
    b. DDDM capabilities that is constituted from DDDM technology and DDDM enablers.

Considering the above, the conceptual model shown in Figure 1 was developed.

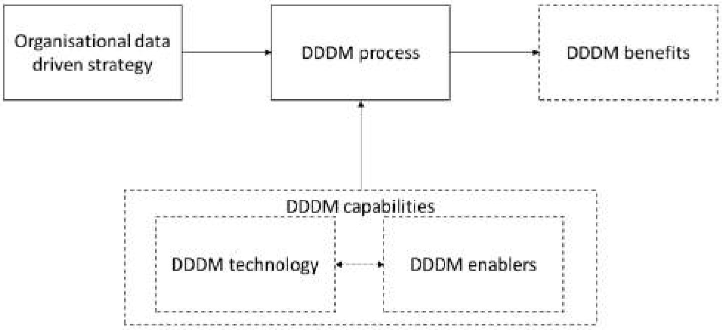

Figure 1: Conceptual model

The conceptual model does not intend to analyse the DDDM process itself, and it assumes that this process is in place. The effectiveness of the DDDM process can be evaluated based on the observed DDDM benefits, which form the final part of the conceptual method.

The proposed conceptual model uses a generic framework design showing the relationship between independent, dependent, and moderator variables. DDDM capabilities are the independent variables that affect the DDDM benefits (dependant variables) through the DDDM process located in the centre of the conceptual model. The presence of a data driven organisational strategy is a moderator variable that does not directly link to the independent variables but enhances the impact of the independent variable on the dependent variable.

The dashed lines used for the DDDM capabilities and the DDDM benefits indicate that these are the areas where the actual research was focused. The research was conducted through interviews, and the technologies, enablers, and benefits of DDDM within the South African mining industry were identified.

4 RESEARCH METHOD

4.1 Ontological and epistemological position

The overall approach taken for the research was exploratory. The research questions were developed without a pre-existing proposition. The scoping literature review performed by Bisschoff and Grobbelaar [1] provided insight into what could be expected within the South African context. The primary research required the researcher to enter the South African mining industry to gather information relevant to that industry.

Easterby-Smith et al. [11] state that the ontological position of relativism assumes that there is room for more than just one singular truth and that the best results are obtained by observing from more than one perspective. Within the context of the proposed conceptual method, this meant that answers to the research questions had to be obtained from multiple sources. These sources included mine employees at a managerial level, non-managerial mine employees, and consultants working with mining organisations.

Easterby-Smith et al. [11] state that a relativist ontology is generally paired with a constructionist epistemological position, which was the position taken for this research. A constructionist perspective means that research should consider people’s experiences rather than focusing only on external factors.

Easterby-Smith et al. [11] provide the following advantages and disadvantages for the chosen position.

Advantages:

- It accepts valuable inputs from multiple sources.
- It enables generalisations to be made beyond the present sample.
- It has better efficiency than other positions and has the potential for outsourcing.

Disadvantages:

- Access to sources can be more challenging to obtain.
- It is challenging to accommodate institutional and cultural differences.
- It can be difficult to reconcile discrepant information.

4.2 Research methodology and techniques

The type of data that applies to the constructionist viewpoint is qualitative [11]. The data is expected to be mainly words with the potential to include some numbers. Qualitative data requires the researcher to develop theories, create categories and concepts, and identify truths [11]. Qualitative data is usually collected using natural language techniques, which means that the information is spoken words or written text [11]. Easterby-Smith et al. [11] suggest that the qualitative interview is the primary method used for this type of research. A qualitative interview allows for rich and detailed information to be gathered from respondents, revealing aspects of their lives, understandings, and experiences.

At the time of this study, the outbreak of the COVID-19 pandemic still affected South African citizens’ day-to-day lives and activities. This had a tangible impact on the freedom available to the researcher regarding the choice of in-person vs. remote interviews. In-person interviews were the preferred choice. However, where this was not possible, the researcher used remote interviews. Remote interviews were conducted via video or telephone calls, giving the interviewer some similar advantages to in-person interviews.

The type of interview used was an in-depth interview. This technique allows the researcher to probe deeper into specific topics of conversation to reveal additional insights [11]. The format of the interview was semi-structured. Easterby-Smith et al. [11] recommend using a topic guide to provide a researcher with a loose structure during interviews.

The sampling strategy used was convenience and snowball sampling. This choice was made purely based on the researcher’s existing level of access to individuals within the South African mining industry. As a consultant providing computer simulation-based services to the South African mining industry, the researcher had an existing network of contacts. These contacts were approached first to request their participation in the research. Willing participants were asked to provide the researcher with additional candidates. This is an advantageous strategy in an environment where it is difficult to gain access to participants [11].

An ethics application was submitted to the institution’s ethics committee, and the research was approved. The ethics clearance number is EBIT/65/2022.

5 RESULTS

This section contains the results obtained from in-depth interviews, as described in section 4. A total of 13 participants took part in the research interviews. These participants included mine employees and consultants in the South African mining industry. The participants also varied in experience, from having one or two years of experience to being a Chief Digital Officer (CDO) with many years of experience. The participants could speak on behalf of at least four large mine organisations that own mines within South Africa, with some of these being international mining organisations and others being South African-based organisations. The interviews were conducted over almost 11 months, spanning from 17 June 2022 to 25 May 2023.

5.1 Discussion of research questions

5.1.1 What DDDM tools are used in the South African mining industry, and how are they used?

As discussed in sections 1.2 and 2.1, the DDDM tools used in the mining industry can be grouped into the following types:

- Enterprise information technologies/Transactional systems
- Data analytics technologies
- Data gathering technologies
- Simulation/DT technologies

All four technology groupings are used within the South African mining industry. It is worth noting that some of the mentioned technologies have been widely used across the industry for several years, while others are still new.

The most widely used tool mentioned by several participants is Microsoft Excel. This tool is used for various functions, including data capturing, data storage, analytics, and visualisation. Some participants indicated that the wide use of Microsoft Excel is not part of their DDDM strategies and that they are working on transitioning the organisation away from this tool.

Many of the tools mentioned by research participants are used for data gathering, storage, or visualisation. All the participants indicated that having accurate and reliable data available is an ongoing challenge. Even those mines that are viewed as leaders in the use of advanced tools such as simulation modelling still struggle to maintain data integrity across all departments of the mine.

Referring to the five DDDM capabilities discussed in section 1.3, it seems that the South African mining industry is still working on developing its data governance capabilities to the point where accurate and reliable data is readily available. Those mines that have obtained a high level of data governance capability are believed to still be in the minority.

The South African mining industry uses several data analytics and visualisation tools. Most participants specifically mentioned data visualisation as a key part of their DDDM process and that many benefits and insights can be obtained from visualising historical and real-time data.

Simulation modelling is also used in the South African mining industry, and a couple of different tools were mentioned within this group. The use of data analytics and simulation modelling tools points to the existence of a data analytics capability, which is mentioned in section 1.3. Although all the participants indicated that data analytics capabilities exist, it was clear that this capability is not widely available and that obtaining and retaining employees with the required skills to perform this function is challenging.

5.1.2 What are the key enablers of DDDM in the South African mining industry?

The DDDM enablers identified in the scoping literature review performed by Bisschoff and Grobbelaar [1] were compared to those identified by the research participants. These enablers can be summarised as data availability, data visualisation, and data processing or analytics [1]. This comparison is displayed in Table 1 with a frequency column indicating the percentage of participants that mentioned each enabler.

Table 1: DDDM enablers in the South African mining industry

Enabler	**Found in the scoping review**	**Mentioned in interviews**	**Frequency**
Domain knowledge		Yes	54%
Skills from education and training		Yes	54%
Data processing/analytics	Yes	Yes	38%
Tools or technology		Yes	23%
Collaboration		Yes	15%
Data quality		Yes	15%
Interpretation capability		Yes	15%
Data availability	Yes	Yes	8%
Data visualisation	Yes	Yes	8%
Culture		Yes	8%

The two most mentioned DDDM enablers listed in Table 1 are ‘domain knowledge’ and ‘skills from education and training’. Having technical skills and domain knowledge within either an individual employee or within a team enables them to analyse and interpret data to make better data driven decisions. The top two DDDM enablers can be linked to ‘data processing/analytics’ and ‘interpretation capability’, listed in Table 1.

Referring to the DDDM capabilities framework mentioned in section 1.3, two of the five organisational capabilities required for DDDM are data analytics capability, which can be linked to the data processing/analytics enabler, and insight exploitation capability, which can be linked to the interpretation capability enabler.

Collaboration as a DDDM enabler, mentioned by 15% of participants, refers to the need for individuals within a team and departments within an organisation to integrate and work together towards becoming data driven. This can be linked to integration capability, one of the organisational capabilities required for DDDM listed in section 1.3.

5.1.3 What are the benefits of using DDDM in the South African mining industry?

As indicated in section 2.2, the international mining industry has observed several benefits from DDDM. When asked about the benefits of DDDM that they have observed within the South African mining industry, research participants mentioned many of these same benefits. Table 2 shows a comparison of the DDDM benefits that were found during the scoping literature review performed by Bisschoff and Grobbelaar [1] and those that were mentioned during the interviews. The frequency indicated in Table 2 is the percentage of research participants that mentioned each benefit.

Only one of the DDDM benefits found in the scoping literature review performed by Bisschoff and Grobbelaar [1] was not mentioned by any of the research participants. In contrast, seven additional DDDM benefits were mentioned by research participants that were not identified by the scoping literature review performed by Bisschoff and Grobbelaar [1].

Table 2: DDDM benefits in the South African mining industry

Benefit	**Found in the scoping review**	**Mentioned in interviews**	**Frequency**
Increased production	Yes	Yes	69%
Financial		Yes	54%
Faster decision-making/response time	Yes	Yes	23%
Improved maintenance	Yes	Yes	23%
Stakeholder satisfaction		Yes	23%
Improved planning		Yes	23%
What-if analysis	Yes	Yes	15%
Control		Yes	15%
Improved decision making		Yes	15%
Decreased energy usage	Yes	Yes	8%
Improved safety	Yes	Yes	8%
Allows more people to contribute to decisions		Yes	8%
Long term decision making		Yes	8%
Prolonged equipment life	Yes		0%

5.1.4 What lessons can be learnt from DDDM in the South African mining industry?

When learning from past implementations of DDDM, it is important to consider both the challenges experienced by the parties involved and the direct advice they can give after going through the process themselves. Research participants were asked to mention the challenges they encountered when implementing and using DDDM and any lessons they learned from the experience.

Table 3 summarises the responses in the form of lessons to be learned and indicates instances where similar lessons were also found during the scoping literature review performed by Bisschoff and Grobbelaar [1]. The frequency column contains the percentage of participants that mentioned each lesson. Note that if the same participant mentioned the same lesson more than once, it was only counted once for the frequency calculation.

Table 3: Lesson learnt from DDDM implementations in the South African mining industry

Lessons to be learnt	Found in the scoping review	Mentioned in interviews	Frequency
Ensure data is reliable and usable and that good data-capturing processes are in place.	Yes	Yes	62%
Perform change management to enable users and improve the adoption of DDDM.		Yes	62%
Continuously develop the skills required for DDDM.	Yes	Yes	46%
Avoid having multiple systems that are not integrated or not fully implemented.	Yes	Yes	31%
Choose the right solution for your environment.	Yes	Yes	31%
Get buy-in from stakeholders and users.	Yes	Yes	31%
DDDM needs collaboration.		Yes	31%
Clearly define the scope and purpose of your implementation.		Yes	23%
Consider all financial implications.		Yes	23%

The top two lessons that can be learnt were mentioned by 62% of participants, indicating that they relate to common issues encountered when implementing DDDM in the South African mining industry.

Ensuring that data is accurately captured, reliable, and in a usable format corresponds to lessons learnt from the literature, as indicated in section 2.4. Many participants explained that the availability of reliable data is still a challenge, even though DDDM has been in use for several years. This affects the time it takes to perform DDDM and often makes it difficult to convince others of the accuracy of DDDM output as they question the inputs used for the process. Not having reliable data, therefore, contributes to the challenges of DDDM not being adopted by users and stakeholders.

The second lesson to be learnt is the importance of change management in enabling users and improving the adoption of DDDM. Participants mentioned that users often do not understand or trust DDDM and then fall back to their old ways of doing things. One participant pointed out the challenges of change management in the South African mining industry due to working with white-collar and blue-collar workers and customising your approach for these very different groups.

The third most common lesson is the importance of continuously developing the skills needed for DDDM, with 46% of participants mentioning it. Many participants mentioned skills shortages as a common problem encountered when implementing DDDM and explained that there is a high demand for highly skilled individuals. Participants also pointed out that high employee turnover within the mining industry contributes to skills shortages as skilled individuals do not remain in one position long enough to finish projects they start.

5.2 Discussion of the conceptual model

The conceptual model proposed for this research in section 3 consists of organisational data driven strategy, DDDM capabilities, DDDM process, and DDDM benefits. This research focused on identifying the DDDM capabilities and DDDM benefits in the South African mining industry. These two aspects of the conceptual model are therefore addressed in section 5.1. This section will shortly discuss research findings linked to the remaining two parts of the conceptual model.

5.2.1 Organisational data driven strategy

When asked about an organisational data driven strategy, 46% of participants indicated that a definite organisational strategy exists. In comparison, 39% stated they were unsure if these strategies exist across the organisation or within certain departments. Interestingly, among those who indicated that an organisational strategy exists, other respondents from the same organisation responded that they were not aware of any existing strategy.

Participants explained that the level of data driven strategy or data awareness differs between departments and mines within the same organisation and is highly dependent on the individuals that drive it. The lack of top management support for the implementation of DDDM was also mentioned as a challenge that has been encountered by 15% of participants.

Considering the above leads one to question how effective the implementation of the existing organisational data driven strategies are. Although these strategies are not a prerequisite for the implementation of DDDM, the lack of clearly communicated and driven strategies limits the effectiveness of the DDDM process within the South African mining industry.

5.2.2 DDDM Process

Research participants mentioned several ways in which DDDM is used in the South African mining industry. All these applications can be loosely grouped into the following three categories:

1. Gaining insight: Gathering and analysing historical data to understand past events.
2. Monitoring: Continuously monitoring data from various processes to identify areas where action needs to be taken before an unwanted event occurs.
3. Gaining foresight: Using historical data and simulation models to forecast, gain insight into, and plan for the future.

When asked about their DDDM processes, only a few participants could provide meaningful insights. All these responses touched on the importance of having data available in a central location like a database or the cloud. The responses also included the steps of analysing and visualising data. Lastly, the respondents also mentioned that the information should then be used to inform decision-making.

Considering the DDDM process proposed by Jia et al. [5] and discussed in section 1.1, the process described by research participants corresponds with steps one to eight. Steps nine, ten, and eleven (implement, evaluate, and feedback) were not included in the process described by the research participants. In most cases, the implementation step would form part of the DDDM processes followed in the South African mining industry. Still, the evaluation and feedback steps might be missing.

By not completing the entire cycle of the DDDM process and not providing feedback on the effectiveness of the decisions that are made using data, the South African mining industry could be limiting the effectiveness of its own DDDM implementations. Several research participants clearly stated that they do not believe that the implementation and application of DDDM have been successful across the industry.

5.3 Proposed DDDM implementation framework

By combining the insights gained from the scoping literature review performed by Bisschoff and Grobbelaar [1] and the primary research results, a new framework is proposed for implementing DDDM in the South African mining industry. This proposed framework is presented in Figure 2 and builds on the work done by Jia et al. [5] and Davenport et al. [7]. The four research questions and the conceptual model were considered when developing the framework. The DDDM tools being used should continuously be defined, evaluated and improved. The organisational strategy acts as a key enabler for DDDM implementation, and the benefits achieved should be measurable. Once new lessons are learned, the process should be adapted. If this process is embedded in the organisational behaviour it will lead to an organisational DDDM culture. This framwork attempts to remove specific emphasis on any particular type of technology or any specific capability required for DDDM. Instead, the model is built around the circular process for DDDM capabilities, which include:

1. Defining what capabilities are required to meet the organisations' strategy to become data-driven.
2. Building and applying the required capabilities.
    a. Defining capabilities.
    b. Evaluating existing capabilities.
    c. Building or applying the capabilities.
    d. Continuously repeating this process.
3. Evaluating each capability level within the organisation to identify capability shortcomings.

Organisational Culture

According to Davenport et al. [7] [illegible] a business strategy for any data-driven initiative. This helps to cre [illegible] and can even assist with obtaining funding [7]. As discussed in section 5.2.1, the South African mining industry does not seem to have sufficient organisational strategies to become more data-driven. Therefore, the proposed framework starts with setting a business strategy. The strategy can be for a specific case where a data-driven approach is required, but ideally, it should be a broader strategy to become a data driven organisation.

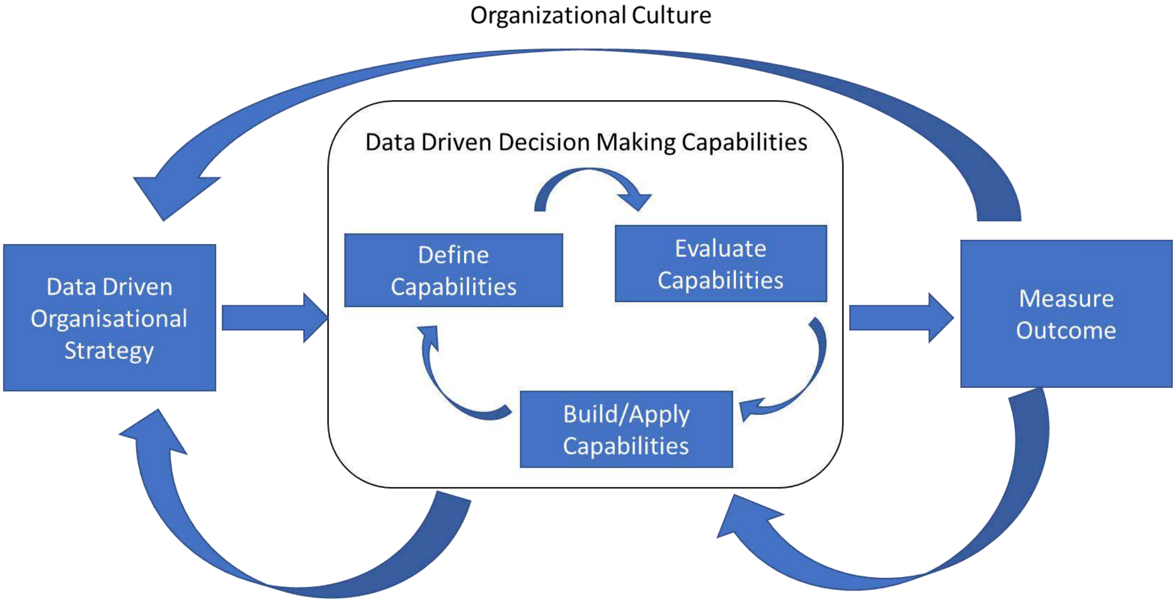

Figure 2: Proposed framework for the implementation of DDDM

Once a strategy has been defined, the focus should move to the DDDM capabilities required to meet the strategy. The DDDM capabilities process, which forms the centre of the conceptual model, is a circular process. The reason for this is to ensure that an organisation does not become complacent in its abilities but continuously strives to improve them. Gökalp et al. [12] define the highest level in their capability assessment model as "Innovation", indicating that a company that achieves this level becomes innovative and finds ways to improve its processes further. The conceptual model similarly expects the organisation to always have room to improve its DDDM capabilities.

When a new strategy has been defined, the first step within the DDDM capabilities process should be to define or identify which capabilities are required to meet the strategy. These capabilities are likely to closely match the five dimensions of DDDM capabilities defined by Jia et al. [5]. However, the conceptual model leaves room for an organisation to identify its capabilities. The capabilities must cover technological hardware and software, human resources, and personnel skills. The next step is to evaluate where the organisation currently stands regarding each capability. This evaluation should be performed using a process similar to the one proposed by Gökalp et al. [12], which is discussed in the scoping literature review performed by Bisschoff and Grobbelaar [1]. The last step is building/applying capabilities. Focus can be placed on those capabilities where the organisation achieved a lower level during the evaluation. However, all capabilities require continuous improvement. There is no specific time limit attached to the circular process. However, an organisation can define their own timelines and expectations as part of the strategy development. An organisation that has reached the build/apply capabilities step will start using their DDDM capabilities and can expect to start seeing the outcomes while continuously building its DDDM capabilities.

Based on the discussion in section 5.1, some of the capabilities defined by Jia et al. [5] already exist within the South African mining industry. By focussing on evaluating and enhancing these capabilities, it is expected that increased benefits will be obtained from their DDDM processes.

The final step is measuring the overall outcomes of the data-driven strategy. Business outcomes should be continuously measured against predefined key performance indicators (KPIs). A feedback loop should exist to provide feedback on the business outcomes of all previous phases of the model. This feedback loop further drives the idea of becoming a data-driven organisation and allows for faster management action when the desired outcomes are not achieved. Based on section 5.2.2, such feedback does not currently form part of most DDDM processes in the South African mining industry.

The role of organisational culture within the proposed model is twofold. Firstly, the overall process of setting a data driven strategy, defining, building, and evaluating the capabilities to meet the strategy, and measuring the business outcome of the strategy is expected to influence and build an organisational culture that encourages being data driven. Secondly, once the organisational culture encourages a data driven approach, it will continuously drive the circular process of reviewing the organisations' data driven strategy and following the process as depicted in Figure 2.

This proposed framework is depicted as a high-level process, leaving the finer details of how each phase will work and how an organisation will implement it to be unique for each organisation. Managers must have a good understanding of the theory and concepts to provide the context needed to use the conceptual model [5], [7], [12].

6 CONCLUSION AND RECOMMENDATIONS

6.1 Research conclusion

The primary goal of this study was to provide the South African mining industry with a framework for the successful implementation and application of DDDM. The study set out to answer the four research questions proposed in section 1.4.

The primary research portion of this study focused specifically on the South African mining industry. The conceptual model and research methodology are discussed in detail in sections 3 and 4. The research was conducted through in-depth interviews with individuals who work in the South African mining industry. During these interviews, specific questions were asked to find answers to the research questions and to draw further insights from the experiences of these individuals.

In section 5, each research question is discussed with reference to the scoping literature review performed by Bisschoff and Grobbelaar [1] and the research interviews. The research findings indicate that although DDDM is used in the South African mining industry, it is not evenly implemented and applied throughout mining organisations and often suffers due to poor adoption by users and stakeholders. Therefore, it is believed that there is still a lot to be gained from better implementation and adoption of DDDM in the South African mining industry.

A proposed DDDM implementation framework is provided in section 5.3. Applying this framework as part of their greater digital transformation strategy will assist the South African mining industry in transitioning into data-driven organisations. However, This framework is not a plug-and-play solution but rather a tool to assist in understanding the areas where management should focus on improving both organisational culture and DDDM capabilities to become more data-driven.

6.2 Research limitations and contributions

6.2.1 Research limitations

This study targeted a small sample pool of individuals working within the South African mining industry. Only 13 participants could be interviewed due to challenges in finding willing participants and obtaining the required ethical permissions from employers. Only four mine organisations operating within South Africa were represented among the participants. All of the represented mine organisations are, to some extent, part of large international mining groups. Therefore, this research cannot claim to represent the entire South African mining industry. There is no representation for any South African-based mine organisations or privately owned mines operating in South Africa. This limits the generalisability of the research. However, future research may assist with confirming the conclusions of this research and, subsequently, its generalisability.

The sample pool of research participants is very small compared to the number of people working in the South African mining industry. In some cases, only a single participant could be found within an entire company, increasing the risk of individual bias influencing the research results.

6.2.2 Research contributions

This research contributes to the existing body of knowledge on DDDM within the mining industry, specifically focusing on the South African mining industry.

This research contributes to the South African mining industry by providing insights into the current application of DDDM. The paper provides a DDDM implementation framework to the mining industry that is expected to assist them in improving the implementation of DDDM and increasing the benefits obtained from DDDM.

6.3 Recommendations

6.3.1 Recommendations for the mining industry

The following recommendations are made for the South African mining industry:

- The South African mining industry should work on creating data-driven organisational cultures and implementing organisational strategies to become more data-driven.
- The South African mining industry should build on the existing DDDM capabilities and find ways to strengthen these capabilities continuously.
- The South African mining industry should adopt a framework such as the one proposed in this paper to assist them with the successful implementation of DDDM.

6.3.2 Research recommendations

The following recommendations are made for future research:

- Future research should attempt to gain access to a larger sample pool of participants as well as participants that are more representative of the different companies and organisations in the South African mining industry.
- The research found that even though organisational strategies towards becoming data-driven exist, these strategies are not clearly defined or communicated. This leads to discrepancies in how strategies are implemented in different departments, ultimately leading to inefficiency. Future research on this topic is recommended to understand better the challenges of defining and implementing organisational strategies in the South African mining industry.
- A unique challenge that was revealed by this research is the retention of skilled employees and the issue of high employee turnover in the South African mining industry. Future research is recommended to identify the reasons for high employee turnover and identify possible solutions to counteract this.
- The industry may benefit from the development of a DDDM implementation roadmap. This roadmap may include acquiring capabilities and technologies required to improve the DDDM processes and, subsequently, the benefits achieved. Future research may focus on the development of such a roadmap.
- This research used qualitative data analysis. The validity and rigour of the research can be improved by triangulating the qualitative data with quantitative data.

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INDUSTRIAL POLICY IS A KEY DRIVER OF LOCAL CONTENT IN SOUTH AFRICA'S AUTOMOTIVE INDUSTRY

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ABSTRACT

The South African automotive industry strives to increase local content significantly in the next 10 years. This study investigates the policy implication of local content implementation in the automotive sector. The policy framework provides direction to the industry in implementing local content. Convergent mixed-methods research was conducted, and secondary data was collected from management information systems, government documents, and industry reports. Automotive Policy played a critical role in the growth paths of local content, the study reveals policy must include targeted components and technology that the industry can focus on, to develop capacity, skill, and demand. The paper provides a novel perspective on the impact of the local content policy on the industry, key gaps were identified that affect the effective implementation of local content in the industry, Further-more the paper presents solutions to the industry to accelerate the local content programs.

Keywords: Policy, Local content, Automotive industry

1 INTRODUCTION

Globally the automobile industry ignites economic growth and technological advancements [1], Automotive policy instruments have been key drivers of the growth in the industry with supportive funding models and volume incentives [2]. The automotive sector typifies a global value chain (GVCs), with global production networks (GPNs) and supplier networks that cover the global footprints [3], making significant economic contributions to local economies in host countries.

Automotive multinationals operate in different jurisdictions and are subject to different local content policy frameworks, with some being flexible while some policies are rigid in paper and application giving governmental entities a significant upper hand to interfere and direct their business operation [2], flexibility and dynamism from automakers is a key success to operating sustainable multinational operations within specific policy frameworks.

At the heart of Local Content policies is the development of local capabilities to build local reliance and establish a sustainable platform to maximize the effects on the economy [4]. Given that most automotive industrial policies aim to positively change the composition of commercial activity related to sectors, value chains, and technologies [5]. Effective policy framework can drive development in a specific economic sector through clear guidelines and a comprehensive set of rules and goals [6].

Even though there is resistance to local content policies [7] , Policy makers must have the space and freedom to distinguish and trail the best suitable blend of fiscal and collective policies to reach just and sustainable development best fitted to the national interest [8].The Organisation for Economic Co-operation and Development (OECD), promotes a transparent policy framework with the following key foundations:

- Policy directing principles.
- Specified numerical targets linked to the vision.
- Analyses of the results
- Corrective action development.
- Review of results and a reassessment of idea corrective action [9].

Greater appreciation must be given to effective policy framework due to the complexity of the policymaking process, governance, consultation with stakeholders, and balancing the policy requirement with the sustainability and economic viability of the sector [10] The automotive industry is Intensely competitive across segments, it would be a step back for any policy framework to dilute the competitiveness because it keeps the sector innovative [11]. The industry requires a clear well-defined policy framework to significantly contribute to the effective and efficient management of industry activities [12].

The automotive industry has an intricate value chain encompassing various tiers of suppliers generating 70-80 % of value [13], Can local content regulations enhance the development and attractiveness of local industries? The most pessimistic view is that local content requirements will slow down the manufacturing process due to a lack of capacity to meet the large volume requirements and stringent quality standards required [14]. Local content policy instruments in one form or another are being applied in all automotive active manufacturing economies, from established automotive players like China, the USA, and the EU to upcoming markets like South Africa, Brazil, and India [7].

1.1 Background

The automotive industry is rapidly evolving in several directions, with technological innovation and new energy systems being at the forefront, Governments are deploying stronger local content regulatory frameworks to ensure the change can also be a driver of capacity and technological development in their local industries through these regulations [1], South Africa like most active automotive manufacturing countries has developed a policy framework that aims to archive 60% of total local content by 2035 from a base of 40 % in 2024.

Specific policy instruments can turn around a sector to be more profitable [15], Local Content Policies (LCPs) that contain specific sectors have been a key driver in the accelerated development of Chinese Indigenous automotive companies, through the joint venture policies that ensure 50 % Indigenous ownership of multination entities [2]., skills transfer, technological collaboration, and innovation have ensured that local firms build the capacity to develop their products. [4], by looking at the success of other automotive markets like China, the South African government in collaboration with the industry has developed the 2035 automotive industry master plan.

The study aims to identify the key driver of localization in the automotive industry, identifying the policy gap within the South African automotive industry in contrast with BRICS partners. Traversing the policy landscape to find success drivers of local content policy implementation that provides positive development.

1.1.1 Methodology.

The BRIC countries provided $401.5 billion to the international car manufacturing industry [16].A case study was conducted for this research study to investigate the local content policy within the BRICS member countries [17], Case study research allows for numerous possibilities [18] and it is primed for in-depth case studies in the automotive industry. It provides a platform for carrying out a thorough analysis of localization policy instruments within the automotive industry of the BRICS member countries [19]. Figure 1 illustrates a summary of the research process.

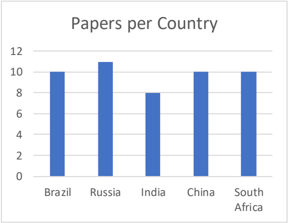
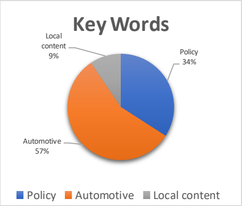
Research Aim	Methodology	Population	Search engines	Search words	Key findings
To identify the key driver of localization in the automotive industry	Case study	BRICS 	Google scholar Elsevier Emerald Insight Science direct Scopus Webscience		Import tariffs Export incentives Tax break Industry liberation Local brand's market share State-owned Automotive Company

Figure 1: Methodology

The strength of the case study allowed the researcher to perform an in-depth exploration of complex phenomena of localization within the automotive industries of the BRICS member countries [20]. The use of case studies in the research allowed robust evidence collection for understanding the complexities in the policy landscape [20].

Secondary data is gathered from public databases such as organizational reports, financial statements, and operational reports to analyze the policy landscape comprehensively. The paper is structured as follows; Section 2 serves as a literature review that gives an in-depth view of the learning areas. Section 3 presents a detailed presentation of the localization policy instruments within the BRICS group and expands on how the different iterations and instruments within the policy context lead to the success or failure of the implementation. From traversing policy frameworks six key moments were identified as key success drivers to the implementation and future sustainability of the industry and section 4 displays the discussion, recommendations, and conclusion.

2 LITERATURE REVIEW

2.1 Automotive industry

Globally, the automotive is characterized by high capital investments in production technologies and innovation. [21], the automotive industry is a trailblazer in the manufacturing industry [22] Effective policy framework composed of government agencies and their collaborative relations, industrial development, and policy choices in driving the automotive industry toward a sustainable and inclusive future [23].

Pro-car policies that advance the consumption of automotive products are critical to the survival of the industry [24].The effectiveness of a policy framework is a key success driver for meaningful positive impact on incumbent automotive players and will improve the effectiveness of the entire industry ecosystem [10] In recent times through policy interventions, emerging economies such as China, India, and Brazil have experienced a drastic expansion of their domestic automotive sectors and are becoming major players in the export market [1].

The European Union (EU)'s automotive sector is a significant industrial sector, employing 3.5 million people and 14 million people benefiting from its value chain [25], In 2009, China's automotive industry became the largest in the world overcoming the United States (U.S) [26], currently, the EU's production output is only second to China with 21% of global car production i [25] Automotive manufacturing is a key pillar of economic growth and development in developed and developing economies [27].

2.1.1 Local content in policy in the automotive industry

Ideally, policymakers aim for strong local industries with local content policy instruments [28], in the United States, there is a 50% local content requirement for goods that are to be sold within its territories [29], in 2022 the European Union has imposed 45 percent local content requirements on any new Electric vehicle that does not originate from the region [30].

The challenge that local content policymakers face feasibility challenges due to a lack of global competencies [28], The European Union's local content policy aimed to stimulate the development of Europe's battery supply chain but the supply is concentrated in China [30].

Australia's local content program has been in place since 1948 and continued until 1985 were a gradual process of liberation started, The import duties were reduced from 125 to 10 % only in 2005 to comply with the World Trade Organization requirements [31], In Asia, Malaysia has set a higher local content of 50% and Thailand set a local content of 40% [32].

3 LOCAL CONTENT BRICS COUNTRIES

The BRICS countries (Brazil, Russia, India, China, and South Africa) are a stout economic development block [16], the new block has a shared economic bulk of $29.9 trillion, accounting for 33.8 % of the world GDP [33] together are 29.3 percent of the world's overall geographical land and 41% of the world population [34].

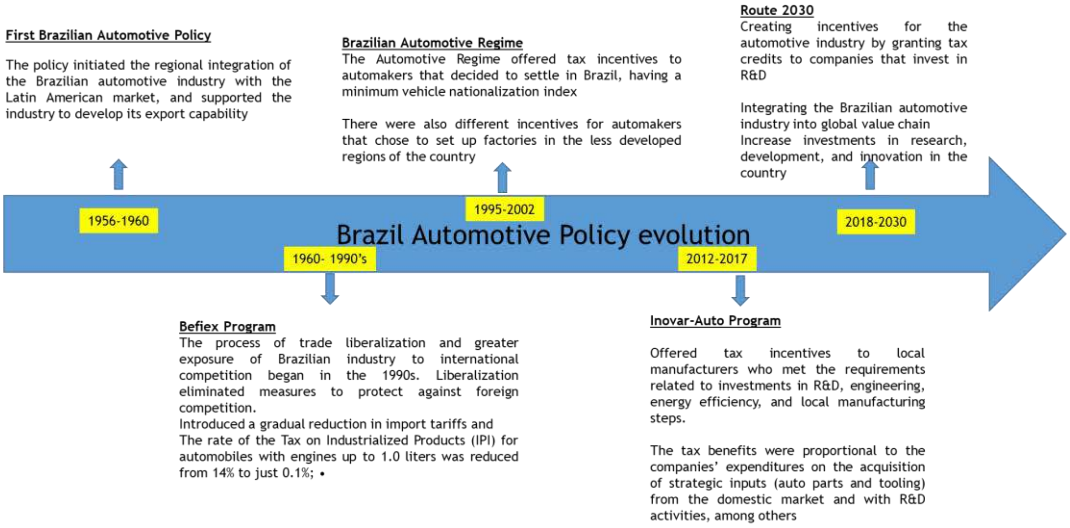
These economies are confronted with policy dilemmas in the political-economic sphere prioritizing economic growth over local capacity development [34], The block as developing countries suffer from weaker legislative frameworks to support accelerated growth in many economic sectors [16].

3.1.1 Brazil

The Brazilian auto industry is an important sector of the Brazilian economy [35]In 2022 Brazil manufactured 1.82 million cars still driving towards the high of 2013 where 3 million-plus cars were manufactured as shown in Figure 2 [36]. Brazil's automotive industry is in the top ten worldwide [37] creating jobs, while providing important productive chains and driving innovation [35].

Figure 2 Brazil's market share and sales [38]

Market protection through tariffs and quotas on imports encouraged companies to establish and increase automotive production facilities within Brazil, stimulating the local economy [36].Brazil implemented the Incentive Program aimed at improving productivity in the sector illustrated in Figure 1 [39], stimuli established by the government to increase local content of production in the country [40]. Illustrated in Figure 3, Tax breaks of up to 30% were offered, and in 2017, tax reductions were also given to vehicles manufactured in Brazil that achieved a reduction in fuel expenditure [39].



First Brazilian Automotive Policy

The policy initiated the regional integration of the Brazilian automotive industry with the Latin American market, and supported the industry to develop its export capability

Befiex Program

The process of trade liberalization and greater exposure of Brazilian industry to international competition began in the 1990s. Liberalization eliminated measures to protect against foreign competition.
Introduced a gradual reduction in import tariffs and
The rate of the Tax on Industrialized Products (IPI) for automobiles with engines up to 1.0 liters was reduced from 14% to just 0.1%; •

Brazilian Automotive Regime

The Automotive Regime offered tax incentives to automakers that decided to settle in Brazil, having a minimum vehicle nationalization index

There were also different incentives for automakers that chose to set up factories in the less developed regions of the country

Inovar-Auto Program

Offered tax incentives to local manufacturers who met the requirements related to investments in R&D, engineering, energy efficiency, and local manufacturing steps.

The tax benefits were proportional to the companies' expenditures on the acquisition of strategic inputs (auto parts and tooling) from the domestic market and with R&D activities, among others

Route 2030

Creating incentives for the automotive industry by granting tax credits to companies that invest in R&D

Integrating the Brazilian automotive industry into global value chain
Increase investments in research, development, and innovation in the country

Figure 3 Brazilian local content policy evolution [5], [40]

Sustainable goals are crucial to the survival of the automotive sector [41], To achieve a sustainable scenario and minimize emissions from the Brazilian automotive fleet by 2050, a decarbonization target has been proposed [35].

3.1.2 Russia

The Russian automotive sector industry plays an important role in the Russian economy [42] the automotive industry is a key driver of the manufacturing sector of the Russian economy [43], it directly drives more than 900 companies participating in the value chain [44].

Russia is one of the leading automotive producers worldwide. In 2021, nearly 1.4 million vehicles were produced in the country [45], Shown in Figure 4 is the historical for the industry in Russia showing 1 million vehicles sold in 2023 still far from the highs of 2.6 million sold in 2011.

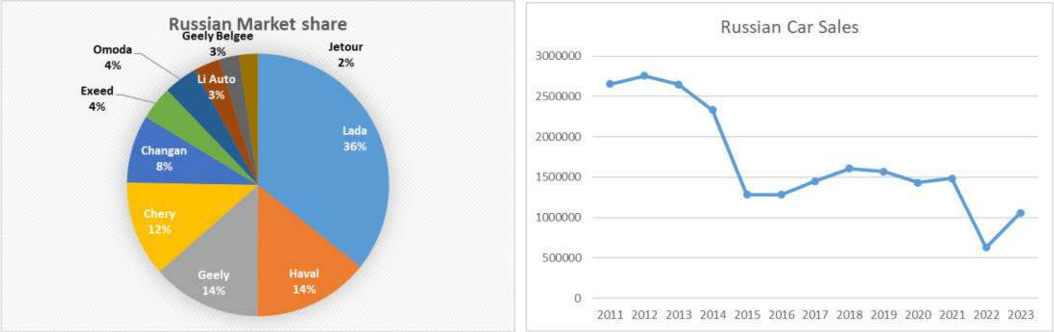


Figure 4 Russian market share and sales [44], [46]

The Russian market is dominated by multinational automotive companies illustrated in Figure 4 by market share in the figure, with just a handful of local companies enjoying success [45]. The government of Russia introduced a set of policy instruments to drive the development of local capacity through a different set of localization policies. The policy evolution is shown in Figure 5 [46]. The Russian government creating policy initiatives to ensure that current manufacturers continue to operate, protectionist measures to drive the growth of local companies through skills and technology [47].

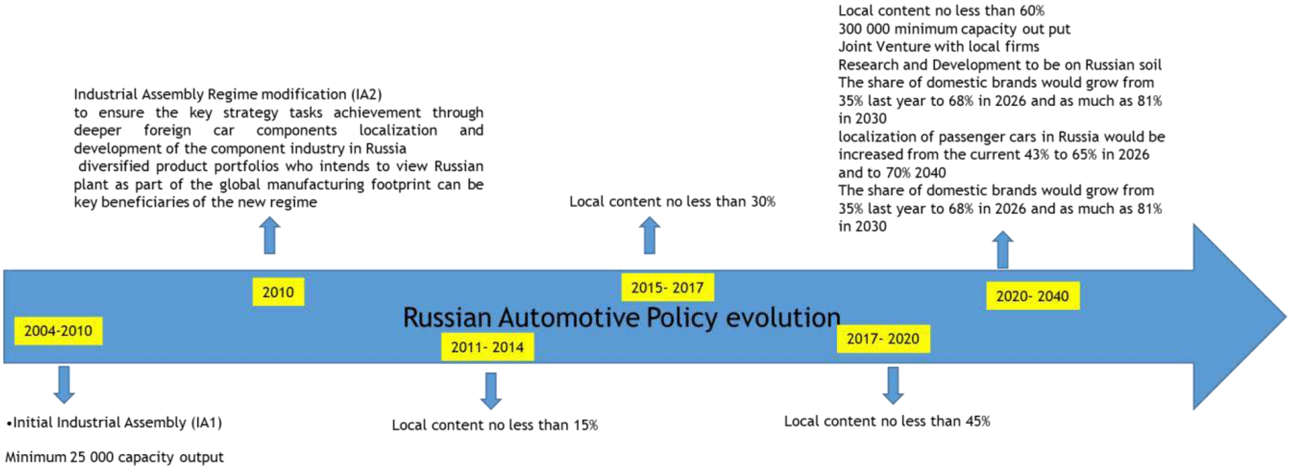


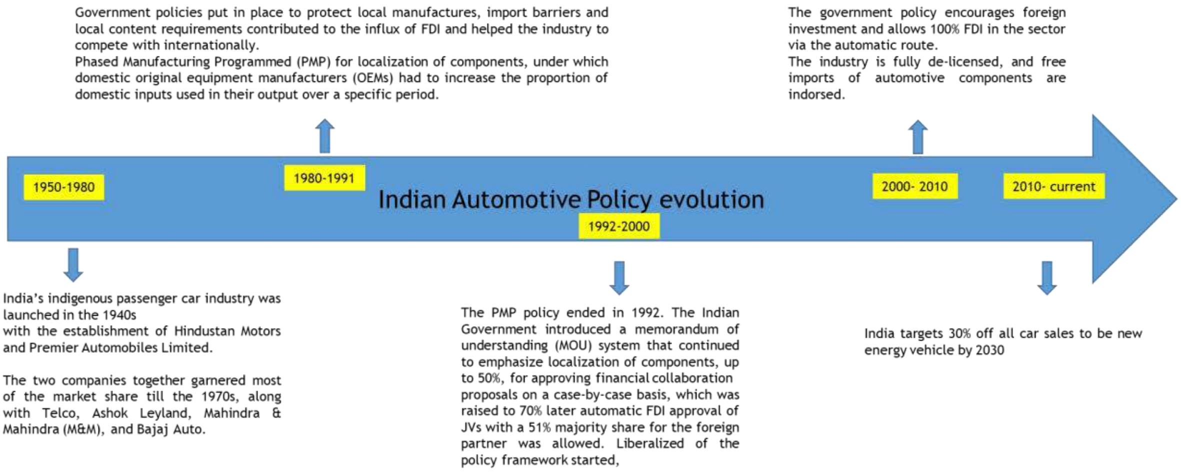
Figure 5 Russian Automotive Local Content Policy Evolution [48], [22] [47]

Local suppliers' network is still the weak link of the Russian automotive industry lacking behind in quality, productivity, and technological advancements [21], The Russian automotive policy evolution aims to drive the development of local suppliers with the directive to develop an 80% local car [22].

3.1.3 India

India is another fast-growing market for automotive products behind China [49].By 2050, India is targeting a total production output of 9 million units. In 2019, India was the fourth-largest producer of vehicles in the world and seventh seventh-passenger vehicle manufacturer [50]. The Indian automotive is aiming to be the largest automotive manufacturer by the year 2050 [51].

India attained global supply capabilities, by adopting a mixture of economic reforms that allowed the entry of foreign OEMs for manufacturing and trade through various policy instruments [28], the government introduced new industrial policy reforms in 1991 to encourage the development of local companies, as illustrated in Figure 6 [49].



Government policies put in place to protect local manufactures, import barriers and local content requirements contributed to the influx of FDI and helped the industry to compete with internationally.
Phased Manufacturing Programmed (PMP) for localization of components, under which domestic original equipment manufacturers (OEMs) had to increase the proportion of domestic inputs used in their output over a specific period.

The government policy encourages foreign investment and allows 100% FDI in the sector via the automatic route.
The industry is fully de-licensed, and free imports of automotive components are indorsed.

India's indigenous passenger car industry was launched in the 1940s with the establishment of Hindustan Motors and Premier Automobiles Limited.

The two companies together garnered most of the market share till the 1970s, along with Telco, Ashok Leyland, Mahindra & Mahindra (M&M), and Bajaj Auto.

The PMP policy ended in 1992. The Indian Government introduced a memorandum of understanding (MOU) system that continued to emphasize localization of components, up to 50%, for approving financial collaboration proposals on a case-by-case basis, which was raised to 70% later automatic FDI approval of JVs with a 51% majority share for the foreign partner was allowed. Liberalized of the policy framework started,

India targets 30% off all car sales to be new energy vehicle by 2030

Figure 6 Indian Automotive Local Content Policy Evolution [52] [28] [50]

Indian car sales continue to increase as local firms dominate as shown in Figure 7 [51]

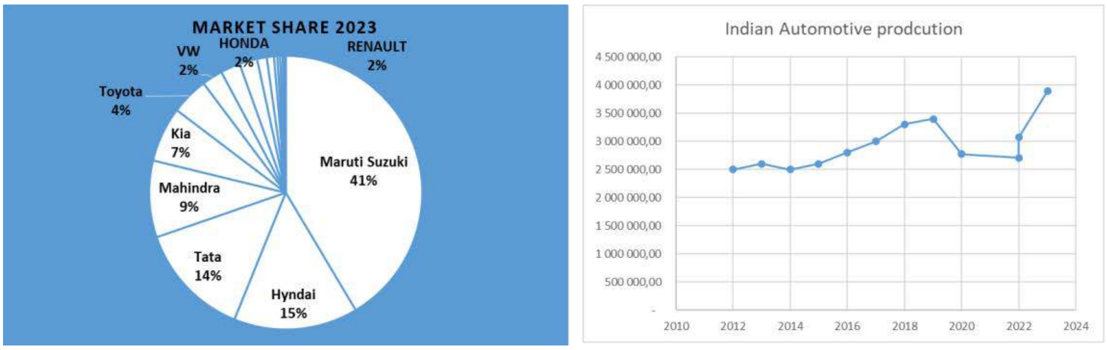


Figure 7 Indian automotive market share and output, [51], [29]

The Indian Government introduced a memorandum of understanding (MOU) system which is a policy instrument that sustained the drive for localization and a funding instrument that supports joint ventures between international companies with local manufactures [52], figure 8 illustrates some of the joint ventures between multinationals and local Indian manufacturers

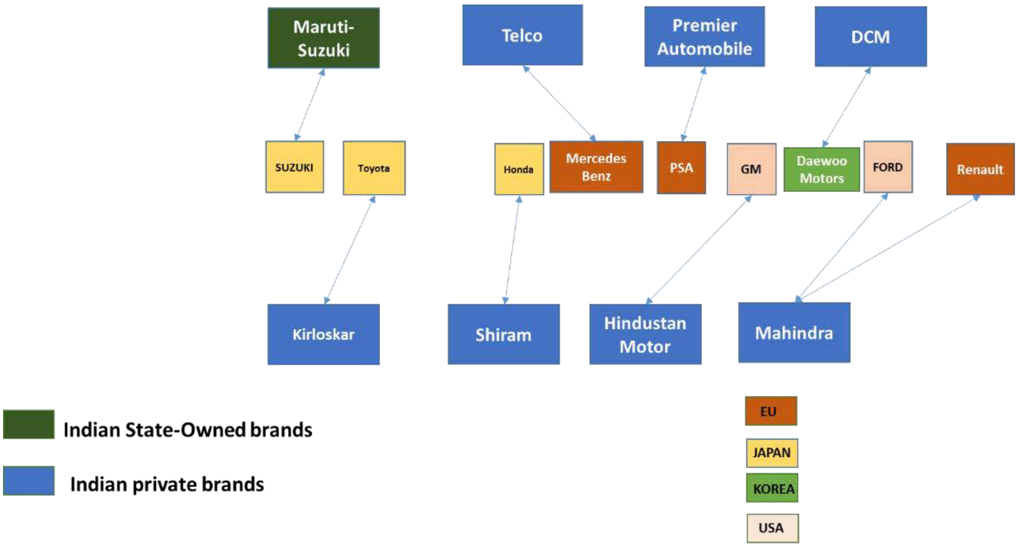


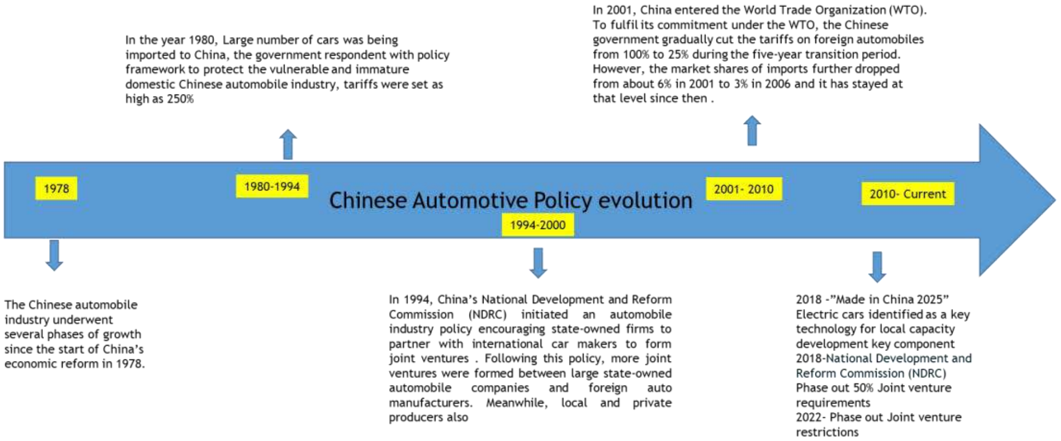
Figure 8 Demonstration of Indian automotive local content policy in action [52], [50].

Government policy has shaped the automobile industry and nurtured a microeconomic environment to help the sector flourish. Through direct impact using fiscal policy instruments, the industry policy even influenced the development of the Indian automakers [50]. India world's third-largest passenger vehicle market and is a significant player in the global automotive industry [51].

3.1.4 China

Hardly 5000 vehicles were produced in China in 1985 [53], Since 2010, China has become the world's largest automotive market [23], The total volume of automobile industry sales in China reached 26.9 million units in 2022 [54], The hurried expansion of the Chinese economy in the 21st century has been astonishing and drew many intercontinental firms to enter the Chinese market [2].

In 1994, China's National Development and Reform Commission (NDRC) initiated an automobile industry policy encouraging state-owned firms to partner with international car makers to form joint ventures [26], figure 9 illustrates the evolution of the Chinese automotive policy that protected local manufacturers through policy tools such as joint ventures and high import tariffs with the highest level of import tariffs being at 250% in 1980 going down to 100% in 2001 and 3 % in 2006



In the year 1980, Large number of cars was being imported to China, the government respondent with policy framework to protect the vulnerable and immature domestic Chinese automobile industry, tariffs were set as high as 250%

In 2001, China entered the World Trade Organization (WTO). To fulfil its commitment under the WTO, the Chinese government gradually cut the tariffs on foreign automobiles from 100% to 25% during the five-year transition period. However, the market shares of imports further dropped from about 6% in 2001 to 3% in 2006 and it has stayed at that level since then .

The Chinese automobile industry underwent several phases of growth since the start of China's economic reform in 1978.

In 1994, China's National Development and Reform Commission (NDRC) initiated an automobile industry policy encouraging state-owned firms to partner with international car makers to form joint ventures . Following this policy, more joint ventures were formed between large state-owned automobile companies and foreign auto manufacturers. Meanwhile, local and private producers also

2018 -"Made in China 2025"
Electric cars identified as a key technology for local capacity development key component
2018-National Development and Reform Commission (NDRC) Phase out 50% Joint venture requirements
2022- Phase out Joint venture restrictions

Figure 9 China's Automotive Localisation Policy Evolution [45] [26]

International joint ventures (IJVs) by design have been the driving force in the development of local capacity which ushers the rise of China's automotive company to the international market, by working closely and gaining knowledge, skills, and technological capacity from the industry giants through the joint venture policy [2]. Chinese automobile policy states that Chinese automobile companies can form joint ventures with multiple foreign car manufacturers with 50% local ownership. Several large state-owned automobile enterprises in China tried to partner with foreign auto manufacturers to form joint ventures to increase their capacity and enhance their technical capabilities. However, foreign ownership was capped at 50% to protect domestic producers [26].

The gigantic success of joint ventures can be seen in how the industry is structured, The Chinese industry has two types of manufacturers: indigenous-brand manufacturers, and joint ventures between domestic manufacturers and foreign manufacturers, as shown in Figure 10 and the Chinese brands [26]

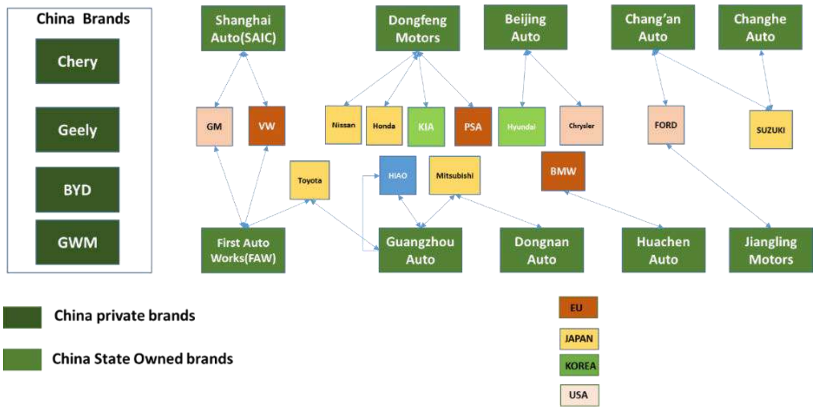


Figure 10 Demonstration of China's Automotive industry localization policy in action [26]

The joint ventures continue to accelerate the growth of the Chinese brands increasing their market share and the industry output number keeps climbing as illustrated in Figure 11 [26].

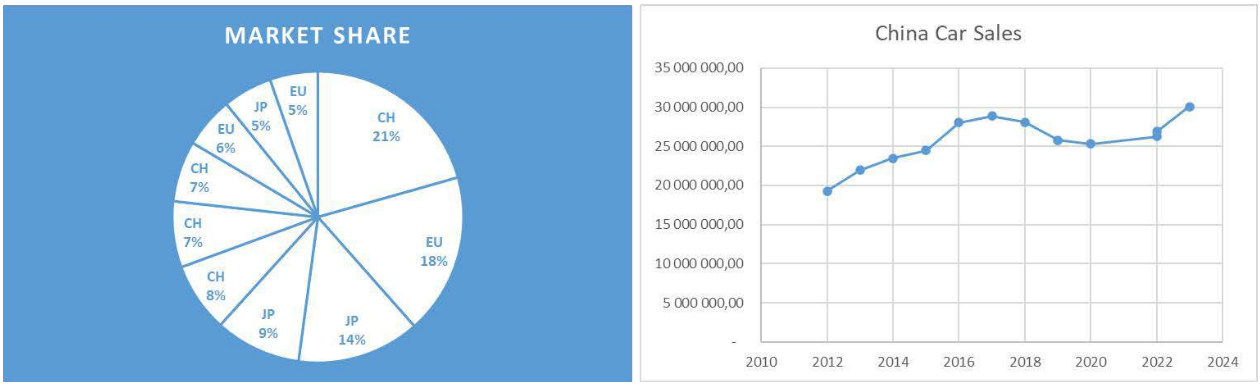


Figure 11 Chinese automotive industry market share and sales [54]

Maintain joint ventures represent the largest percentage of market share, China's design brands increased their market share to 41.2 percent in 2021 [53]**.** Similar to between India and China joint venture instruments, the policy instrument ensures that local capacities are developed and local automakers can compete with the best in the world.

3.1.5 South Africa

The South African automotive industry is small in output and sales compared to the other BRICS partners as illustrated in Figure 12 [55], in fact, it can be categorized as a tier 2 automotive industry or an export-oriented industry because the bulk of the output is for export markets.

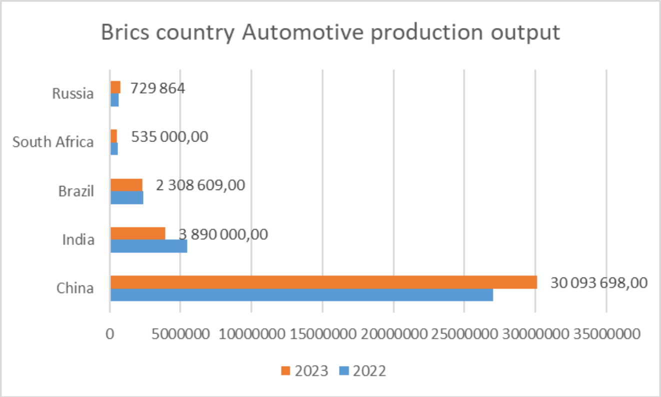


Figure 12 BRICS country's automotive production output [55]

Local content in the South African automotive industry has been part of government policy since the 1960s as displayed in Figure 13 provides a roadmap of policies to support the industry, the policies have evolved over decades, Still, with the evolving policy frameworks, economies of scale is still a challenge to archive and to justify the number of models for domestic production over time [56], In 1961, The government started with local content Phase I with a modest target of 15% and illustrated table provides a summary of key policies that have been adopted in the automotive industry and highlights how the policy affected the success of implementing local content, currently, SAAM 2035 aims to archive local content of 60 % by 2035, While Local content Phase VI managed to archive more than 66% weight based local content [57].

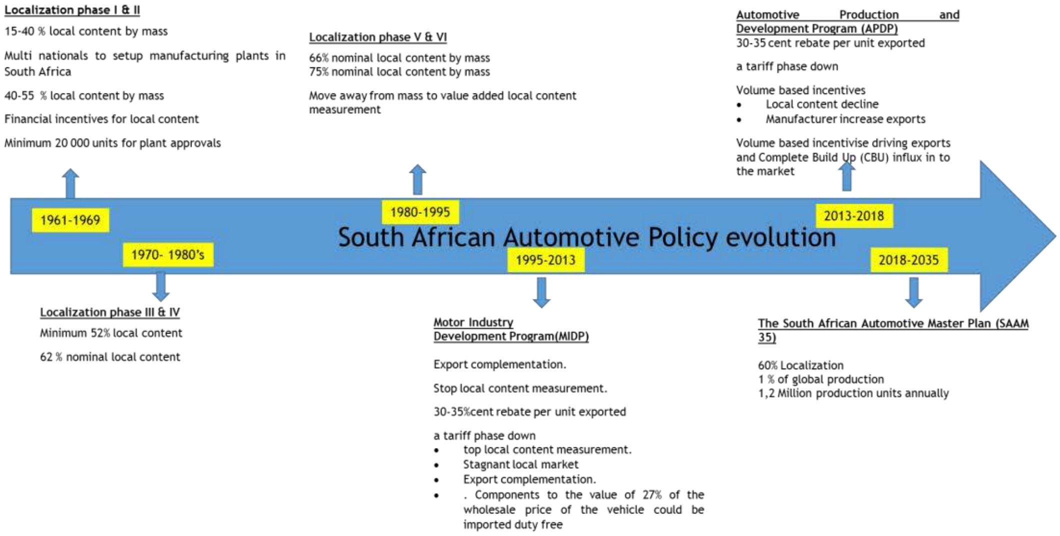


Figure 13 South African Automotive Local Content Policy Evolution [56], [57]

By 2002, the import tariffs on automotive components were only 30 percent down by nearly 20% which led to more imported parts and vehicles which further set local content backward. Furthermore, lowering of tariffs has led to increased demand for imported complete built-up units (CBUs) which currently account for 43 % of the cars sold in the local market illustrated in Figure 14 [58].

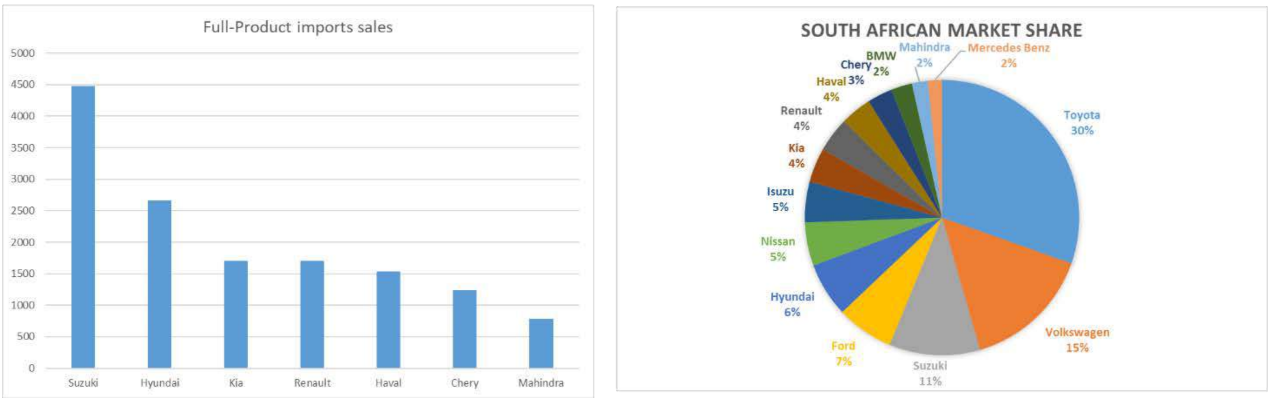


Figure 14 South African automotive industry sales and market share [58]

In the industry, 43% of the value generated yearly goes to international companies, which is the inverse of what the new SAAM 2035 policy is aiming to achieve. The MIDP as a policy provides clear evidence of how policy can shape and drive an industry in a particular direction. The plan is that the SAAM 2035 can be as effective as the MIDP and reverse all the local content losses the industry suffered during the MIDP.

Localization is a complex issue in the industry with both structural and capacity challenges [59], key industry changes require industrial policy to support the development of new capabilities [60] One of the top key success drivers for localization is the high-cost profile of the South African industry along with the high logistics cost [59], The government has put substantial support behind the automotive industry with progressive policies and instruments illustrated in figures and financial support, but neither the MIDP nor the APDP has substantially shifted in improving local content contribution to the value chain [61].

The new policy that is to lead the industry to 2035 does not provide concrete direction for dealing with localization challenges, it provides a set target. Even though the SAAM35 seems more aspirational, the plan lacks decisive detail on how to achieve all its 6 strategic goals, not to mention localization [62].

When South Africa is compared to four similar automotive manufacturers, it is found that there is stagnation in the industry even though the industry has been around for more than 60 years with adequate support from government policies [63]. The concept of a masterplan was derived from analyses of Thailand’s automotive industry development experiences, along with research on developments in Turkey, Morocco, Malaysia, and Australia [64].Benchmarking with these markets must not only end on plan development but bust propagate further in how Thailand archived a high local content and developing local capacity.

Deep liberations of the industry that have taken place over the last 40 years have been decreased at an accelerated rate to local support manufacturers, the liberations have not assisted the local market and local manufacturing production to grow to international competitiveness but diminished the local content drive when compared to other counterparts that are driving local content through aggressive policy instruments. [63], Localisation remains a key policy instrument to drive local capacity development, local ownership, and overall economic benefit that the host country can derive from the automotive value chain [65].

4 DISCUSSIONS

The dynamic policy framework is required to deal with the change and introductions of new technological trends due to their potential to change the global industrial landscape [66].overtime the Chinese and Indian localization policy through the joint venture instrument has changed the develop their local firms and industries to compete favourably with established automotive multinationals.

Table 1 illustrates similarities and differences in approaches that BRICS countries have taken over the years to promote local content and develop local capacities. being called different things, and implemented differently, but the overall theme shows that local content policies are key to host nations, The policy instruments of South Africa and Brazil are mild while others are aggressive in their approach, China, and India, with Russia being in the middle in terms of requirements and approach, both presenting benefits and challenges.

Table 1 Local content policy drivers

Main Characteristics	Brazil	Russia	India	China	South Africa
Localization concept	Local content	Local content/Local Car	Joint venture	Joint venture	Localisation/Local content
Local Content targets	95% local content for	70% local content by 2040	venture with a local firm	50% in 1st year of production	60% by 2035

	passenger cars by 2018	60 % of the industry be controlled by local brands by 2040	as the entry point (50% local content if 50% of the joint venture is local and 70% joint venture is 51% foreign-owned	and 70% by 3rd year of production. Joint venture with a local firm as the entry point and 50% local ownership of the venture	
Import tariffs	30 %	20-30 %	125%	Max 250%,	18-25%
Export incentives	Yes	Yes	Yes	Yes	Yes
Tax break	Yes	Yes	Yes	Yes	Yes
Industry liberation	1990	2010	2000	2022	1995
Local brand's market share	N/A	44%	64%	55%	N/A
State-owned Automotive Company	N/A	Yes	Yes	Yes	N/A
A new energy vehicle policy exists	Yes	Yes	Yes	Yes	N/A

Local content requirements in China have had strict timelines and are cascading with the time of operations, requiring companies to get to 70% local content within 24 months of operating in China, While Russia has a more “reasonable” time frame of requiring companies to increase local conte gradually by 15 % every 3 years, South Africa is openly broad with 60% local content required in 6 years.

Table 2 Local content policy instruments key moments

Time phrase and policy instrument	Effect
Local content targets	Compared to Russian local content requirements, shown in the figure, Russia has a 15% over every 3 years that must be archived and has a local content target for manufacturing and sale, With the sales target for market share to be 60%

	owned by local firms and South Africa does not have a local brand
No joint venture policy with 50% local ownership	Countries in BRICS that enforced joint ventures developed their owner local car bards that support localization of technology and the development of local value chain driven by the policy instrument, both Chinese and Indian brands dominated their local market with over 50% of the sales while in South Africa 43% of the sale are complete built-up units and rest of the market are multination brand assembled in the country with only 37% local content
Liberation of the industry and Import tariff reductions/Incentives	Brazil and South Africa opened their automotive industry earlier than other BRICS countries, which affects the development of local competencies. Local industries require protection to grow to a competitive stage, allowing an infant industry to compete with multinational companies that are part of a global value chain puts pressure on the survival of the local industries resulting in loss of capacity and market share, relaxation of import duties has also contributed to the dominance of import compel built up units in both Brazil and South Africa

In Table 2 comparison, South Africa's policy did not yield the same results, the policy instrument and their impact measurement are a challenge that does not board well for the success of local content in the industry, over the years local content has hovered between 28-37% in 2023, making the 60 percent required by 2030 a mountain to climb. The industry still requires a policy revolution that will drive the industry in the desired direction. BRICS peers like China and India have developed indigenous companies driven by joint ventures and government involvement funding state-owned companies' joint ventures with global giants, this move has seen the Chinese state-owned and privately owned companies take the market share from established multinationals.

South Africa does not have its own local automotive manufacturing company, but there is always an opportunity for development in the industry through the following steps championed by the Department of Trade, industry, and Competition:

1. Identify a technology or process (e.g., plastic molded parts) as a country's specialty and focus on its nationalization.
2. Consolidation of funding mechanisms to have a specific localization instrument tool.
3. Identify current automotive small and medium enterprises (SME's) (Tier 2/3).
4. Attach identified SMEs to mentor companies with process and technological experts.
5. Mentor company allowed equity of up to 45% in the SME.
6. Create a market for their products locally through OEMs and internationally to ensure future sustainability.

South Africa can learn from other BRICS countries to develop local capacity in the industry on the Tier2 level, The joint venture principle can still be applied in South Africa to develop strong Tier 2 or 3 networks to facilitate localization.

5 CONCLUSION

There is an increasing demand for sustainable operation in the automotive industry seeking to achieve climate neutrality goals [67], the development of sustainability in the automotive industry is critical for transportation, the economy, and the environment [68]. All BRICS countries have policy instruments to govern new energy vehicles and to promote the drive towards a sustainable automotive industry. At the same time, in South Africa, the SAAM 2035 does not provide a direct policy on new energy vehicles, which delays the industry's progress and makes investing uncertain.

Policy instruments are critical in driving the industry into the future, ensuring the value chain's sustainability. Policymakers will continue to play a key role in shaping the future of industries. Farsighted policymaking is required in the automotive industry due to the fast pace of changes and technological advancement. New energy vehicle poses new challenges to policymakers and will require a toolkit of policy instruments to manage the entire value chain and life cycle of the products to ensure profitability and environmental and societal protection, this research has demonstrated what can be achieved with good policy instrument that can archive long-lasting benefits for all stakeholders.

Policymaking will continue playing an important role in shaping the automotive industry through policy instruments to create a competitive and sustainable industry. The evolution of the industry towards carbon neutrality and mobility solutions will require policy agility to support the innovations as they come to ensure the industry's sustainability.

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RISK MANAGEMENT FRAMEWORKS OF GOVERNMENT HEALTHCARE INFRASTRUCTURE PROJECTS IN AFRICA

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ABSTRACT

This research endeavours to develop a robust risk management framework to address Africa's complex and dynamic nature of government healthcare infrastructure projects. This framework aims to provide a comprehensive and effective approach to identify, analyse and manage risks inherent in these projects. A systematic review evaluated the risks, effectiveness, limitations, and challenges of existing risk management frameworks and practices in African healthcare infrastructure projects. This study recommends developing and utilising a contextually relevant risk management framework. This research identified that adopting innovative project financing models, improving project governance structures, developing local infrastructure, and effective stakeholder management are crucial to improving the outcomes of these projects on the continent.

Keywords: Risk Management, Healthcare Infrastructure, African Government Projects

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1 INTRODUCTION

Healthcare infrastructure is critical for any country's health promotion and health system improvements [1], [2]. Consisting of the physical infrastructure (buildings and structures), supply facility systems, waste management systems, medical devices, information and communication systems and extended care services (such as ambulances, mobile clinics and telemedicine equipment) [3], infrastructure plays a crucial role in comprehensive healthcare delivery.

Over the years, African governments have been the main drivers of healthcare infrastructure development on the continent [4]. African governments often sponsor, initiate and manage healthcare development projects and initiatives [5]. Despite healthcare infrastructure being pivotal in health promotion, these development projects are usually characterised by schedule delays, cost overruns, sub-standard quality and even project abandonment [6]. These worrying phenomena affect project success and pose significant drawbacks to the overall effectiveness of efforts in improving health systems in Africa.

Healthcare infrastructure is complex and requires large sums of money to develop [7]. In the African setting, where scarce and often insufficient resources are allocated for these healthcare infrastructure projects [4], project failure hits hard and is inimical to socio-economic development. One of the causes of project failures in Africa is inadequate risk management practices [8]. Effective project risk management may help identify probable risk events, put contingencies and management measures for the risks identified, minimise the threats, and maximise opportunities [9].

Few studies have been done to assess risk management practices in African healthcare infrastructure projects. Therefore, A systematic literature review is necessary to evaluate the risks, limitations, and challenges of existing risk management frameworks in government-led healthcare infrastructure projects. It is the first step in developing a holistic risk management framework to address Africa's complex and dynamic nature of government healthcare infrastructure projects.

The main questions this study seeks to answer are:

1. What are the current prevailing risks with government healthcare infrastructure projects?
2. What peculiar factors affect risk management in the African project management context?
3. What risk management practices can make government-led healthcare infrastructure projects successful in Africa?

1.1 Role of Governments in Healthcare Infrastructure Projects

African governments, through their health ministries, departments and agencies, have been the main drivers of healthcare infrastructure development in their countries [2], [10]. African governments formulate policies, provide funding, initiate and supervise projects, and sometimes perform direct project management [10], [11], highlighting their role in ensuring the success of healthcare infrastructure projects. Studies [6], [8], [12], [13] have shown that persistent challenges such as technical constraints, human resource constraints, corruption, funding constraints, political interference and political instability have made many government-led projects in Africa highly volatile and precarious for project stakeholders.

1.2 Impact of Project Failure on African Healthcare Systems

The limited availability of resources is a common feature in many African countries; therefore, the effective use of funds allocated to projects is important. However, project failure in healthcare infrastructure projects in Africa remains a worrying trend [6], [14]. Despite the large amounts of resources invested, there are many reports of healthcare infrastructure projects in African countries having been delayed or abandoned [15], [16], [17], [18]. The failure of healthcare infrastructure projects negatively impacts healthcare delivery and worsens poverty and inequality on the continent [19]. Therefore, developing and implementing mechanisms to ensure that healthcare infrastructure projects undertaken in Africa succeed is imperative.

1.3 Risk Management Process

Project risks are uncertain events or conditions that affect any project objective [78]. Project risk management involves the processes of identification, analysis, response, and monitoring and control [20] of risks. Project risk management includes strategies for managing risks in the project and assigning responsibilities relating to risk management to project personnel [21]. Risk identification involves comprehensively assessing possible threats and opportunities that may arise with the project [22]. After identifying risks, they are analysed to prioritise them based on impact and likelihood of occurrence [21]. After identifying and analysing project risks, appropriate and adequate response strategies are developed to address these risks. While the project is ongoing, monitoring and control mechanisms must be in place to track possible triggers of risks, assess the effectiveness of risk response measures and adapt strategies to the ever-changing project dynamics [21].

1.4 Risk Management Frameworks in Healthcare Infrastructure Projects

From the literature [7], [23], [8], major risk factors in healthcare infrastructure projects arise from financial constraints, project management inefficiencies, human resource challenges, procurement challenges, stakeholders, litigation and statutory constraints. International standards such as the ISO 21500, ISO31000/IEC62198, PMBOK Guides, PRINCE2 and IPMA [24], [25], [26] have been predominantly adopted to manage these risks. However, implementing these standard frameworks in the African environment may have unique challenges due to cultural, economic and political factors peculiar to the African continent.

Strategies such as early involvement of contractors during the design phase, flexible contract terms, technology adaptation, communication strategies and innovative project delivery models have been proposed for mitigating risks in healthcare projects [23].

2 METHODOLOGY

This study involved a comprehensive systematic literature review of relevant government healthcare infrastructure projects in Africa and worldwide. The systematic review focused on existing project risks, project risk management practices, and the challenges of managing risks in healthcare infrastructure projects. The study adopted the strategy used by [27] in review question formulation, search execution, and initial and full-text screening. A SWOT analysis was done on the findings. A framework for risk management in African government healthcare infrastructure projects was also proposed.

2.1 Relevant Papers Search

An extensive search was done on the SCOPUS and Web of Science electronic databases for peer-reviewed publications. The titles and abstracts of identified literature from search results were read and included based on the inclusion and exclusion criteria developed for this study [27], [28], [29] [30]. Search terms included “government”, “public”, “healthcare”, “hospital”, “project”, “risk”, “infrastructure”, “Africa”, “risk framework” and “project failure”. Search strings involving Boolean operators “OR” and “AND” were used for an effective literature search. The stopping rule, as applied in a previous study [28], was used in this study to end searches. After acceptance of an identified literature, backwards and forward searches were done to identify further relevant literature that was not initially captured.

2.2 Screening and Review

The literature's titles and abstracts were reviewed as done in a previous study [31] for the initial identification and sorting of relevant literature. The literature text was further examined to determine its final inclusion in the study. The inclusion criteria for this review were that only peer-reviewed literature that focused on projects undertaken by public entities in the healthcare infrastructure sector, either wholly or partially, that discussed project success, failure or risks were included. Literature on projects in the healthcare infrastructure sector undertaken solely by private entities and projects that did not concentrate on project success, failure or risks were excluded from the study. Also, only English-language publications made from 2014 to 2024 were selected. The search returned 1,673 results, and after screening through the abstracts, 66 papers were selected. After further screening to remove duplicates, the number of papers was brought to 54. After a full-text review, the final number of research publications included in this study was 49. After the backward and forward searches were conducted on the papers, 3 papers were included, bringing the total number of research papers for this study to 52. Atlas.ti version 9.1.3 software was used for the full-text analysis. Some key journals where relevant studies were published are found in Table 1.

Table 1: Key journals in healthcare infrastructure projects

Title	**Number of Articles**	**CiteScore**
Buildings	4	3.1
IOP Conference Series	3	N/A
JMIR Medical Informatics	2	5.6
Sustainability	2	5.0
MATEC Web of Conferences	2	N/A
International Journal of Project Management	2	13.0
International Journal of Managing Projects in Business	1	4.3
Computers & Industrial Engineering	1	11.9
Engineering	1	14.5
BMC Public Health	1	4.9

3 RESULTS

The findings from the systematic literature review are presented in this section, similar to other studies [21], [32].

3.1 Publications Analysis

The highest number of papers published within the study period was recorded in 2023, with 11 research papers. A total of 8 publications were made for the years 2019, 2020 and 2022. One research publication was made for the years 2021 and 2024. The graph showing the trend in annual publications is shown in Figure 1.

The projects covered by the literature include a medical oxygen implementation project [33], health information system projects [34], [35], a mobile diagnostic unit project [36] and hospital construction projects [7], [37], [38]. The nature of the projects researched was diverse, with 15 publications focussing on construction works, 14 studies on digital projects, 2 studies on medical device projects, 1 extended care study and 20 studies covering broad or multiple areas.

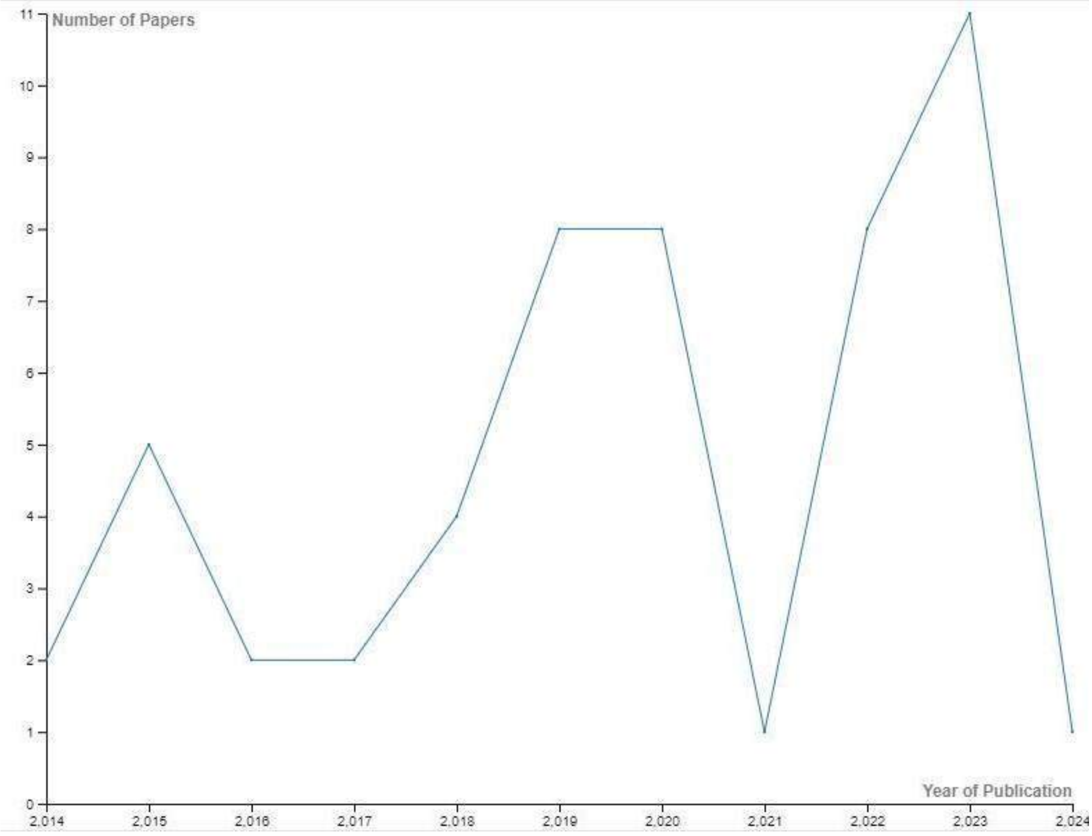

Figure 1: Annual publications trend

Publications across at least 44 countries were included in this study. The distribution of the studies worldwide can be seen in Figure 2. 5 research papers came from China and Norway, whereas 4 were from Kenya and Malaysia. Italy and India had 3 publications, whereas South Africa, Nigeria, and others had 1 paper each. A selection of countries and the number of publications included is found in Table 2.

Table 2: A selection of countries with identified studies

Country	**Number of Papers**
China	5
Norway	5
Kenya	4
Malaysia	4
Italy	3
India	3
Pakistan	3
Rwanda	2
Australia	2
United States	2
Nigeria	1
South Africa	1

Among the studies identified, 5 were multinational, and one had no specified country. Only 7 publications were from Africa, while 23 studies were done in Asia and 14 from Europe.

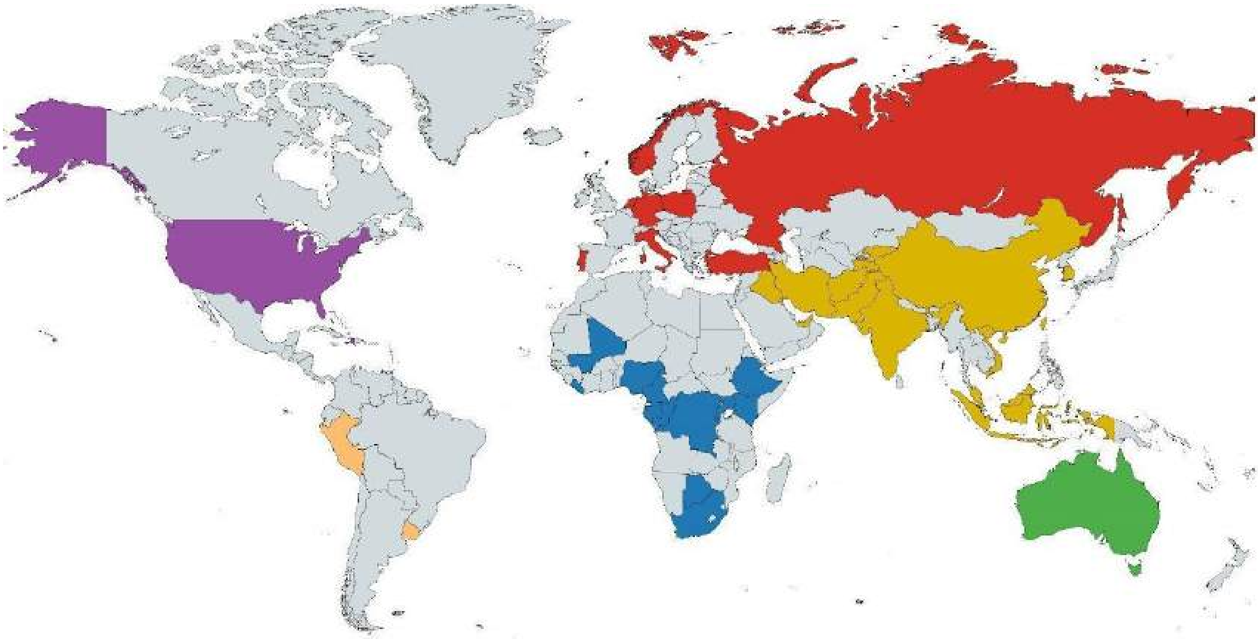

Figure 2: Distribution of studies across the globe

Researchers utilised different research methods, approaches, and tools in their studies. These studies deployed qualitative, quantitative and mixed research methods. The summary of the primary research tools and techniques used is shown in Table 3.

Table 3: Research tools and techniques used in studies

Tool/Technique	Number of Papers	References
Case study	22	[6], [20], [33], [34], [35], [36], [37], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53]
Interview	18	[7], [20], [35], [37], [42], [43], [44], [50], [51], [54], [55], [56], [57], [58], [59], [60], [61], [62]
Survey	14	[20], [38], [40], [44], [57], [58], [60], [63], [64], [65], [66], [67], [68], [69]
Systematic Literature Review	4	[21], [32], [69], [70]
Concept Design/Modelling	15	[20], [22], [41], [44], [46], [49], [51], [53], [54], [58], [63], [65], [66], [67], [71]
Delphi Study	3	[40], [51], [65]

The text analysis done on the literature revealed limitations encountered in previous studies. Some of the studies adopted the case study approach, with some using a small sample size [38], [74] and others conducted the study in only one country, thereby making these studies unable to draw generalised conclusions from their findings [6], [7], [14], [32], [34], [35], [36], [37], [39], [40], [41], [43], [45], [47], [50], [51], [52], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [68], [72], [73], [75]. Another limitation was found in studies involving the development of risk models where the studies were unable to test or validate their proposed models [22] vigorously, [46], [71]. A study did not consider other factors that could affect the validity of their findings [61]. One study also did not involve local participants from the host country in their study [44]. It will help to consider the identified limitations with the methods used for these studies for future project risk management studies and for developing holistic risk management frameworks for projects in the healthcare sector.

The annual publication trend indicates that there needs to be a sustained interest in this area of research. Also, with only about 13.5% of the published studies focusing on Africa and none concentrating on healthcare construction projects, the authors assert the need for sufficient literature on the continent to help manage risks in healthcare infrastructure projects.

3.2 Project Risk Management Concepts

The concepts identified from the studies can be adopted in formulating enhanced risk management approaches. One study [6] explained that total or partial project failures may occur at any phase of the project. The study also indicated that failure can occur post-completion of the project. This study listed failure in achieving the project goals, failure with adoption of project outcomes, sustainability failure of projects and failure in replication of projects as the types of failures that can occur at the project post-completion stage [6].

Other studies focused on concepts and models relating to project organisations. These studies argue that these concepts can help reduce project failure due to the project organisation. For an efficient evaluation of organisations involved in projects, SWOT analysis and System Theoretic Process Analysis (STPA) [53] was utilised to establish areas of strength, weakness and risks and to identify and address threats to systems within organisations. The concept of enterprise risk management [58] as an approach that takes the perspective of the entire organisation for risk management was proposed. The adoption of a mediation model in conflict resolution was also promoted in one study [55]. Another study [51] explored the use of data envelope analysis to assess the efficacy of organisational units. The study showed the combined use of these concepts in classifying risk evaluation factors into compartments. This enhanced risk evaluation system may help key project stakeholders improve their decision-making. Another study [45] touched on the concept of planning fallacy, which can negatively affect projects. It indicated that it is a bias that leads to underestimating risks, costs and time constraints in projects.

In other areas, studies focused on technological tools in project risk management. The use of the Analytic Hierarchy Process and Fuzzy Comprehensive Evaluation Method for developing risk evaluation systems was explored [51]. The Agile Development Maintainability Measurement (ADMM) model, as a valuable tool for the reduction of risks associated with requirement changes in construction projects [71], was examined in a study. The feasibility of blockchains for data encryption in ensuring the security of project data [22] was explored in another study. Another study highlighted the opportunities and challenges of building information modelling (BIM) for healthcare infrastructure projects [56]. The study indicated that BIMs present an efficient workflow that provides digital visualisation of the project. This can aid in designing, planning, constructing and managing healthcare infrastructure projects. The "as low as reasonably practical" approach in risk management was studied. This approach to risk management incorporates all the needed resources to manage project risk [68].

Studies also proposed concepts and models to address financial risks in projects. A study explored the social enterprise business model [33]. This model aims to ensure that social goals align with project objectives. The use of Hyperledger fabric for smart contracts [22] was also studied. The use of public-private partnership (PPP) models [38], [43], [69], [70], [71] to lessen project risks in governments was extensively examined. The Beveridge system [52], where governments levy their citizens specifically for healthcare provision, was propagated to mitigate government project financing challenges.

Theories such as Hofstede's cultural dimensions [44], [67] and cultural contingency theory [67] were examined as essential considerations to reduce the occurrences of culture-related risks.

3.3 Gaps in Project Risk Management Research

The systematic review of the literature enabled the identification of areas in project risk management where future studies can be conducted. These areas include the use of enhanced research tools for risk studies [53], developing systems for collaborative risk management among project stakeholders [22], investigating the sustainability of risk models [14] and comparative studies of risks between different infrastructure projects [74]. Some studies proposed evaluating the effectiveness of risk theories, models, tools and frameworks across various countries, regions and contexts [7], [38], [41], [53], [57], [62], [74].

One study proposed investigating risk factors in healthcare infrastructure projects [40] to enhance the understanding of the causes of cost overruns in these projects. Some studies also indicated the need for the development of risk management strategies to address culture-related risks [62], [66], [70]. Assessing the effectiveness of plan-driven approaches for risk management in digital projects was also proposed for future research [67]

Utilising research techniques such as SWOT-STPA methods in risk control studies is one area that has yet to be explored extensively. SWOT-STPA aids in identifying areas of strength, weakness and risks within the studied organisations. It also aids in identifying and planning strategies to address threats to systems within organisations [53].

Developing and evaluating systems that foster collaborative risk management among project stakeholders is one area that can be focused on in future studies [22]. Studies have also proposed future research in evaluating risk taxonomy tools [6], failure risk assessment models [14], the suitability of different types of software for risk management in healthcare infrastructure projects [56], [63] and the effectiveness of integrated risk management conceptual models [72],

Studies also proposed future studies to either develop or assess the feasibility and sustainability of financial risk reduction models for healthcare infrastructure projects. Future studies in PPP models were proposed [21], [46], [52], [63], [70]. Utilising integrated project delivery frameworks [43] was an area that was proposed for investigation. A study [54] identified the need for studies that will develop failure prevention models for health information projects.

3.4 Risks in Government Infrastructure Projects

This section answers the research question on the prevailing risks associated with government infrastructure healthcare projects. These findings will aid project management practitioners, government agencies, key project stakeholders, and researchers in getting a fair idea of the risks inherent in these projects. These risks are presented across different countries and regions in the world. The risks identified from the studies are categorised under technical risks [6], [32], [36], financial risks [6], [38], [57], political risks [21], [35], organisational risks [6], [32], [58], nature or force majeure risks [7], [14], contractual and legal risks [32], [44] and stakeholder risks [34], [62]. A fishbone diagram (Figure 3) was developed to present the various risks identified in the literature.

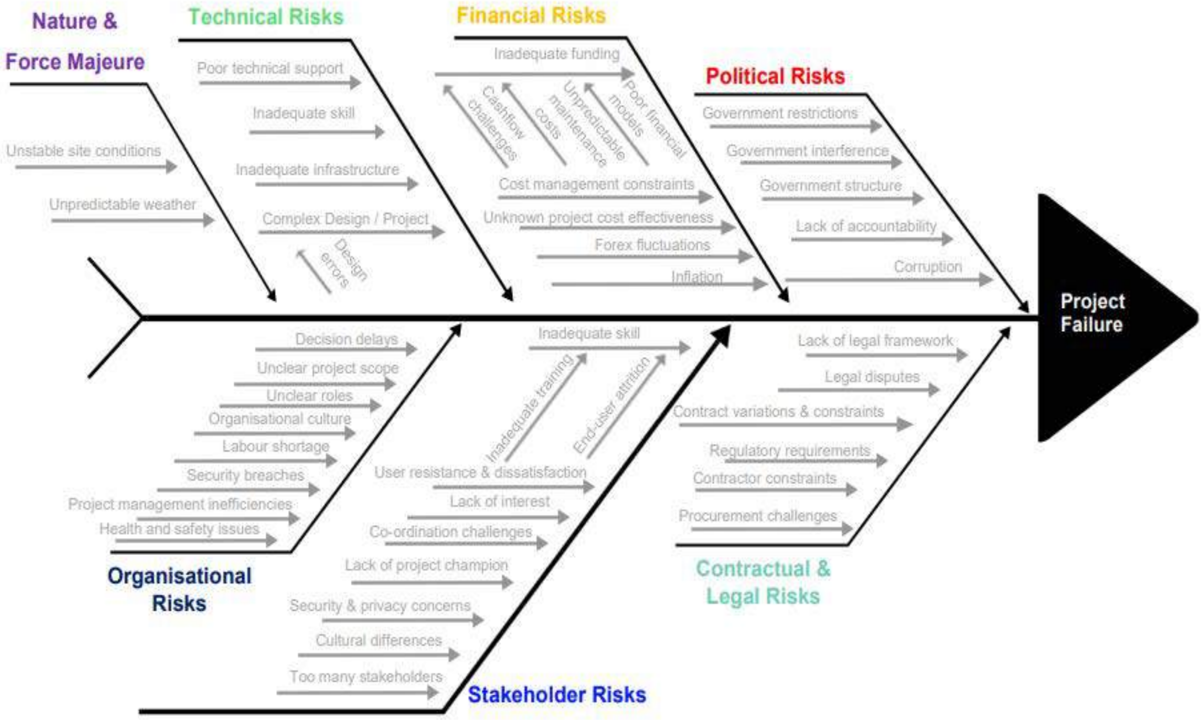

Figure 3: Fishbone diagram of risks in government infrastructure projects obtained from literature

Financial challenges from central governments have been identified as a significant risk factor with government healthcare infrastructure projects on the African continent. There is also the seeming lack of motivation by African governments to fund projects after project commencement [34]. Inadequate infrastructure and technology, such as internet connectivity, were also identified as a risk when implementing healthcare infrastructure projects in Africa [36]. Risks such as the government's undue interference were also identified [32], [34]. Project stakeholders in African countries also present unique risks to projects. Some of these risks include their resistance to embrace change [34], cultural differences and language barriers between locals and project organisations [32] and inadequate information technology skills [34]. The perception of the complexity of projects also presents itself as a risk that can lead to project failure in the African environment [14].

3.5 Risk Management Frameworks

For the successful implementation of any risk management framework in government projects, the government must buy in and prioritise risk management [32], [33], [53]. To ensure the reduction of risks in healthcare infrastructure projects, one key strategy that African governments are encouraged to adopt is aligning project goals with the goals of health facilities [42], [66].

Stakeholders' potential to bring about conflicts and disruptions in projects is not new. It is, therefore, essential to ensure that adequate measures are in place to manage the risks they pose to these projects. Strategies used in previous projects to manage stakeholder risks include extensive sensitisation and engagement [14], [33], [34], [35], [41], [50], [57], [67], [68], [70], [76] to ensure stakeholders have their needs captured [76], they are informed of the benefits of the project [57], [76], their privacy is guaranteed [22], are sufficiently trained [33], [34], [48] and have the organisation prepared to meet the demands of the project [35].

Project organisations are responsible for ensuring that risk management activities are carried out. Studies have indicated that due to gaps in personnel and competency levels within project organisations, it is vital to collaborate with external institutions such as universities, civil society organisations, non-profit organisations, research agencies and consultancies, especially in the African terrain to bridge that gap [32], [35], [45], [60], [72]. It is also recommended that internationally recognised risk management standards be adopted for African projects [61], [62]. Project organisations that had well-defined roles of their personnel [7], [57], monitored their project goals [57], set achievable project timelines [14], had clear communication channels [14], [65], [72], adopted clan control [44], identified and allocated risks during each phase of the project [22], [51], [60], [72] and were consistent with risk supervision and risk reviews [22], [37], [57], [60], [67], [70], [72] were successful in managing the risks in their projects. Project organisations that also considered culture-related risks [62], [67], [74], leadership and management risk factors [62] and relied on historical data in assessing risks [37], [49], [60], were successful in managing risks. Studies also indicated that projects that had pilot projects to determine project feasibility at larger scales [35], adopted the scrum method in risk management [71], had a phased utilisation of project resources [53], conducted a cost-benefit analysis on preliminary designs instead of conceptual designs [45] and had change management strategies in place [14] were successful in managing their project risks.

Studies have indicated that developing and adopting risk management tools and techniques is vital to effectively managing risks in government healthcare infrastructure projects. Qualitative and quantitative risk analysis activities are crucial for effective risk management [63], [77]. The tools and techniques identified for effective risk management are outlined in Table 4.

Table 4: Risk management tools and techniques

Risk Tool/Technique	References
Risk taxonomy and database tools	[6], [22], [57], [60], [61]
Risk analysis tools	[6]
Risk workshops	[22], [60]
Risk burn-down charts for risk monitoring and control	[71]
Decision support tools	[41], [63]

Strategies used in previous projects to address technical risks are presented in Table 5. These strategies include having in place alternative backup technologies such as generators to ensure that there is continuous power for the project [33], [36], [48]. This is relevant in African environments where power supply from the national grid may not be stable. Previous projects have utilised BIM technology to enable digital visualisation of the projects [50], [53], [56]. This BIM technology enables an efficient workflow and visualisation that helps design mock-ups [50], [51] and assessments. BIM technology also helps to reduce the risk of design errors.

Table 5: Strategies to address technical risks

Strategy	References
Provision of standby backup technologies	[33], [36], [48]
Adoption of web-based tools for collaboration	[22]
Utilising open-source software	[35]
Utilising BIM technology	[50], [53], [56]
Utilising blockchain technology	[22]
Provision of maintenance services at post-completion	[33], [76]
Developing and testing mock-up designs	[50], [51]

Studies have identified innovative business [33], [47] and financing models [33], [73] as effective ways of reducing financial risks in projects of this nature. The use of non-concession models [73], project bonds [73], grant financing [33] and public-private partnerships [52] help reduce financial risks associated with African government healthcare infrastructure projects.

Utilising the prevailing market situation in risk assessment [37] was also identified as an effective risk management strategy. These strategies are presented in Table 6.

Table 6: Strategies to address financial risks

Strategy	References
PPP arrangements for projects	[21], [52]
Adopting non-concession models for PPPs	[73]
Replacing credit financing with project bonds	[73]
Securing grants for project financing	[33]
Use of guaranteed maximum price contracts	[65]
Developing innovative business models	[33], [47]
Providing post-completion sustainability budgets	[33]
Incorporating contingency sums into budgets	[45]
Use of prevailing market situation in risk assessment	[37]

Incorporating the strategies outlined in Table 7 will help tackle legal and contractual risks in healthcare infrastructure projects. For instance, in PPP arrangements, allocating rewards according to the share of risks motivates private partners to be innovative in risk management, enabling them to reap the benefits allocated to their share of the risks [46]. Simplifying payment processes also helps reduce delays that may drag the project [65]. Involving persons in the project environment also helps identify, analyse, and respond to project risks [36].

Table 7: Strategies to address legal and contractual risks

Strategy	References
Incorporating punitive measures for poor performance in contracts	[49]
Higher reward allocation to higher risk share in PPP arrangements	[46]
Developing project guidelines and regulations	[39], [50]
Stating quality requirements in contracts	[37], [65]
Simple payment process for contractors	[65]
Contracting local persons to the project	[36]

The studies identified several challenges that may hamper the implementation of risk management frameworks and strategies in healthcare infrastructure projects, particularly in Africa. In Africa, inevitable technical challenges such as unreliable internet connectivity remain a stumbling block in implementing risk management strategies in healthcare projects [6], [22]. Ranging from resistance, lack of cooperation, and ineffective supervision to cultural and language differences between project organisations and stakeholders contribute to difficulties in implementing risk management frameworks [22], [58], [60], [67], [75], [76]. Further, the unavailability of skilled personnel also presents competence challenges in implementing effective risk frameworks [35], [60]. The absence of standardised industry risk management tools and techniques [60] for healthcare infrastructure projects may pose challenges with benchmarking and referencing. Funding challenges and time constraints have been identified as significant challenges to performing effective risk management strategies [46], [56], [58], [60]. The complexity of some projects and contractual arrangements make it challenging to implement risk management frameworks [58], [75].

A strategy for African governments' healthcare infrastructure projects was developed based on the SWOT analysis of the identified risks in healthcare infrastructure projects, risk management strategies and frameworks, challenges with risk management implementation and peculiar factors to consider from the African perspective. The SWOT strategy (Table 8) maps strengths to opportunities (SO), strengths to threats (ST), weaknesses to opportunities

(WO) and then weaknesses to threats (WT) to present a robust strategy to ensure success in healthcare infrastructure projects.

Table 8: Summary of SWOT strategy

	Strengths	**Weaknesses**
Opportunities	**SO strategies**: ● Encourage the use of innovative technological tools for collaborative risk management ● Reliance on open-source software to ensure faster rectification of challenges ● Use of blockchain technology to ensure security and safety of stakeholders	**WO strategies**: ● Collaborate with external institutions to address competence challenges ● Develop and test design mock-ups to address design error risks ● Adopt innovative business models and progressive financing models to address financial risks ● Provide health and safety measures to ensure safety of personnel
Threats	**ST strategies**: ● Early assignment of roles to key stakeholders to ensure buy-in and adequate supervision and control ● Provide end-user incentives to encourage project utilisation ● Ensure government buy-in and long-term support throughout the project through innovative contracts and advocacy ● Government share project risks through PPP arrangements	**WT strategies**: ● Include post-completion costs in project budgets to address the sustainability risks ● Provision of backup technology to tackle infrastructure challenges in Africa ● Utilise international risk management standards in the face of no regional standards ● Private partners engage governments to ease restrictions and interferences ● Governments enact legislation and regulations to increase project accountability and reduce corruption

3.6 Proposed Framework

A risk management framework for African government healthcare infrastructure projects is proposed (Figure 4) based on the findings from the systematic literature review and the SWOT strategy developed. This framework was developed based on successful risk management strategies. The framework acknowledges the roles of risk communication and risk governance systems in ensuring the effective management of risks in healthcare infrastructure projects in Africa.

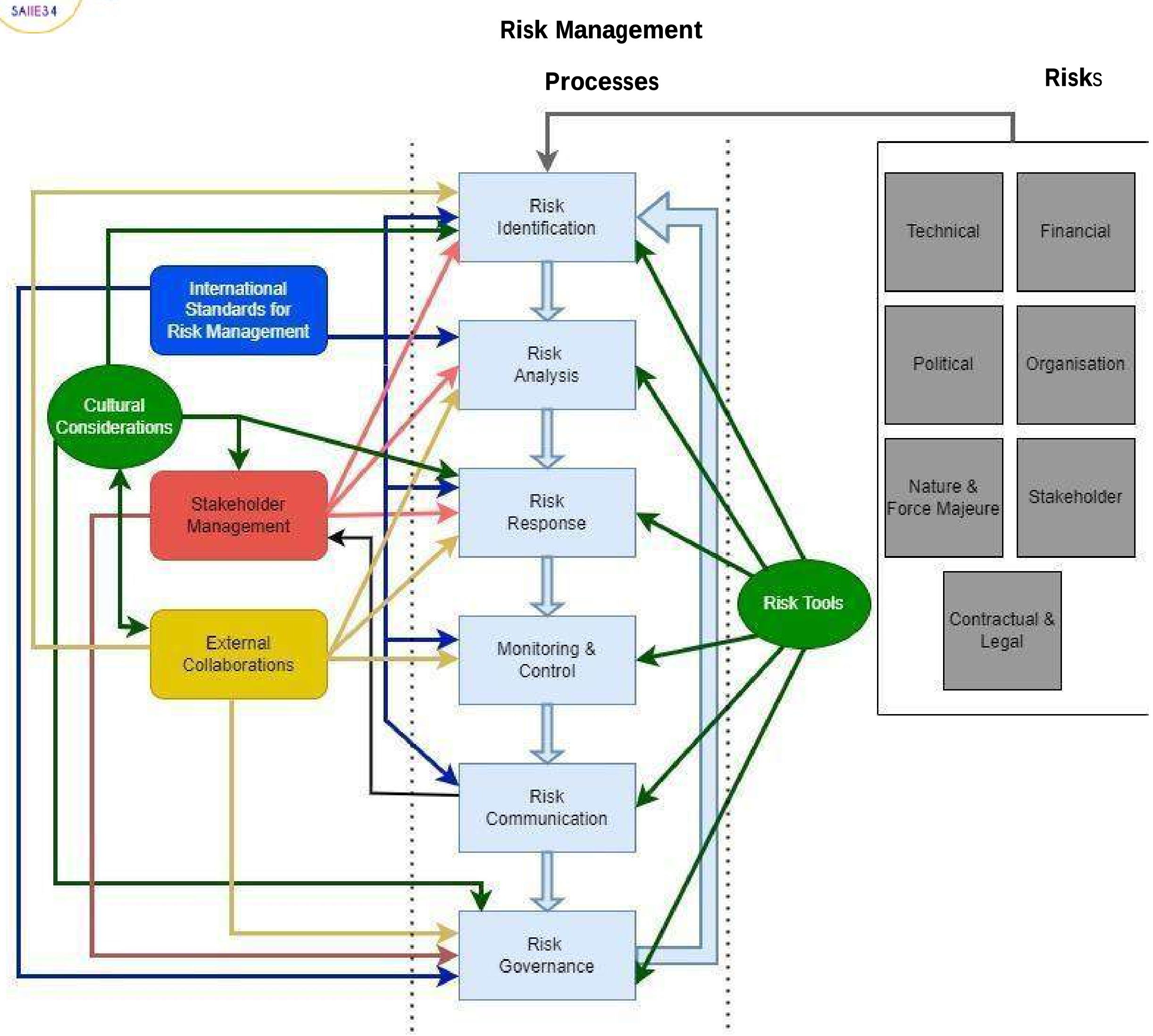

Figure 4: Risk management framework proposed by authors

The framework focused on the people, structures and systems to ensure a comprehensive guide for future healthcare infrastructure projects. From the diagram, culture maps with stakeholder management and collaborating with external partners work together in risk identification, developing risk response measures and governance. External collaborations will help develop strategies for implementing risk management processes and guide project risk governance. External collaborations also map to cultural considerations since they will provide knowledge and experiences relevant to the environment in which the project is being undertaken. International risk management standards will be relied on as benchmarks for best practices in project risk management, thus mapping all the risk management processes in the framework. Involving stakeholders in risk management will help ensure their buy-in and involvement throughout the project. Stakeholder management will ensure that the framework works with their essential role in the risk management processes. The governance of the projects affects project stakeholders, thus mapping to stakeholder management. Managing risk communication is vital in stakeholder management and maps to it.

4 DISCUSSIONS

This study identified key areas that require focus to ensure an effective management of risks in healthcare infrastructure projects on the African continent. The findings showed that the poor infrastructure in Africa affects project performance [36]. It was also identified that project end-users were not adequately versed in using technological tools [34]. Therefore, African governments must invest in developing physical infrastructure and citizens' general competencies in information technology to reduce the risks posed by infrastructural and IT deficits. African governments' lax attitude towards risk management may be the causative factor for their reluctance to meet budgets for project risk management. Some governments do not see the benefit of implementing risk management strategies, whereas others do not have adequate risk information [60]. Financial challenges remain a significant risk to healthcare projects in Africa and a challenge to implementing risk management frameworks and strategies. African governments are being encouraged to adopt innovative business models [33], [47] and financing models [33], [73] for healthcare infrastructure projects. Adopting PPP models [52] will help reduce the financial burden and risks on governments. The undue interference of government officials in projects has also been identified as a cause of project failure [32], [34]. Governments must develop regulations and frameworks to reduce government officials' over-reach of these projects and increase transparency and accountability. Some of the risks identified were due to project stakeholders. In Africa, stakeholders pose challenges such as their resistance to change [34], cultural differences and language barriers between locals and project organisations [32] and their perception of the complexity of projects [14]. It is, therefore, essential for project organisations to have a sustained stakeholder engagement strategy [34], [41], [50], [70], provide training and support services [32], [33], [48] to end-users to ensure the success of their projects.

The study could not identify regional risk management policies or standards for African healthcare infrastructure projects. This challenges a standardised risk management practice with no regional benchmarks to ensure effective risk management. Therefore, there is a need for the development and utilisation of an African risk management framework [61], [62], as proposed in this study. The study also could not identify a risk management strategy to address force majeure risks in Africa. There is, therefore, the need to bridge this gap.

It was identified that national culture affects the approaches to risk management [44]. It is essential to consider culture when formulating any risk management strategy. Also, the project organisation’s culture is an equally important factor [67]. It was proposed that applying theories such as Hofstede’s cultural dimensions [44], [67], and cultural contingency theory [67] may help to reduce the occurrences of culture-related risks. Behavioural and clan controls have also been suggested as an effective way to ensure organisational cohesion for project success [74].

Risk management is an iterative process that cannot be done without considering a handful of factors. Therefore, the proposed framework in this study attempted to consider all factors identified from the literature and presented a holistic approach to solving the problem of effective risk management in African healthcare infrastructure projects.

5 CONCLUSIONS

This study sought to identify the causes of project failure with government healthcare infrastructure projects in Africa and proffer suitable strategies for effective risk management. The study categorised risks in the healthcare project sector into technical, financial, political, organisational, nature or force majeure, contractual, legal, and stakeholder risks. The significant risks identified specifically with government health infrastructure projects in Africa are primarily due to inadequate financial models, governance structure and technological deficits. Risks due to project stakeholders’ technical competence and cultural differences were also identified with these projects in Africa. It was proposed that in developing any risk management framework for healthcare infrastructure projects, it is essential to consider cultural factors, financial models, risk management models, political landscape, technical landscape, legal and regulatory frameworks, organisational structure and the stakeholders.

One limitation of this study is that only English-language publications were selected and reviewed, limiting insights from non-English language publications. It is proposed that future studies look at developing a risk matrix with the likelihood of occurrence and potential impact of the risks identified. The proposed framework is also proposed to be tested on case studies to validate its effectiveness.

This paper presents a comprehensive overview of the risks, management strategies, challenges with implementing these strategies, and the peculiar factors that pose challenges to risk management in Africa. This will help project stakeholders and researchers develop adequate risk management strategies.

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USING SYSTEM DYNAMICS MODELLING TO DETERMINE THE IMPACT OF CHARGING ELECTRIC VEHICLES ON THE LOAD PROFILE IN THE RESIDENTIAL SECTOR

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ABSTRACT

With the electricity tariffs increasing year on year, and due to persistent loadshedding in the country, the prolific adoption of electric vehicles in the current economic climate presents uncertainty. This study focuses on the residential sector with specific focus on the impact of charging electric vehicles at home, taking into consideration changing tariffs. The premise is that households in the residential sector, assigned the residential Homeflex tariff, are likely to optimise expenditure on electricity consumption by charging Electric Vehicles (EVs) at specific times when the residential Homeflex tariffs are lower. This in turn means that the load profiles for households would change and may require load management strategies. A system dynamics simulation model was developed to analyse the impact on the total household electricity costs, at various charging times hours. Charging EVs at 20h00 or at 22h00 provided the optimal cost impact for user groups who are likely to purchase EVs (Quintile 4 and Quintile 5).

Keywords: system dynamics, load profile, electric vehicles, residential sector

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1 INTRODUCTION

Addressing the challenge of mitigating greenhouse gas emissions has become a global priority, with the transition from internal combustion engine (ICE) vehicles to electric vehicles (EVs) recognized as a key strategy towards achieving a zero-carbon future. To address these issues, South Africa has implemented the Green Transport Strategy (GTS) [1], which aims to reduce the carbon footprint of the transport sector through various measures. These include promoting the use of electric vehicles (EVs), improving fuel efficiency standards, and encouraging a shift from road to rail transport. Given the annual increase in electricity tariffs [2] and the persistent load shedding [3] in the country, the widespread adoption of electric vehicles (EVs) in the current economic environment remains uncertain.

This research is predicated on the assumption that households in the residential sector are likely to optimize their electricity consumption to manage costs, which could influence the shift from ICE vehicles to EVs, particularly due to the convenience of home charging. The timing of EV charging is crucial as it affects household load profiles, necessitating revised load management strategies [4], especially for those under the residential Homeflex tariff structure [5]. To explore this, system dynamics modelling was employed to simulate various scenarios, assessing the impact on both cost and electricity consumption based on different time-of-use charging strategies.

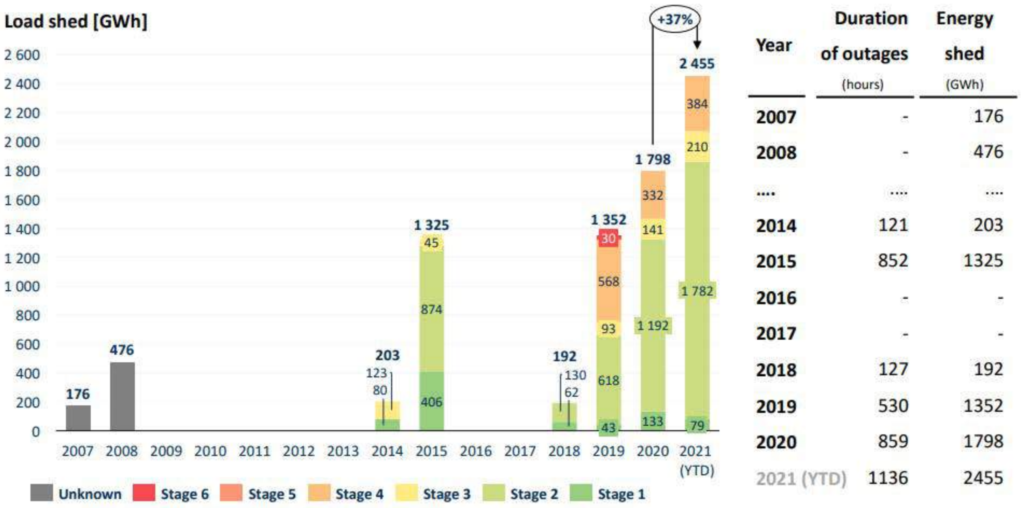
2 BACKGROUND

Road transport has been identified as being the largest source (>90%) of greenhouse gas (GHG) emissions within the transport sector in South Africa [6]. Despite initiatives to improve vehicle efficiencies, the use of alternative fuels and a shift to other mobility solutions, transport emissions have continued to increase [7].

South Africa pledged to introduce mitigation efforts to reduce emissions as per the 2015 Paris Agreement [8], as have other countries in global efforts to decarbonise the economy. The country’s Green Transport Strategy [1] was drafted to include strategies that would support efforts to reduce greenhouse gas (GHG) emissions, which also includes a move away from the ICE vehicles to the adoption of EVs. It was proposed that transport transition levers and measures could either be modal (changes in mobility options) and/or energy related changes to energy use and the energy mix in transport [9].

The constitution of the vehicle parc and the choice of vehicle would, however, be dependent on a variety of factors which in many countries may vary from incentives, retail prices, market availability, maintenance costs, carbon taxes, fuel costs, range anxiety and vehicle efficiency [10]. In South Africa, there are additional dynamics which may influence the purchase of electric vehicles such as:

Loadshedding: these are controlled processes which respond to unplanned events in order to protect the electricity power system and results in planned power outages for short periods of time [11]. The South African grid has experienced unprecedented pressure due to rapid urbanization, growth in mining and the industrial sector, as well as aging coal power stations, delayed maintenance and inadequate new capacity which have resulted in these power outages/ loadshedding events [12]. Figure 1 shows the increase in loadshedding from 2014 until 2021. Stage 1 to 6 indicates the amount of MW that needs to be saved from the network through loadshedding. The stages are Stage 1 = 1,000MW, Stage 2 = 2,000MW, Stage 3 = 3,000MW, Stage 4 = 4,000MW, Stage 5 = 5,000MW and Stage 6 = 6,000MW [3].



Year	Duration of outages (hours)	Energy shed (GWh)
2007	-	176
2008	-	476
....	....	....
2014	121	203
2015	852	1325
2016	-	-
2017	-	-
2018	127	192
2019	530	1352
2020	859	1798
2021 (YTD)	1136	2455

Figure 1: Loadshedding statistics in South Africa [3]

This means an interruption in charging EVs during the loadshedding periods, which has then made prospective EV owners question the decision on whether to migrate from ICE vehicles to EVs. While EV owners would be concerned about electricity availability, the electricity utility would be concerned about additional demand that would be introduced by EVs being charged in the household sector, thus necessitating this study.

Rapidly increasing electricity tariffs: Figure 2 shows the overall average increase in electricity tariffs in South Africa from 1988 to 2022 plotted against the Consumer Price Index (CPI) [2].

During the first period from 1988 until 2008 (when South Africa experienced the first electricity crisis), the Government policy ensured that electricity tariffs were kept low for low-income households and since there had been an oversupply in electricity in the 1990's [13]. From 2007 until 2022, electricity tariffs increased by 653% whilst inflation increased by 129% [2]. In other words, electricity tariffs quadrupled over a 14-year period. The electricity utility, Eskom, then applied to the National Energy Regulator of South Africa (NERSA) to restructure the tariffs to protect lower-usage residential customers from high price increases and to also temper heavy electricity users [14]. The new structure for residential customers, known as the Homeflex tariff (price of electricity changes according to the time of day) as opposed to the Homepower tariff (block charges based on usage) [5], was deemed suitable for medium- to high-usage residential urban customers, who were able to shift load from the expensive peak periods to the less expensive off-peak periods.

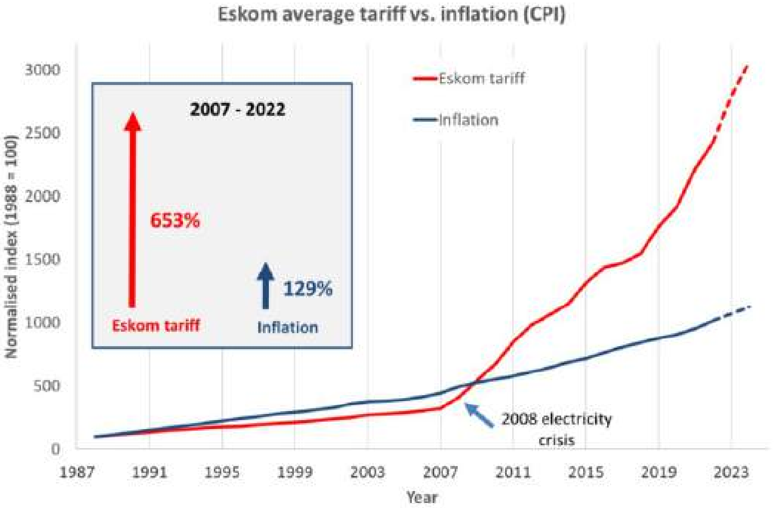


Figure 2: Eskom tariff versus Inflation from1988 until 2022 [2]

In view of the changing tariff structure, the question that remained to be answered was what the impact of charging EVs would be on the load profile during peak times and what the cost implications for the consumer would be.

Due to the high household costs with the increase in electricity tariffs, we needed to understand if South Africans in the different income groups would be able to afford to charge their EVs. With South Africa's Gini coefficient of 0.67, affordability is a very important consideration in purchasing EVs [15].

The National Income Dynamics Study (NIDS) in South Africa defines socio-economic classes based on a household's potential to have opportunities to grow or if they are at risk or vulnerable to dropping to lower income levels [16]. The five social classes and the fraction of the population per class is shown in Table 1 [16].

Table 1: Household Definitions by Class [16]

Class	Description	Number of Households
Quintile 1	Chronically poor	7,524 million
Quintile 2	Transient poor	1,655 million
Quintile 3	Vulnerable middle class	2,257 million
Quintile 4	Stable middle income	3,010 million
Quintile 5	Elite	0,602 million

In this study, it is assumed the Quintile 4 (stable middle class) and Quintile 5 (elite) are likely to be able to afford EVs based on their disposable incomes.

The general rule of thumb is that 25% of the monthly salary is allocated to transport/ vehicle costs [17]. The annual salaries for the various social classes were obtained [18] and based on 25% allocated to vehicle purchases, the size of vehicle was ascertained. This means that Quintile 5 would be able to afford small, medium and large cars (Minimum Monthly Income (>110,820 Rands)); and Quintile 4 would be able to afford small and medium vehicles (Minimum Monthly Income (>110,820). The Nissan Leaf was selected for a small car (40 kWh battery capacity, average range 200 km), and the Renault Megane E-Tech EV60 220hp as a medium car (60 kWh battery capacity, range 320 km) [19].

Simulator runs were conducted to determine the difference in costs between households in the different income quintiles using the Homepower 1 block structure [5] when compared to the time-of-use (TOU) Homeflex tariff structure [5].

Table 2: Homepower (block) tariff values [5]

	Block 1	Block 2
	(0-600 kWh)	(>600 kWh)
Homepower 1	253,54	400,33

Table 3: Homeflex (Time-of-use) Tariffs in cents per kWh [5]

	High Demand	Low demand
Peak	624.21c	204.4c
Standard	189.91c	141.04c
Off-peak	103.7c	89.92c

3 METHODOLOGY

The software used to develop the quantitative model was iSee Stella Architect Version 3.7 [20], in which stocks, flows, and converters are visually and mathematically represented (i.e., stock-and-flow diagram (SFD)). Equation 1 was used in the model structure, which determines that the Stock at time t is found from the Stock at a previous point in time, $(t\text{-}dt)$, by adding the net quantity accumulated as the result of the inflow and outflow during the period dt.

$$Stock\ (t) = Stock(t - dt) + (Inflow\ Rate - Outflow\ rate) \times dt \tag{1}$$

Equation 1 is solved through numerical integration techniques that require specifying time horizon and time steps. The selected integration method was Euler solved hourly over 744 time units (equivalent to a month). Model structures were developed that allowed the sensitivity analysis and scenario analysis. Figure 3 shows EV charging. The completed model is much larger but for this paper, the EV charging model will only be explained.

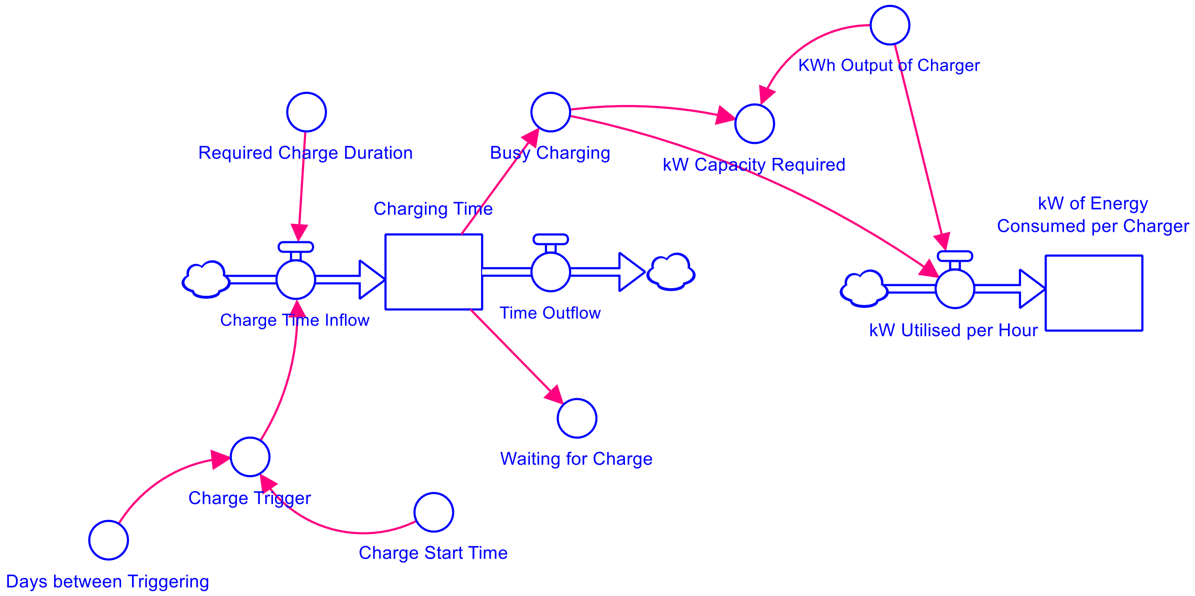


Figure 3: EV charging model structure

In order to replicate the anticipated demand pattern of a consumer owning an electric vehicle the control theory basis of system dynamics was used. The basic charging switch design demonstrates how a particular user charges his or her vehicle. While no feedback loops are shown in the charging switch model, the obvious feedback loop would include the battery charge status. As the vehicle gets used, the energy stored in the battery is utilised. As the battery drains down, the owner can decide when a charge is required. The current design of the charge switch assumes that the owner does not want to keep the charge in the battery as high as possible at all times, but rather only charges the battery once a lower limit has been reached. The battery will then charge for a longer duration at less frequent intervals.

In summary, the charging switch will simulate the behaviour of an owner of an electric vehicle that charges the vehicle for a fixed amount of time, starting at a specific time every time on regular intervals that can exceed one day. In the demonstration case the following is assumed:

Charge Start Time: 7:00 PM or 19:00

Required Charge Duration: 6 hours

Days Between Charges: 3 days

Starting Day: 0 - reflecting the start of the simulation run

The charging switch structure is a single stock model that keeps track of the number of hours that the battery needs to be charged for. This function could be replicated by a state variable, but that will introduce the inflexibility of a fixed repeating pattern. By using a stock - Charging Time - to keep track of the time needed for charging, both the amount of time required, and the frequency of charging can be varied by changing the values in 2 converters. It also makes the structure sufficiently flexible to add the feedback loop from real battery usage. When the Charge Trigger has a value of 1 then total value of Required Charge Duration flows into the Charge Time stock. As long as the Charging Time is greater than 0, the battery of the electric vehicle will be charged as indicated by the Busy Charging converter. Multiplying the capacity of the charger as the converter kWh Output of Charger by the Busy Charging signal the total energy consumed by the vehicle battery can be calculated. The total amount of energy consumed is calculated in the stock kW of Energy Consumed.

The Charge Trigger converter calculation requires the user to select the time of day at which the vehicle will be plugged in and the charging must start. Charge Start Time uses a 24-hour clock to simplify calculation and is set at 19 to reflect 19:00 or 07:00 PM. The second element is the Days Between Triggering converter which has been set to work in days and not hours. The calculation of the Charge Trigger adjusts any day values to a 24-hour cycle. The final converter needed for the calculation is the Starting Day converter that reflects the day on which the first charge is required.

The calculation in the Charge Trigger uses the PULSE built-in functionality of the STELLA Architect software. The following Equation 2 is used:

$$Charge\ Trigger = PULSE(1, Charge\ Start\ Time + Starting\ Day * 24, (Charge\ Start\ Time + 24 * Days\ between\ Triggering)) \tag{2}$$

The PULSE function allows the inflow to the stock to be triggered at regular intervals on the 24-hour clock. The same functionality can be achieved using the STEP built-in function in STELLA. The STEP function will reduce the model to a converter only model which does not show how the time runs down. Using the STEP function the following Equation 3 is required:

$$Charge\ Trigger = STEP(1, Charge\ Start\ Time + Starting\ Day * 24, Required\ Charge\ Duration, Days\ between\ triggering * 24) \tag{3}$$

While functionally the same, the use of a stock adds a visual element that the converter on its own does not achieve and the Charge Switch can be replicated in other software systems that does not contain the same built-in functionality. Of course, a series of converters using the COUNTER built-in function can also be used to achieve the same result.

The assumptions used: daily charging, with a small EV battery size for Quintile 4 and a medium EV battery capacity for Quintile 5. The other assumption was that the car battery still had residual charge of 35% in the small EV battery and 40% in the large EV battery when plugged in at home. A Level 1 AC charger (3.7 kW) [21] was used for Quintile 4 which meant a charging time for the small EV battery of 7 hours. A Level 2 AC charger was used for a medium EV battery capacity [21] for Quintile 5 which meant a charging time of 2 hours.

The annual base consumption for a single household in Quintile 4 is set at 7,144.11 kWh and for Quintile 5 is set at 11,113.3 kWh based on actual measured data from Eskom's records [22].

4 RESULTS & DISCUSSION

A series of scenarios were run to analyse the impact of alternative load management strategies on electricity consumption to identify optimal strategies. The baseline was obtained from actual measured load data from Eskom [22].

Figure 4 shows the change in load profile depending on the type of home charger for a single household.

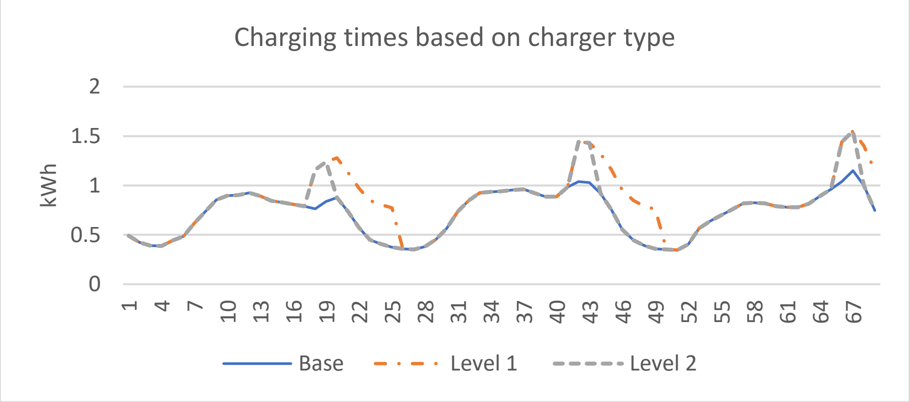


Figure 4: Profile change due to type of EV charger

Figure 5 shows the single household consumption for Quintile 4, with and without EVs and Figure 6 shows Quintile 5. The calculations assumed daily charging at 6pm. The highest consumption months are June and July and the lowest was in January and February.

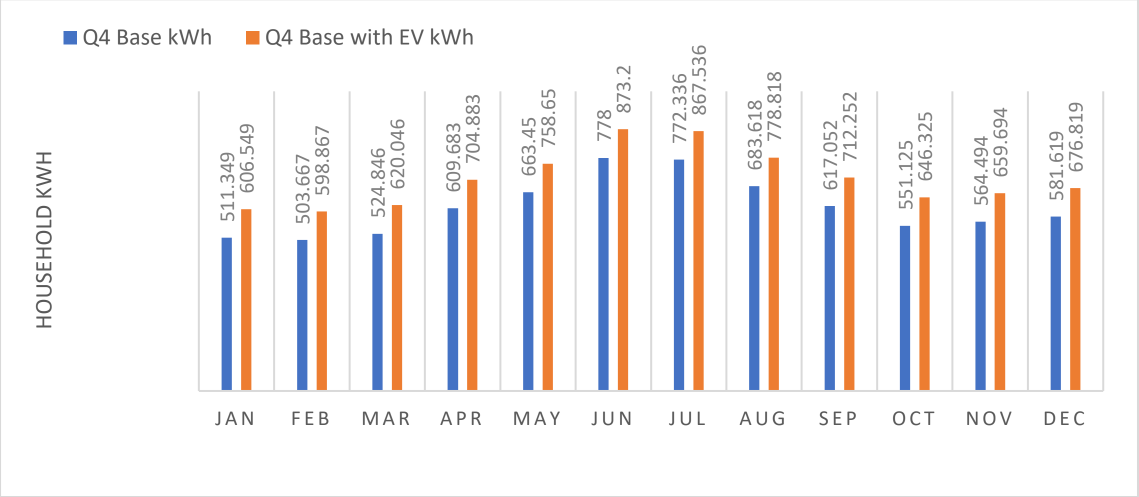


Figure 5: Quintile 4 household consumption with and without EVs

Results for Quintile 4 show an increase of 576 kWh per year. Based on the base annual consumption of 7,361 kWh per year for Quintile 4, this is an increase of 7.82% in the electricity consumption for the year. For purposes of generating scenarios for this paper, the researchers assumed a daily charging frequency, the simulator allows a selection of frequencies of daily, every second day or every third day.

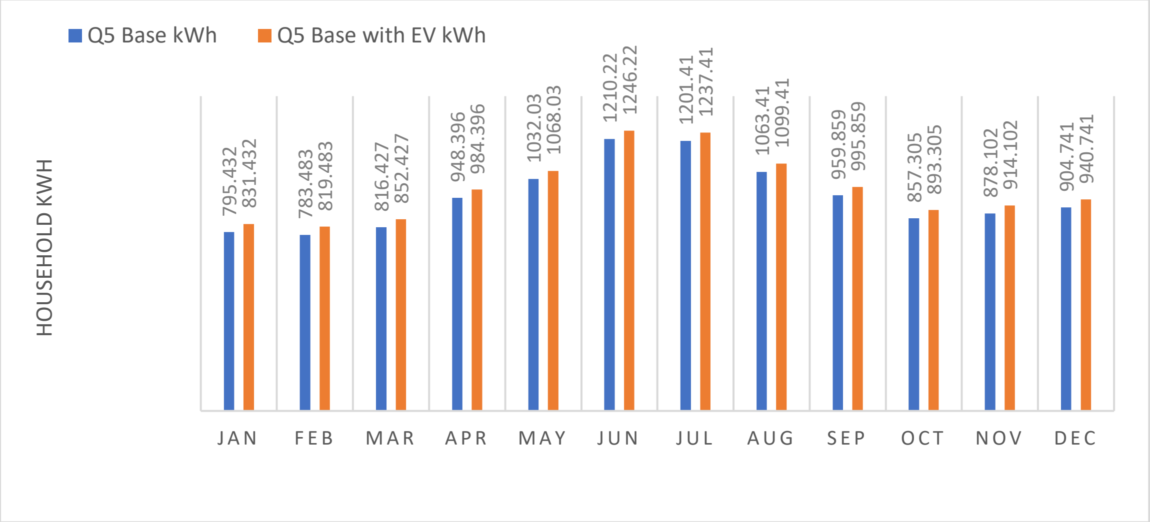
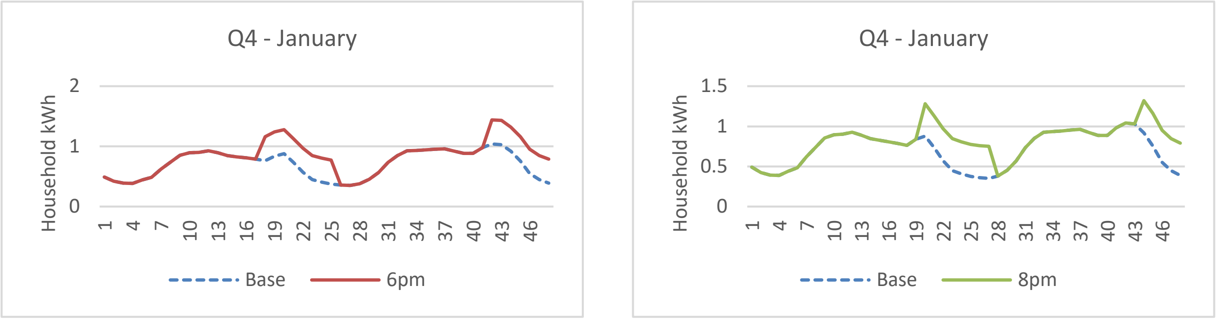


Figure 6: Quintile 5 household consumption with and without EVs

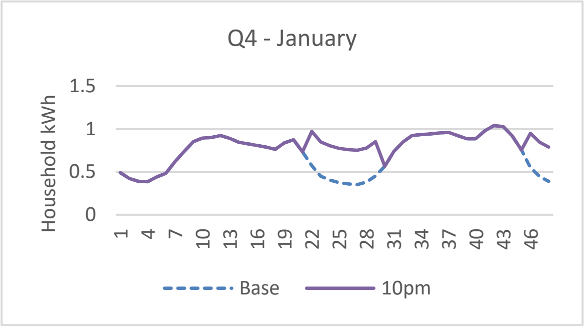
Results for Quintile 5 show an increase of 864 kWh per year. Based on the base annual consumption of 11,451 kWh per year for Quintile 5, this is an increase of 7.55% in the electricity consumption for the year.

Figure 7 shows the impact of varying the daily charging start times on a Quintile 4 load profile, assuming a small EV battery capacity.



(a) 6pm

(b) 8pm

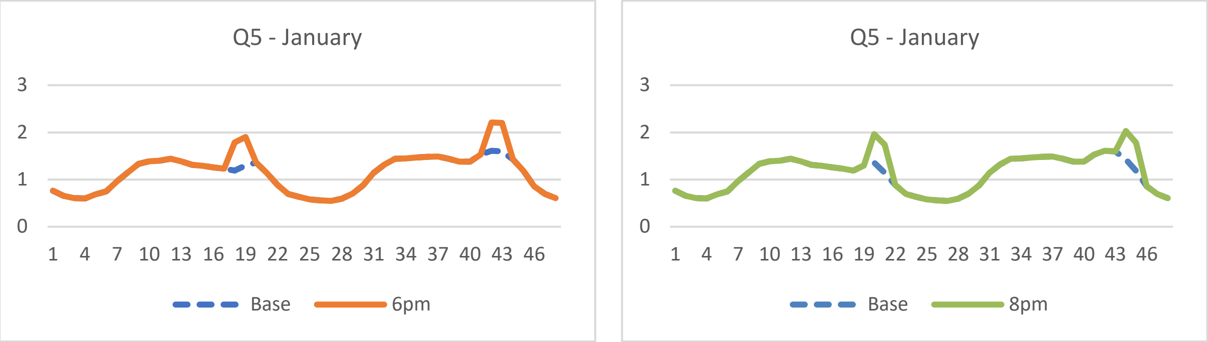


(c) 10pm

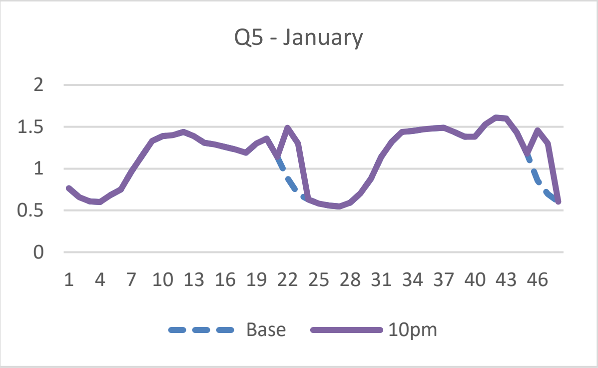
Figure 7: Q4 load profile with varying EV starting charge times

Visually it is clear that charging at 10pm and at midnight would reduce the peak, however, would a financial driver be sufficient to change the behaviour when it comes to charging times by EV owners. This dynamic was the explored later on.

Figure 8 shows the impact of varying charge start times for Quintile 5 - assuming a level 2 charger (shorter charging times).



(a) 6pm (b) 8pm



(c) 10pm

Figure 8: Quintile 5 load profile with varying EV starting charge times

Based on the above profiles, visual inspection shows that 6pm and 8pm charging are still in the peak demand times.

In terms of the additional electricity costs due to charging EVs at home, Figure 9 shows the cumulative monthly values at the different charging times for Quintile 4 and Figure 10 shows the results for Quintile 5.

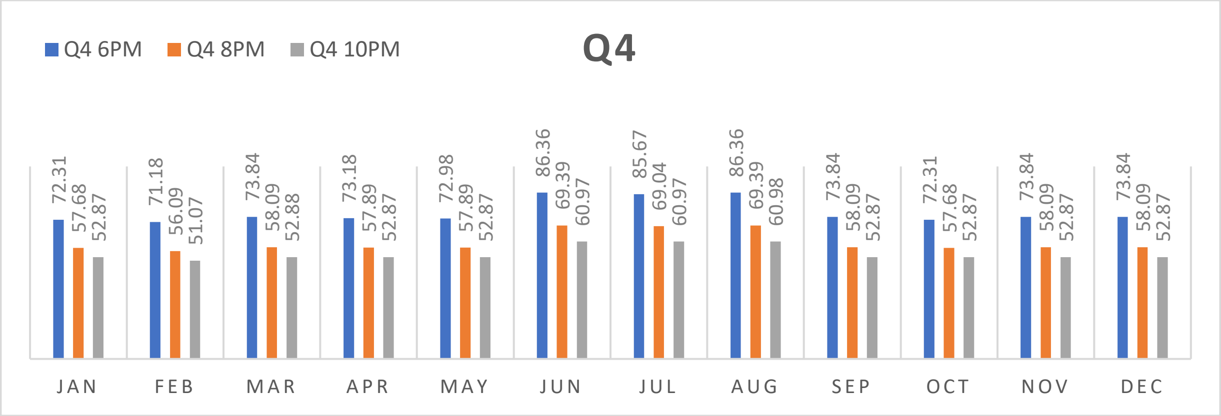


Figure 9: Quintile **4 EV household costs based on Homeflex tariffs over a month**

When looking at the difference between 6pm and 8pm charging or 6 pm and 10 pm charging, there is a saving. However, the additional costs when charging at 8 pm versus charging at 10 pm is very small. Using January as an example, moving from charging at 6 pm to 8 pm means a saving of R14.99 while moving from 8pm to 10pm means a saving of 72 cents. It would be expected that charging at 10 pm would provide no real financial incentive for EV owners and they would likely go for a cheaper tariff period at a convenient time which is then 8pm charging. The additional annual electricity costs due to EV charging is approximately R430.80 in a Quintile 4 household.

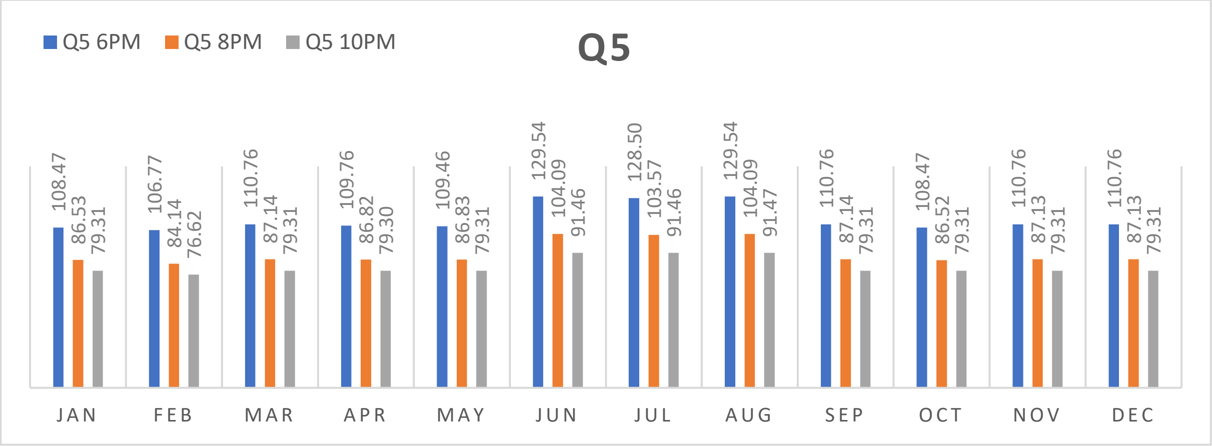


Figure 10: Quintile **5 EV household costs based on Homeflex tariffs over a month**

Based on the results for Quintile 5, the cheapest charging time is at 10pm. If charging takes place at 8pm instead of 6pm, there could be a savings of about R15.00 per month or R3.70 per week. Charging at 10pm instead of 8pm means an additional savings of R6.14.

Figure 11 shows the difference in additional household costs due to EV charging between using the Homepower (Block) tariff and the Homeflex (TOU) tariff for Quintile 4 over a period of a week and Figure 12 for Quintile 5.

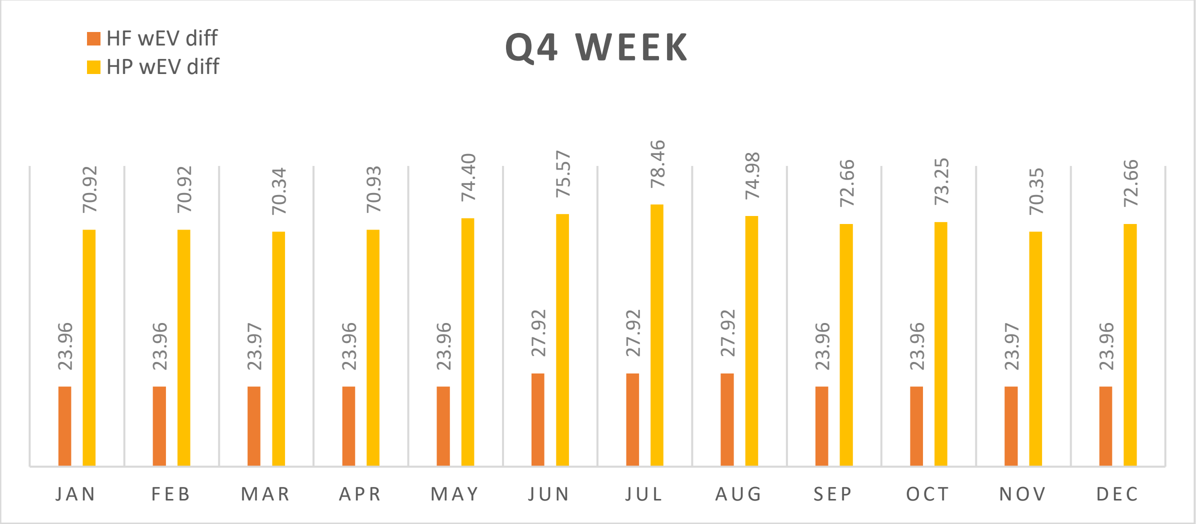


Figure 11: Weekly EV costs for Quintile 4 for different tariff structures

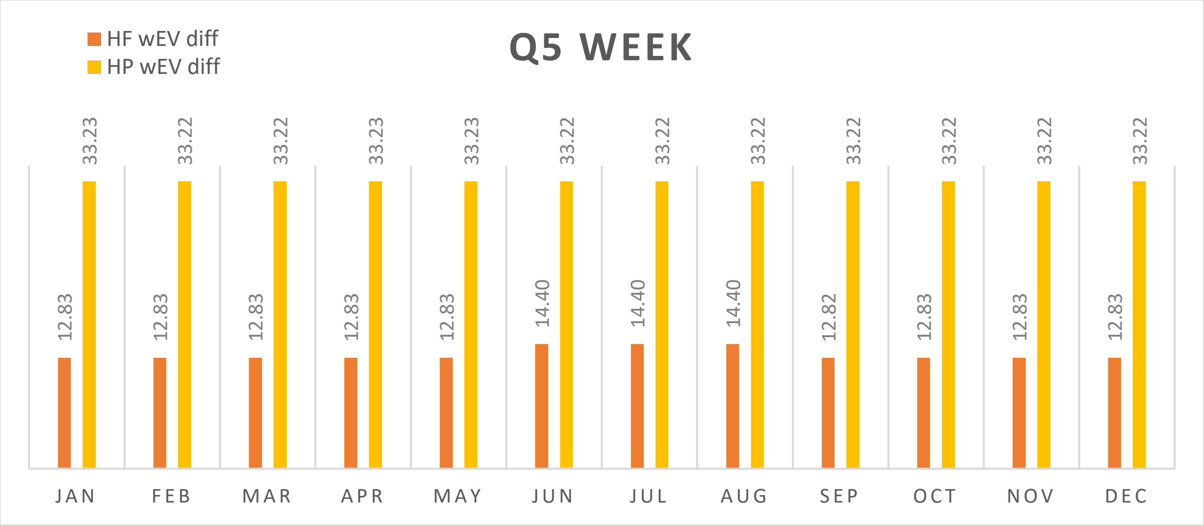


Figure 12: Weekly EV costs for Quintile 5 for different tariff structures

Results indicate that EV owners are likely to pay almost four times more on the Homepower block tariff than when using the Homeflex TOU tariff structure. The reason why the Quintile 4 has more EV costs than Quintile 5 is because of the Level 1 charger in Quintile 4 which means longer charging times.

5 CONCLUSIONS

A single household, Quintile 4 could experience an increase of approximately 576 kWh over a year (40 kWh EV battery) and for Quintile 5 (60 kWh EV battery) is approximately 864 kWh over a year. Further work for the national EV charging impact will differentiate between weekday and weekend charging and split the EV owners into different groups who will charge non-synchronously.

For Quintile 4, charging at 6pm (peak demand time) is the most expensive. The best TOU charging time would be at 8pm; additional costs when charging at 8 pm versus charging at 10 pm is very small. Based on the results for Quintile 5, the cheapest charging time is at 10pm.

There is a clear incentive to move charging away from peak tariff periods to off-peak, however, it is likely that there will be households where tariffs as a load shifting tool, may not be effective. These are the households where disposable income does not present restrictions because their investments and income are significant.

In terms of system dynamic modelling, by using an array of charging switches with random initial starting days and a variety of days between triggering, a close representation of a real population of electric vehicles could be obtained. When the driving feedback loop was added, the use patterns of different users and vehicles provided the same representative behaviour of the system as a whole. Following this approach allowed for a closer approximation of reality, which is critical to electricity suppliers who are both interested in the energy used to charge batteries, as well as the peak demand required.

6 RECOMMENDATIONS

It is recommended that the research be expanded to include an EV tariff to determine if that would provide a better incentive for EV owners to move off peak demand times.

It is also recommended that solar PV be simulated so that during loadshedding events, to determine the capacity required to power basic appliances and adequate power to charge the EVs.

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CRAFTING OF A DECARBONISATION STRATEGY FOR THE SOUTH AFRICAN FOUNDRY INDUSTRY: A ROADMAP TOWARDS SUSTAINABLE METAL CASTING

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ABSTRACT

The South African government is committed to achieve a net zero CO2 emission by the year 2050. To that end, all major manufacturing sectors are required to reduce their carbon emissions. This study proposes a framework based on CO2 emission scopes to identify all processes involved in cast iron production using the sand-casting foundry process. Through a systematic review of international publications, it pinpoints CO2 sources in the upstream, internal, and downstream processes. Recommendations for reducing CO2 include finding alternatives to pig iron, improving its smelting process, and enhancing energy management in foundries. These energy conservation measures will greatly benefit the South African cast iron foundry sector to contribute to reducing the impact of climate change effects in South Africa.

Keywords: Foundry decarbonisation, South African cast iron foundry, CO_2 Scope emissions, environmentally responsible processes, sand casting

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1 INTRODUCTION

This study focuses on the South African foundry industry, which, as per international industry regulations, is classified into four main categories: ferrous casting (steel and iron), non-ferrous casting (brass, aluminium, zinc), investment casting and high-pressure die casting. The foundry output primarily serves three sectors: automotive (25%), manufacturing (24%) and mining (32%). In addition, it supports agriculture (3%), infrastructure (2%), railways (9%) and other sectors (5%). The local foundry industry employs over 14 000 individuals, highlighting its strategic importance to South Africa. It is a significant player in the country's economic landscape, contributing substantially to the gross domestic product (GDP). In 2013, it was reported that the foundries contribute R9.048 billion annually to the national GDP [1].

In 2020, the estimated number of foundries in the country was 123 [2] [3]. Consequently, South Africa ranks among the top contributors to atmospheric pollution, having the highest CO_2 emissions as reported by the International Energy Agency in 2009. It is no wonder that the country is treating climate change with great seriousness. Due to its abundance in South Africa, coal is used more extensively than other energy sources. The country's heavy reliance on hydrocarbons as a traditional and cost-effective energy supply option has significant repercussions in terms of its impact on global climate dynamics. CO_2, primarily emitted from coal, plays a pivotal role in driving the climate crisis. The escalating emission of CO_2 has become a pressing concern for energy-intensive industries, as potential carbon taxes and regulatory measures loom, necessitating drastic emission reductions [4].

The mining and heavy manufacturing sectors are the country's primary consumers of electricity, accounting for over two-thirds of national electricity usage. Consequently, these sectors constitute South Africa's major CO_2 emitters. The foundry industry falls within the category of sectors heavily reliant on electricity to produce essential components, a trend also observed in regions like Australia, as detailed in Table 1. Each stage in the foundry process demands energy, from metal melting and moulding to conveyor belt operation, sand reclamation and casting heat treatment, all of which contribute to in-house CO_2 production. This scenario presents an opportunity for foundries to devise effective energy management strategies to reduce CO_2 emissions [5].

Table 1 Industries with heavy energy consumption [6]

Industry sector	Electricity (non-heat related)	Process heat from fuels and electricity [%]	Shares of required heat levels (Naegler et. al 2015)			
			<100 °C	100 - 500 °C	500 - 1000 °C	> 1000 °C
Iron and steel	14%	86%	5%	2%	19%	75%
Chemicals and petrochemicals	25%	75%	18%	22%	48%	12%
Non-Ferrous metals	52%	48%	10%	4%	20%	66%
Aluminium	60%	40%	8%	2%	18%	72%
Non-metallic minerals	17%	83%	5%	2%	30%	63%
Cement	19%	81%	5%	2%	30%	63%
Transport equipment	47%	53%	72%	10%	5%	13%
Machinery	34%	66%	57%	15%	9%	20%
Mining and quarrying	41%	59%	13%	2%	28%	57%
Food and tobacco	30%	70%	54%	46%	0%	0%

Paper, pulp, and print	32%	68%	20%	80%	0%	0%
Wood and wood products	29%	71%	37%	63%	0%	0%
Construction	35%	65%	48%	18%	11%	23%
Textiles and leather	42%	58%	100	0%	0%	0%
Unspecified (industry)	40%	60%	43%	19%	12%	25%

The Paris Agreement emerged in response to the pressing issue of global warming. Member states collectively agreed that global warming should be kept below 2°C above preindustrial levels, with an aim to limit the increase to 1.5°C. This target is estimated to significantly mitigate the impacts of climate change, which include catastrophic effects on the environment such as floods, droughts, high temperatures, disrupted agriculture, and threats to human health and ecosystems. Each government is responsible for implementing national climate targets and projects aimed at reducing greenhouse gas emissions, particularly CO_2, to meet the global goal of preventing disastrous climate change. In 2021, atmospheric CO_2 concentrations were estimated at 416 parts per million [7]. The Paris Agreement aims to reduce emissions as close to zero as possible while also removing CO_2 from the atmosphere through ecosystem restoration [6] [5]

To align with the Paris Agreement and reduce emissions to zero, the use of coal, oil, and gas must be reduced by at least 56% by 2030. However, the current climate debate has not openly addressed withdrawal from these fossil fuels, focusing instead on their supply and price security. At COP28 in Dubai, South Africa reaffirmed its commitment to climate action by pledging to triple its use of renewable energy and implementing measures to combat global warming. In response, the South African Parliament introduced a carbon tax bill, imposing a tax of R120 per ton of CO2 equivalent on greenhouse gas emissions from fuel combustion, industrial processes, and other sources. This tax, based on a methodology approved by the Department of Environmental Affairs, will significantly impact the local foundry industry due to its high carbon emissions [8] [9].

Numerous studies concerning the South African foundry industry have concentrated on its environmental compliance. Most notably, on the sustainability of foundry sand which is the largest wasted material in foundries. One such study delved into the air quality within foundries, particularly examining the dust generation rate and the properties of the sand that forecast reduced fine-particle production. Other studies have explored efficient methods to enhance sand reusability, as sand remains the primary waste material from foundries, and can potentially pollute soil and aquatic habitats. These investigations have scrutinised factors like resistance to crushing, alternative green refractory material to silica sand, and comparing various sand reclamation processes to maximise sand recycling. Addressing pollution from chemical binders in sand, including organic binders, has also been a focal point. The toxicity of sand waste is a critical concern, touching on issues such as pulmonary diseases and the presence of hazardous substances like Chrome 6+ [10] [11] [12].

Regarding energy management in South African steel foundries, significant research has been undertaken by Rasmeni and Pan. Their studies focused on mitigating CO_2 emissions from foundries through the implementation of optimal energy efficiency practices. Additionally, the authors proposed utilising the Quick-E-Scan methodology as another contribution to this field. Quick-E-Scan offers a relatively straightforward and cost-effective alternative to the conventional energy audits typically performed in foundries [4].

The novelty of this work lies in its CO2 scope emission methodology, which identifies specific sources of CO2 emissions and highlights critical processes in cast iron production that need intervention. This approach, not yet applied in the South African sand-casting sector, offers significant benefits by targeting key areas for emission reduction.

This work aims to identify and classify CO2 emission sources in a typical cast iron foundry according to CO2 scopes. It examines upstream, internal, and downstream processes involved in casting iron components. This study is crucial given South Africa's commitment to net-zero emissions by 2050 and the impending implementation of carbon taxes.

1.1 Scopes 1,2 and 3 methodologies

There are three scopes of carbon emissions, namely Scopes 1, 2 and 3. Figure 1 illustrates the CO_2 emissions of Scopes 1, 2 and 3.

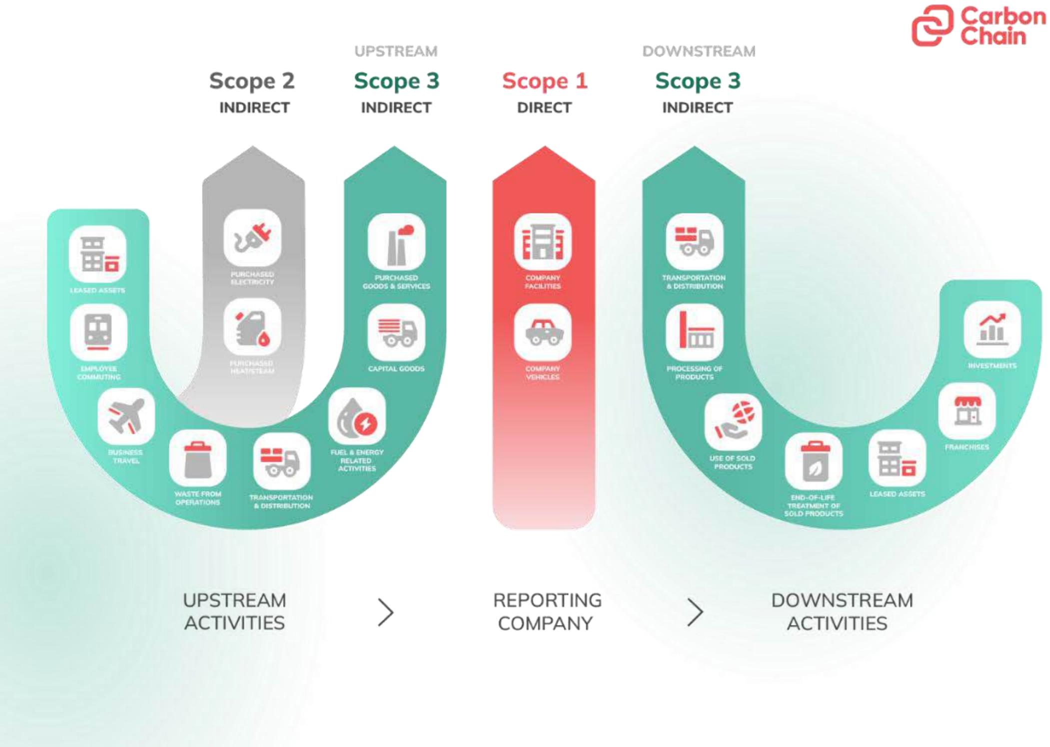


Figure 1 Description of Scopes 1,2 and 3 [13]

1.1.1 Scope 1

Scope 1 represents the direct emission of CO_2 from the company's operations. In a foundry, Scope 1 emissions are the result of fuels combusted in furnaces/boilers, fugitive or vented emissions from process equipment, or process emissions from chemical reactions. Software, such as SimaPro, Gabi and OpenLCA, can be used to determine the CO_2 footprint produced from the process of metal casting itself in the foundry [6] [14]

1.1.2 Scope 2

Scope 2 emissions result from the generation of purchased or acquired electricity, steam, as well as heating or cooling consumed by the company. Scope 2 emissions occur at the facility where electricity is generated, in this case at Eskom itself. To calculate CO_2 emissions based on electricity consumption from Eskom, Eskom itself provides emission factors that can be used to estimate CO_2 emissions. These factors are usually expressed in terms of kilograms of CO_2 emitted per kilowatt-hour ($kgCO_2/kWh$) of electricity generated. These factors can be obtained from Eskom's official website or by contacting them directly. In addition, there are software packages designed specifically for calculating emissions in industrial settings. Examples include SimaPro, GaBi and OpenLCA [6] [5].

1.1.3 Scope 3

Scope 3 emissions are indirect emissions not covered by Scope 2, arising from activities in the company's value chain such as purchased goods, services, waste, and employee commuting. Unlike Scopes 1 and 2, which have established calculation methods, Scope 3 emissions are more challenging to measure due to issues with data availability, reporting, and double counting. In a cast iron foundry, Scope 3 emissions include upstream processes like the processing and transport of raw materials (e.g., pig iron, ferrosilicon, silica sand) and downstream processes like transporting cast iron components to clients [6] [15] [16]

1.2 CO2 scopes in the context of a south African Foundries

Figure 2 illustrates the entire flow of the process required to produce foundry cast iron. Each process can be regrouped into three main sections namely upstream, internal and downstream processes. According to the figure the energy consumption required to produce pig iron is estimated between 20 and 40 GJ/t.

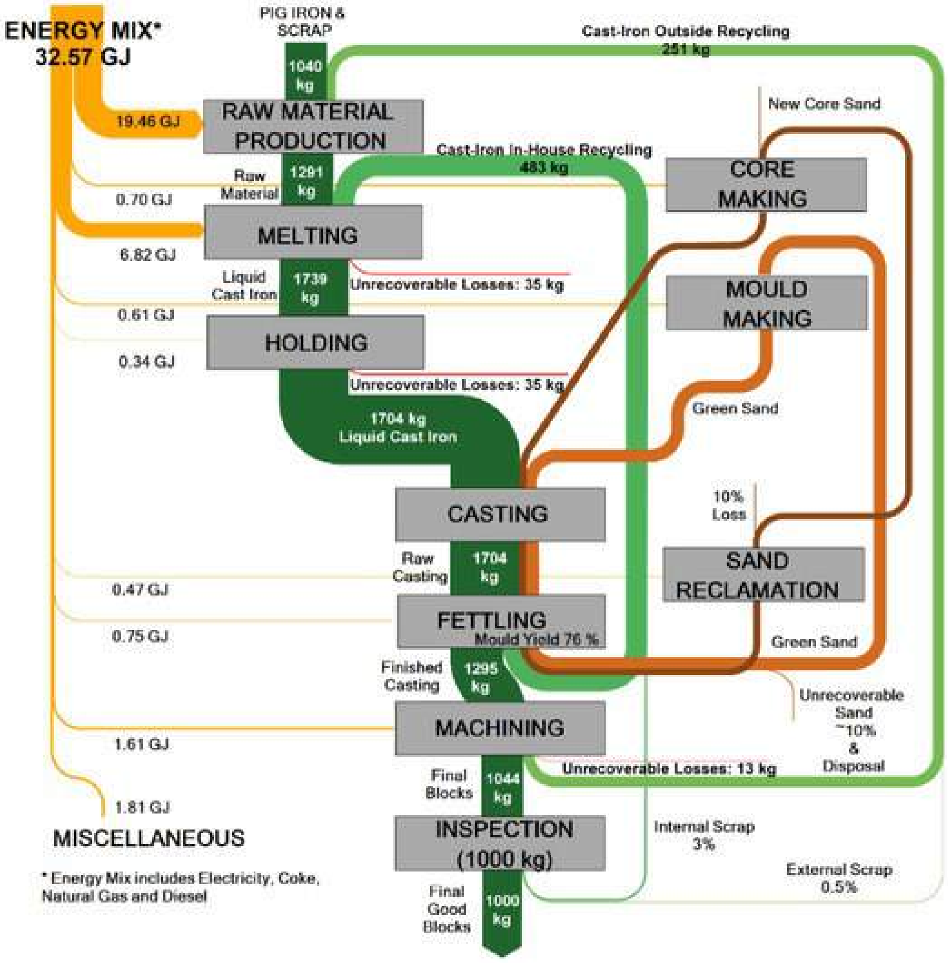


Figure 2 Mapping of electricity usage for the production of cast iron [17]

1.2.1 Upstream processes: Production of raw material

The upstream processes include the transformation of iron ore into pig iron, mineral processing of raw silica by gravity concentration to produce high grade silica, feldspar and iron rich silica. The amount of CO2 produced in the upstream processes is listed under scope 3.

1.2.1.1 Transformation of raw silica to high grade silica, feldspar and iron silicon

Figure 3 lays out the process to produce silica sand. The work identifies CO_2 scope emissions for each stage of the transformation of raw silica into useful output. The most energy-intensive processes in transforming raw silica into high-grade silica are mineral separation, feldspar separation, dewatering, and transporting the mineral on a conveyor belt. Silica sand, also known as quartz sand, is a mineral resource with a wide range of applications, most notably in the glass industry, construction, and foundries. In metal casting, particularly for cast iron, silica sand plays a crucial role as molten alloy is poured into a silica sand mould. [18]

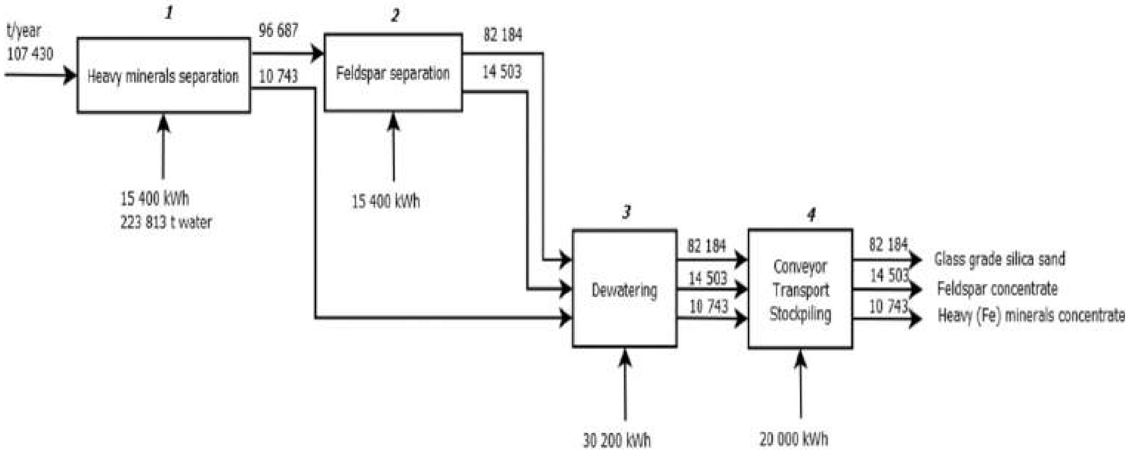


Figure 3 Process flows gravitational concentration of silica sand [18]

1.2.1.2 Transformation of iron ore to pig iron

Figure 4 illustrates the pig iron production process. This study identifies the production of CO_2 for each stage of the transformation of iron ore to pig iron and provides a description of the CO_2 emissions of all the scopes. The smelting stage is the most energy-intensive part of the process, requiring 13 GJ of energy [17].

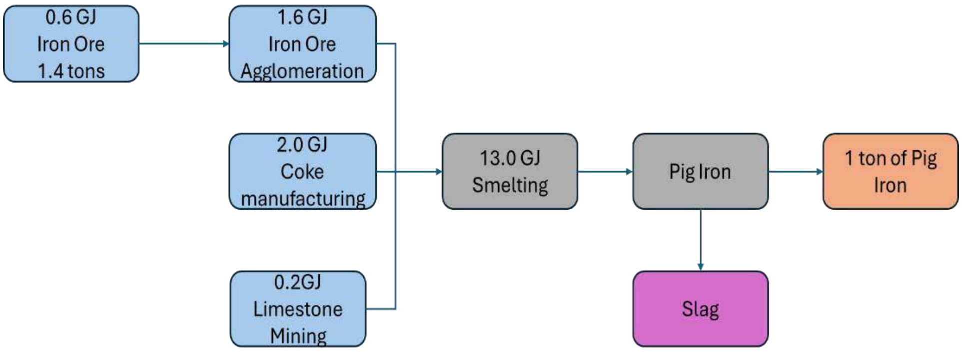


Figure 4 process flow to transform iron ore into pig iron [17]

1.2.2 Internal process: Production of cast Iron by sand casting

Figure 5 illustrates the process required to produce a pig iron casting. This study identifies the production of CO_2 for each stage of the pig iron casting and provides a description of the CO_2 emissions of all the scopes

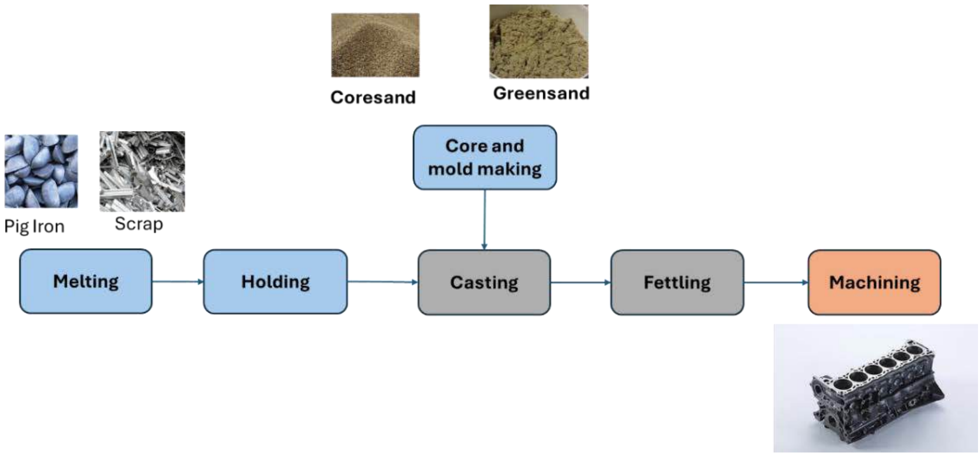


Figure 5 Transformation of iron ore into pig iron [17]

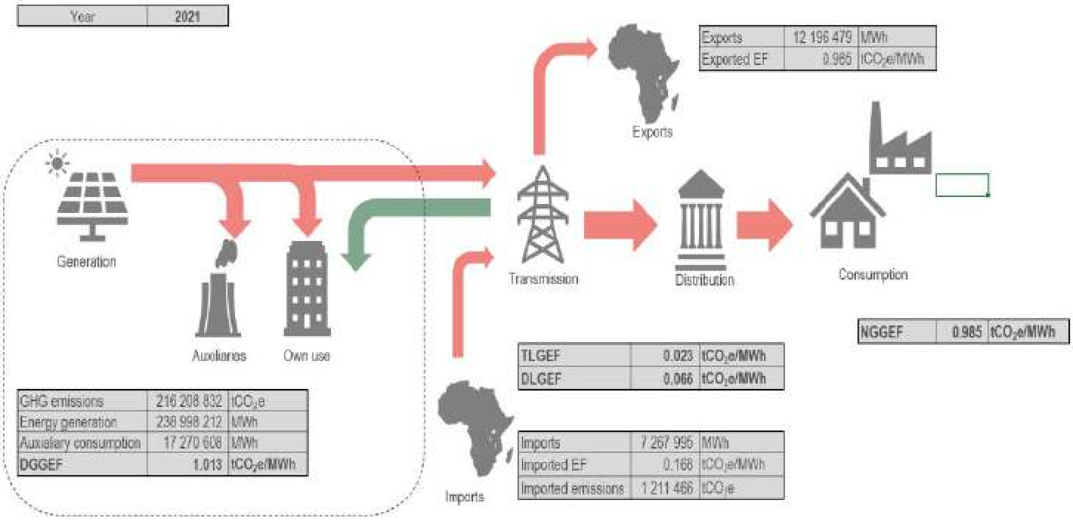
Internal processes in cast iron production, including melting pig iron and alloying elements, vaporising organic binders, recycling and mixing sand, and other activities, generate Scope 1 CO_2 emissions. These processes involve mold and core fabrication with silica sand, melting of materials like pig iron and steel scrap, pouring molten alloy, fettling, machining, heat treatment, and recycling. Electricity needed for these processes, provided by Eskom, results in Scope 2 emissions from coal combustion at power stations [19] [5] [17].

1.2.3 Downstream Processes

The downstream process of the production of cast iron includes the transportation of cast component to the customers. The CO_2 generated because of the transportation of casting is a scope 3 emission.

1.3 CO2 conversion factor from south Africa's 2021 grid emission factors report

The South African Department of Forestry, Fisheries and the Environment's 2021 grid emissions factors report provides carbon factors for converting energy consumption into CO2 emissions from coal burned by Eskom (see Figure 6). This conversion factor is used in the discussion section. Grid emissions factors (GEF) reflect Green House Gas (GHG) emissions associated with electricity and include four types: domestic generation (DGGEF), national generation (NGGEF), transmission losses (TLGEF), and distribution losses (DLGEF) [20].



Year	2021

Exports	12 196 479	MWh
Exported EF	0.985	tCO_2e/MWh

NGGEF	0.985	tCO_2e/MWh

TLGEF	0.023	tCO_2e/MWh
DLGEF	0.066	tCO_2e/MWh

GHG emissions	216 208 832	tCO_2e
Energy generation	238 998 212	MWh
Auxialary consumption	17 270 608	MWh
DGGEF	1.013	tCO_2e/MWh

Imports	7 267 995	MWh
Imported EF	0.168	tCO_2e/MWh
Imported emissions	1 211 466	tCO_2e

Figure 6 four types of Grid Emission Factors [20]

The domestic generation grid emission factor (DGGEF) measures Green House Gas (GHG) emissions per unit of electricity generated in South Africa, excluding auxiliary consumption and wheeling. The national generation grid emission factor (NGGEF) relates emissions to end-user consumption, excluding transmission and distribution losses. The transmission losses grid emission factor (TLGEF) accounts for emissions considering transmission losses. The distribution losses grid emission factor (DLGEF) accounts for emissions considering technical distribution losses [20]. Table 2 provide the value of CO_2 conversion factor based on the type of Grid emission factor.

Table 2 CO_2 conversion factor according to South Africa's 2021 grid emission factors report [20]

GED (year 2021)	**Value (tCO2e/MWh)**
Domestic generation grid emission factor (DGGEF)	1.013
National generation grid emission factor (NGGEF)	0.985
Transmission losses grid emission factor (TLGEF)	0.023
Transmission losses grid emission factor (TLGEF)	0.066

The national generation grid emission factor (NGGEF) was deemed the best choice for this research since it considers the end user's consumption, in this case, the cast iron foundry. It is the most appropriate GEF to determine the conversion of electricity consumed by a given process into CO_2 emissions. For every MWh of electricity used, the conversion factor is 0.985 tCO_2/MWh. Therefore, if a consumer purchased 500 MWh during the year from the grid, the Scope 2 GHG emissions is obtained according to Equation (1):

$$\textit{Scope 2 GHG emissions} = \textit{electricity purchased} \times \textit{NGGEF} \tag{1}$$

Scope 2 GHG emissions = 500 MWh × 0.985 tCO_2 eq./MWh = 492.5 tCO_2 eq. [20]

2 METHODOLOGY

This work is a systematic literature review of articles and books on foundry technology and production of cast iron. The articles were obtained from Scopus, SpringerLink, and Google Scholar. Keywords include "cast iron foundry," "CO2 emission in cast iron foundry," "CO2 emission in mineral processing of silica sand," "energy consumption in the transformation of raw silica to silica sand," "CO2 emission in pig iron production," "energy consumption in pig iron production," "CO2 emission in cast iron production," and "energy consumption in South African foundries." Exclusion criteria are date of publication (between 2010 and 2024) and relevance to the topic.

3 DISCUSSION OF LITERATURE

The discussion includes 4 subsections namely CO2 emission from upstream processes, CO_2 emissions from internal processes, CO_2 emissions from downstream processes, and Recommendations.

3.1 CO_2 emissions from Upstream processes.

According to Salonitis et al, the main upstream processes to the casting of cast iron component includes the mineral processing of the silica sand for the moulds and the transformation of iron ore into pig iron.

3.1.1 Mineral processing of silica sand

The CO_2 generated during the mineral processing of silica sand is considered a scope 3 emission. According to Grbeš the amount of CO2 generated from the gravitational concentration of silica can range between 4.19 x 10 and 5.25 x 10 kgCO2eq or 0.0419 and 0.525 tCO2eq [18].In addition, the process is also energy consuming and requires electricity from the power supplier. Approximately 81000 kWh (sum of energy for each process listed in Figure 3) of electricity is required to operate some of the equipment to produce approximately 107430 ton of output per year. Estimating the energy consumption to 0.75 kwh/t of output. [18]

The total energy spent in a year to produce suitable silica sand is determined by multiplying the total electricity consumption per year 81 000Kwh to the NGGED 0.985 tCO2eq/MWh. The calculation is provided below:

Scope GHG emissions = electricity purchased * NGGEF

= 81 MWh $*$ 0.985 tCO_2 eq./MWh

= 79.785 tCO_2 eq. to produce 107 430 ton in a year (see Figure 3)

Carbon factor for 1 ton = (81 000/107430) * 0.001 * 0.985 = 0.00073875 tCO_2 eq or 0.73875 kCO_2 eq.

3.1.2 Production of Pig Iron from iron ore

The CO_2 generated from the transformation of pig iron to iron ore is a scope 3 emission. According to Salonitis, the production of pig iron is energy intensive and requires roughly 17.4 GJ from specific processes including sintering and pelletising of lump ores, transformation of coal into coke, fluxing of slag from limestone and smelting. [17]The energy in GJ is converted into CO_2 emission as follows:

Total energy required = 17.4 GJ = 4.83 MWh

Scope 2 GHG emissions = electricity purchased * NGGEF

= 4.83 MWh x 0.985 tCO2 eq./MWh

= 4.76 tCO2 eq. (to produce a ton of pig iron)

3.2 CO_2 emission from Internal processes

The internal process of the production of cast iron includes several stages. The focus of the study is on sand moulding, melting of alloying elements, pouring of molten metal, fettling of the casting, machining, and recycling of waste materials.

3.2.1 Sand Moulding

Scope 1 emissions are negligible during the moulding process, the process does not involve the combustion of organic matter or fuel that generates large amounts of CO_2. According to Abdelshafy et al, the process produces mostly scope 2 type of CO_2 emissions. To produce cores, the energy required is estimated to be 0.97 ± 0.3 GJ. Machining is used as well to add finishing touches to the mould. The machining process uses 0.16 ± 22 GJ per ton of green sand. The CO_2 emissions are calculated as follows

Scope 2 GHG emissions = electricity purchased * × NGGEF

Total Energy = 1.65 GJ = 0.46 MWh/t

= 0.46 MWh $*$ × 0.985 tCO_2 eq./MWh

= 0.45 tCO_2 eq. [20] [17]

3.2.2 Melting of alloying elements

According to Abdelshafy al, the typical carbon factor produced by melting each alloying element in a typical iron foundry is laid out in Table 3. The melting of alloying elements produces CO_2 emissions which fall under Scope 1 emissions. The main elements that produce CO_2 are pig iron, ferrosilicon, inoculant, Mg-alloy and carburising agent. The total emission factor is about 28.7 tCO2 eq./t [19].

Table 3 Carbon factor from different input [19]

Input	Emission factor tCO_2 eq./t
Pig iron	1.7
Ferrosilicon	4
Inoculant	14.5
Mg-alloy	5
Carburising agent	3.5

Besides the generation of CO_2 from the melting of alloying elements, the process requires energy from the power supplier. The energy consumption will have an equivalent release of CO2 generated by the power supplier, which will be classified under Scope 2. The results discussed are based on the study of the main inputs into the melting furnace, namely pig iron, ferrosilicon, carbon(graphite), silicon and steel or cast-iron scrap. Unrecoverable metal losses, mainly due to oxidation, are reported by foundries to average 2%. Salonitis et al conducted the study in three major cast iron foundries that produce 60% of all cylinder blocks worldwide and reported the energy per ton of liquid metal to be 3.9 ± 0.1 GJ/t [17]. The CO_2 emissions were calculated as follows:

Scope 2 GHG emissions = electricity purchased × NGGEF

Total energy = 4 GJ/t = 1.11 MWh/t

= 1.11 MWh $*$ 0.985 tCO_2 eq./MWh

= 1.093 tCO_2 eq.

3.2.3 Pouring of molten metal

There is no substantial production of CO_2 during the casting/pouring process of cast iron other than the generation of CO_2 as a result of the combustion of the organic agent binding the sand grains of the mould [21] [19].

Gravity sand casting is generally used to pour molten cast iron in the sand moulding cavity. The process is not energy intensive. [19]

3.2.4 Fettling

There are no direct emissions of CO_2 during the fettling of the casting that constitutes scope 1 CO_2 emissions. The excess material in secondary cavities: risers, runners and gates (also known as fettling), is usually remelted. The mould yield reported from all the energy consumed during the process varies significantly per foundry, and the reported values range from 0.1 to 1.4 GJ per ton of liquid metal [17]. The Scope 2 CO_2 emissions for the melting of cast iron is calculated as follows:

Scope 2 GHG emissions = electricity purchased × NGGEF

Total energy = 1.4 GJ/t = 0.39 MWh/t

= 0.39 MWh × 0.985 tCO_2 eq./MWh

= 0.38 tCO_2 eq.

3.2.5 Machining

Machining does not produce Scope 1 CO_2 gases. The main machining operations in an engine block are cubing, boring, drilling, and threading. Machining performance and, consequently, machining energy consumption may vary according to the machining parameters used. The total energy consumption calculated for machining one cast-iron block is 61 MJ, i.e., 1.6 GJ/ton of cast-iron block generating scope 2 type of CO_2 emissions. The scope emission is calculated as follows: [17]

Scope 2 GHG emissions = electricity purchased * NGGEF

Total energy = 1.6 GJ/t = 0.44 MWh/t

= 0.44 MWh ∗ 0.985 tCO_2 eq./MWh

= 0.43 tCO_2 eq.

3.2.6 Recycling

The recycling of silica sand, pig iron and steel scrap produces Scope 1 CO_2 emissions. In addition, energy is required to transform waste product such as used sand, and the offcuts from the riser and gating system contributing to scope 2 emissions. In addition, Silica sand is reclaimed using mechanical reclamation or thermal reclamation, processes that use electricity to provide a reusable material producing CO_2 gas categorized as scope 2 emissions.

3.2.7 Downstream processes based on CO_2 scope

Downstream processes are essentially processes that take place after the final casting or components have been produced. For example, the exporting of the cylinder block to international customers or the delivery of the cylinder block to car manufacturers based in the country. The CO2 emissions related to the transport of the final component made from cast iron may differ depending on the proximity of the customer and the means of transport, i.e. by land, air or sea. Author et al reported that transport of cast engine block by land will produce 0.16 kg CO2 eq./ton/km in contrast to transport by sea, which will generate 0.02kg CO2 eq./ton/nautical mile [19].

3.3 Mapping of cast iron production processes based on CO2 scope emissions and key findings

Figure 7 below illustrates CO2 emissions across the cast iron production process. The key findings include:

1. The melting stage is the primary source of CO2 emissions in the cast iron production process, contributing over 28 tCO2 eq.

2. The transformation of iron ore is another significant source of CO2 emissions, adding 4.76 tCO2 eq.
3. The high emissions in the melting stage and iron ore transformation are primarily driven by the combustion of carbon and coal.
4. Other processes, including sand recycling, pouring metal in moulds containing organic resin or coal dust, and transportation of cast components, also contribute to CO2 emissions, although to a lesser extent.
5. The machining of metal generates Scope 2 CO2 emissions of 0.45 tCO2 eq.
6. The moulding of sand produces Scope 2 CO2 emissions of 0.43 tCO2 eq.

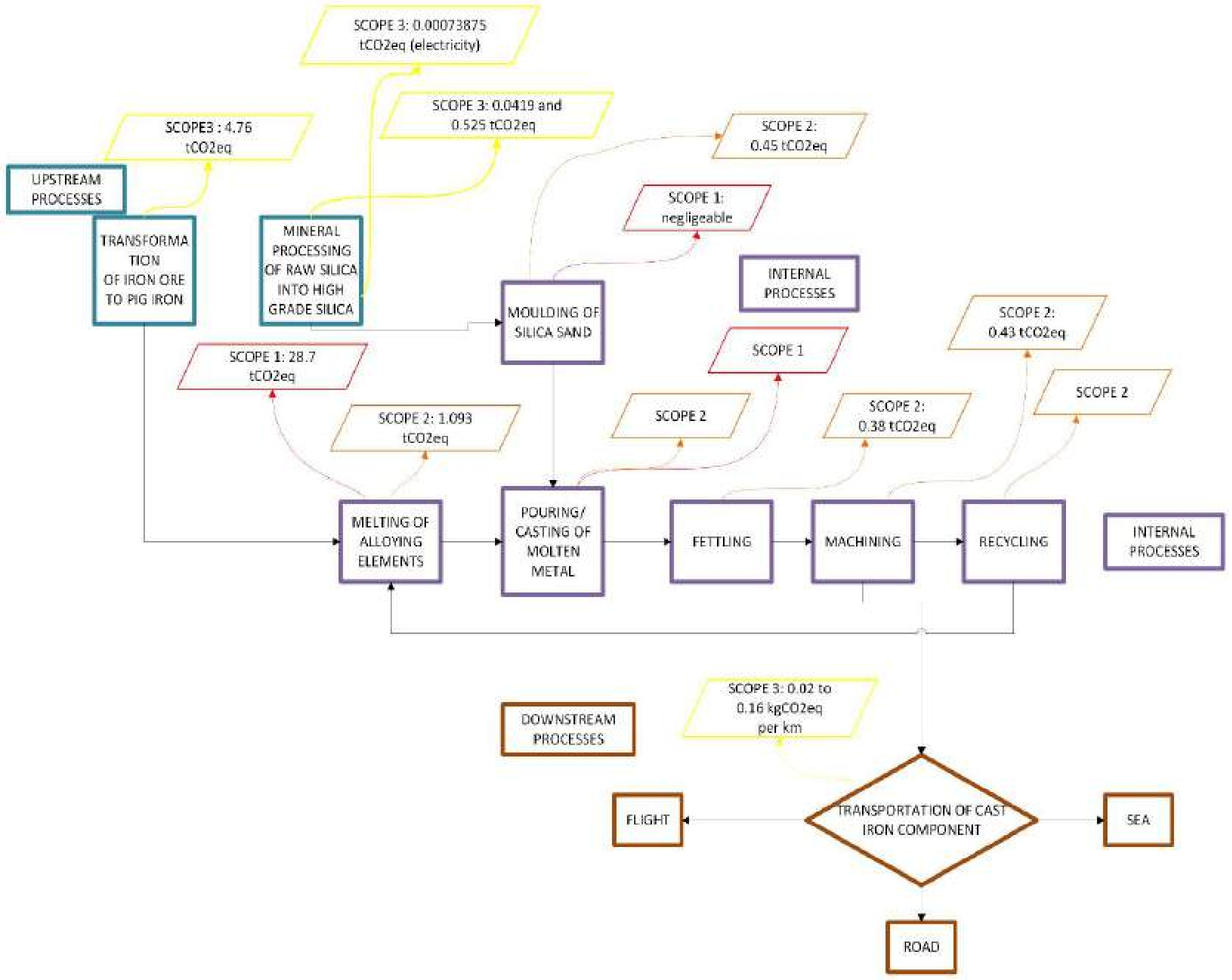


Figure 7 Mapping of CO2 scope emission in the production of cast iron component

3.4 Recommendation and strategies

This section of the work provides suggestions and strategies to reduce the amount of CO_2 emissions in the South African cast iron foundry sector.

3.4.1 Upstream processes: scope 3 emissions

The study covers two processes: transforming raw silica into high-grade silica and converting iron ore into pig iron. To reduce energy consumption and CO2 emissions during smelting, it's recommended to use coal and iron with appropriate calorific values, implement a coal-fluidized bed shaft to enhance smelting efficiency, maintain a highly reducing atmosphere in the smelter, and ensure high post-combustion rates in iron bath furnaces. Additionally, increasing the reclamation of excess gas heat is crucial to managing energy use. Foundries should also prioritize using steel scrap to reduce reliance on pig iron [19] [22].

3.4.2 Internal processes: scope 1 and 2 emissions

Using non-organic binders like sodium silicate instead of organic binders, which emit CO_2 during contact with molten metal or thermal reclamation, reduces Scope 1 emissions. Additionally, coal dust mixed with green sand improves surface finish but increases CO_2 emissions during pouring. Alternatives such as finer sand or mould coatings can achieve similar surface finishes without CO_2 emissions [21] [23]

The thermal reclamation of sand uses fuel combustion to raise the sand to a high temperature, vaporising the binder and producing CO2 emissions. An environmentally friendly alternative is hydrogen. There is a broad consensus among analysts that the hydrogen market will grow significantly in the coming decade. Currently used as feedstock in chemical industries, hydrogen's use is expected to expand in the energy sector. Once electricity generates hydrogen, it can store energy as a gas or pressurised liquid, replacing fossil fuels and biofuels in power plants, cogeneration plants, heating plants, and as a transport fuel for vehicles [6].

A standard cast iron alloy usually contains up to 20% pig iron which is associated with high GHG emissions during the production process. According to studies conducted in German foundries it was discovered that the use of steel scrap instead pig iron reduces the amount of CO2 emissions by 25%. This is a significant reduction and therefore, replacing pig iron with steel scrap should be pursued in order reduce Scope 1 emissions [19].

Implementing casting simulation software such as Magmasoft can benefit the foundry in reducing the amount of casting defects which can help save energy, emissions and costs. The casting simulation has the advantage of reducing casting yield and mitigating the occurrence of casting defects that will in the long term reduce the energy consumption [24].

Better energy management regulations are needed, as successful energy efficiency standards applied overseas have led to significant improvements. South Africa can benefit by amending its own standards. The Draft Energy Bill of 2004 gives the Minister of Minerals and Energy the authority to mandate these standards, making them crucial. Energy labelling of appliances, a proven international tool, can enhance awareness and reduce consumption, with EU standards as a potential model. Energy management formalises monitoring, evaluation, and targeting of energy use, providing sector-specific benchmarks. In industrial and commercial settings, it should also include training, motivation, awareness, and adopting green accounts [5].

3.4.3 Downstream processes: scope 3 emissions

To reduce CO_2 emissions when exporting components, companies can adopt three primary strategies. Firstly, optimising logistics by using more efficient shipping routes and consolidating shipments can minimise fuel consumption. Secondly, switching to greener transport options, such as electric or hybrid vehicles and ships, can significantly cut emissions. Lastly, incorporating sustainable packaging made from recyclable or biodegradable materials can reduce the carbon footprint associated with manufacturing and disposing of traditional packaging. These measures collectively contribute to a more environmentally friendly export process [25].

4 CONCLUSION

The literature review highlights that upstream and internal processes in cast iron production generate the highest CO_2 emissions, with the melting of alloying element and smelting of raw iron being the major contributors. Recommended strategies for reducing emissions include using scrap metal instead of pig iron, utilizing coal with a higher calorific value, and implementing energy management guidelines. Future work will consist of investigating a local

South African cast iron plant to record CO2 emissions by collecting electricity bills and using a CO2 data logger. Subsequently, the investigation will apply the discussed recommendations on energy conservation measures to reduce the CO2 emissions in foundries.

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DEVELOPMENT OF FUNCTIONAL PARTS IN RAPID SAND CASTING FOR HIGH-TECH APPLICATION - A REVIEW

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ABSTRACT

Rapid prototyping of patternless sand moulds using binder jetting has emerged as one of the leading processes that can enhance rapid sand casting (RSC). With this enhancement, RSC can provide fast production of parts, with good surface finishes and dimensional accuracy, as well as minimal overall production costs. However, the use of RSC in producing functional parts for high-tech applications in the biomedical, automotive and aerospace engineering industries has been restricted due to certain limitations. This review will highlight the concurrent engineering mechanisms, including design justification, model verification, process validation, preproduction examination (design validation), and endorsement of manufacturing tooling, that need to be incorporated into, or developed for RSC in order to produce functional parts for high-tech applications.

Keywords: rapid prototyping, rapid sand casting, high-tech applications

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1 INTRODUCTION

Foundries have used sand casting for thousands of years. The development and introduction of the innovative technology of additive manufacturing (AM) to industry in the 1980s has significantly impacted foundries. When AM was first introduced to certain industries, it was used to print models to assist design processes. After years of research and studies, AM technology was developed, according to specific standards, to encompass the introduction of modern procedures and uses that aided in the making of casts for actual products [1, 2]. These changes significantly improved productivity in the industries into which they were introduced [3]. The first application of AM-fabricated patterns as sacrificial patterns in conventional investment casting (IC) started in 1989 [4]. Later, AM became the standard method for cast making to enable the rapid casting of metal parts [5, 6].

Due to the constantly changing demands of the manufacturing industry, caused by the limited lifespan of products, changing consumer requirements, increased quality requirements, intricately shaped models, and the need to reduce manufacturing time and cost to allow product commercialisation [1-3], industries began to investigate how to use AM to produce metal components directly. Hence, the technique ‘rapid manufacturing’, also known as direct metal production, was innovated. This AM technique is used in industries ranging from aerospace and automotive to dentistry and electronics. However, the inadequacy of AM technology for the direct manufacturing of metal parts means that the technique (rapid manufacturing) has not been fully exploited. Since the common or existing AM processes can only be used to manufacture the moulds and cores for conventional metal casting, the direct manufacturing of metal parts is still an ongoing phase of research and exploration, which is driven by the numerous advantages this technology holds for meeting customer needs. The current alternative, therefore, remain the establishment of moulds and cores for conventional metal casting. This manufacturing process is referred to as rapid casting [5-7].

The major requirement for any casting method is to design and fabricate a pattern to manufacture moulds for metal casting. Some casting methods, such as sand casting, involve designing and preparing a gating system and core boxes upon which the general casting quality relies. These mechanisms are costly and time-consuming, particularly for intricately designed castings. The application of AM techniques in developing patterns for casting enables foundries to produce metal parts with minimal use of tooling, specifically using rapid casting for cores and pattern development. Rapid casting is important to ensure the production of parts in less time. The conventional design and fabrication of cast models entail costs and time that are not in line with the current competitive market demand. Currently, it is feasible to produce difficult patterns and some tooling needed for casting in less time and fabricate the casting in a matter of days [7-10].

AM printing has a large material range, comprising ceramics, polymers, metals, sand and concrete. Acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) are the major polymers used in 3D composite printing [11, 13]. However, the intrinsic anisotropic performance and mechanical features of AM printed products still restrict large-scale printing capacity. Therefore, an improved AM priming pattern is vital in regulating anisotropic performance and flaw sensitivity. In addition, modifications in the printing environment affect the quality of the finished product. AM is excellent for producing components of diverse dimensions, from micro- to macro-scale, although the printed materials' precision relies on printing scale and the accuracy of the method [14, 15]. For example, micro-scale 3D printing results in problems with surface finish, resolution and layer bonding, which occasionally create the need for post-processing methods like sintering. These drawbacks create some problems in the use of AM printing across diverse industries [16, 17]. To make AM printing more accessible, more appropriate materials need to be produced; and additional mechanisms are required to improve the mechanical features of 3D-printed products [13, 18]. Continuing research to understand and decrease the challenges that restrict the application of this technology in certain areas will increase the importance of 3D-printing technology [17].

Until now, sand casting has had a huge impact on product production. This is due largely to the abundance of sand and, sometimes, the ease of production, making foundries and some industries reliant on this technique. Recent innovations to this conventional technique entail the introduction of AM. Hence, weeks or months in fabricating patterns or models are reduced to days, thus speeding up the production of parts [19]. However, the production of functional parts has suffered some setbacks from one of the steps in the AM process, i.e., binder jetting, which is used for producing sand core and moulds for casting, referred to as RSC. This process is limited to various factors, like insufficient mechanisms/processes for which parts can be produced without the challenge of property disparity. Therefore, this review elaborates on how RSC can be applied to the functional production of parts for high-tech applications by incorporating 'concurrent engineering mechanisms,' which entail design justification, model verification, process validation, preproduction examination and justification of manufacturing tooling. These processes are being designed to give RSC a comparative and competitive advantage over other techniques that have been applied to parts production in high-tech applications.

1.1 The application of AM in sand casting

In the manufacturing industry, sand casting is a widely used casting technique in which parts are cast by pouring molten metal into a sand mould. The moulding can be achieved with green sand as one of the prominent sand-casting methods. The moulding sand is a mixture of clay, sand, other materials and water [20]. The procedure for sand casting is depicted in Figure 1. The basic stages of sand casting techniques are:

- Pattern preparation
- Mould making (ramming sand about the pattern)
- Preparation of the gating system for the pouring of the liquid metal
- Core development and core arrangement in the mould
- Closing and weighing of the cope and drag
- The pouring of molten metal into the cavity.

In conventional sand casting, the manufacture of core boxes and patterns requires the skilful use of design data either from 2D diagrams or handmade patterns (which could be clay, wood or other materials). The production of these different types of patterns is time-consuming (sometimes taking weeks, or even months, to develop) and involves extensive labour. This manufacturing time can be minimised by introducing different AM techniques or procedures called rapid sand casting [21]. Table 1 states the variation in time when conventional and AM technique were engaged in producing some parts.

Various marketable AM methods have been applied to fabricate tools needed for sand casting with different results. Binder jetting, which is one of the AM techniques, aids in producing patterns with additional cores by designing core prints [21-23]. Binder jetting gives distinctive importance in contrast to other AM techniques since jetting monomer liquid droplets can be applied to cast alloys into moulds on the build platform; for instance, acid-mixed sand can be designed to glue the sand via polymerisation. These sand moulds can also be used for the cold casting of material such as concrete [25, 51].

Various rapid-casting solutions are being applied to sand casting by different researchers and industries. Three main AM processes can be applied to sand-casting systems [26]. The processes applied in rapid sand casting are depicted in Figure 2. In situations where fewer casting products are needed, direct tooling methods can be used as an alternative to conventionally applied wooden patterns [27, 28]. Also, when the bulk volume of production and high pattern durability is needed, the indirect tooling method can be comfortably used in sand casting. The third and last method is applying AM to directly fabricate sand moulds, also called direct fabrication (patternless moulds). ZCast501, ProMetal, Electro-Optical System - DirectCast, and rapid-casting technology (RCT) methods have been successfully used in the casting industry for direct mould fabrication [16, 17].

Table 1: Time measurements for 3D printed and conventional mould parts [53]

Number of batches	Production time for 3D printed parts (min)	Production time for conventional parts (min)
1	45	300
5	225	1500
10	450	3000
50	2,250	15, 000

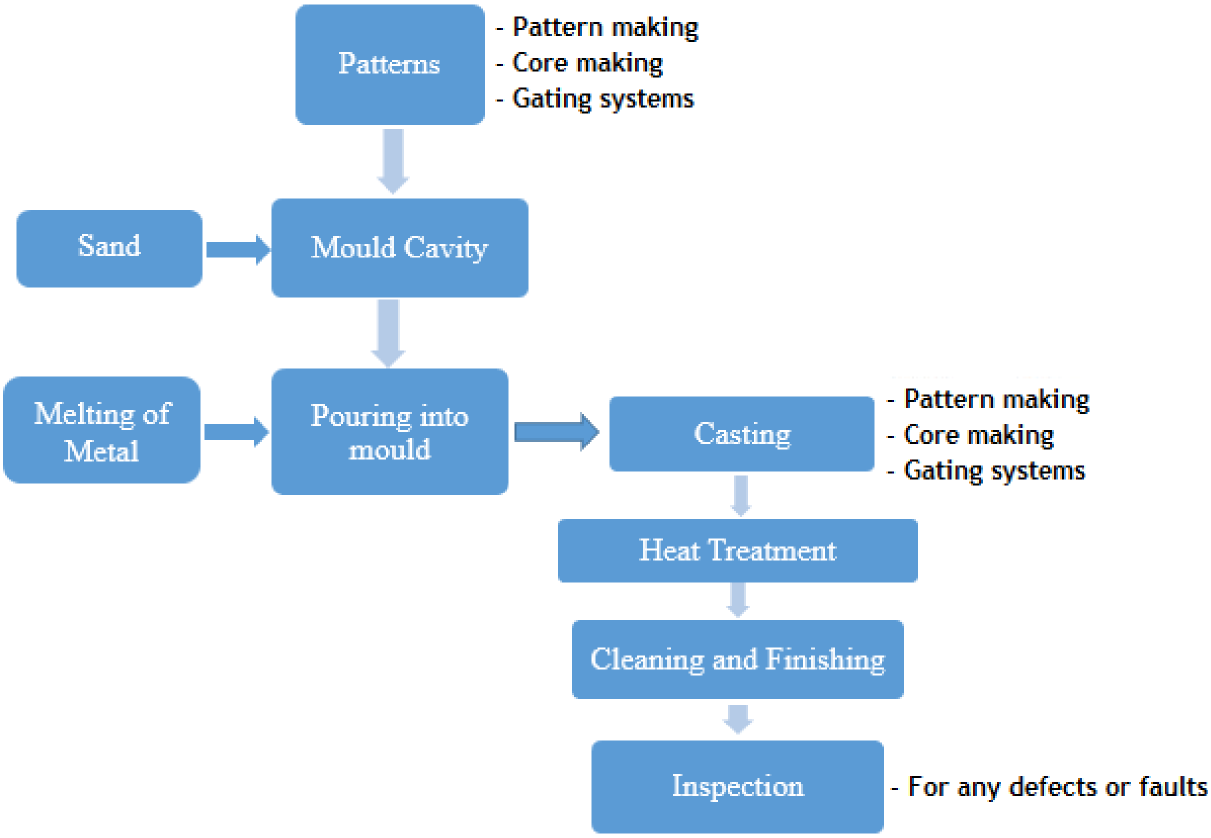

Figure 1: Sand-casting procedures [18]

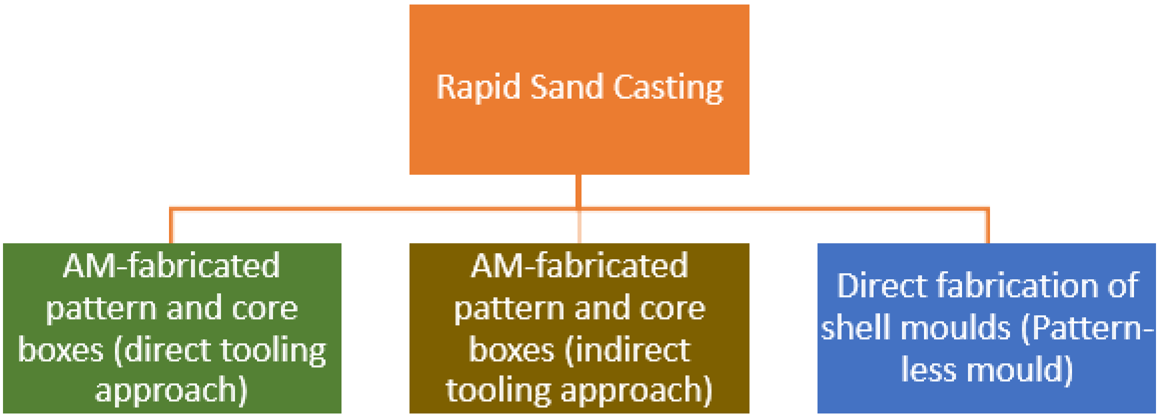

Figure 2: Methods applied for rapid sand casting [22]

1.2 Challenges encountered by AM manufacturers in rapid sand casting

The following list describes the challenges encountered by various AM manufacturers of parts for rapid sand casting [29, 30]:

- Even though rapid sand casting can be used to fabricate complex castings, some parts still need extra post-manufacturing operations, which increases the lead time and the cost of the parts.
- The present rapid sand-casting process for the surface finish of fabricating components, and for accurate dimensional and durable casting parts with less processing time, still requires further examination and improvement.
- Rapid sand casting is still in a developmental phase. Hence, certain parameters must be incorporated into this technique to minimise property disparity in part production.
- It has yet to be shown that the application of rapid sand-casting techniques will reduce the lead time and cost of fabricating a single metal casting.
- Manufacturers and developers need to become acquainted with pattern and cast makers using rapid casting techniques, parameters, and procedures to ascertain if and how these techniques can be applied in the conventional foundry system.
- Cheaper AM machines and rapid-casting materials for small-scale foundries are still lacking.
- There is a high priority at the commercial and industrial level to accomplish bulk manufacturing of metal casting using rapid casting techniques.
- Owing to the advancement of part production, there are still some inadequacies in the ability of rapid-casting devices to easily fabricate huge castings. hence, making the technique to be lagging behind in specific production.

1.3 Modern industrial optimisation of rapid sand casting

Globally, research is being carried out by many groups and organisations to enhance rapid sand casting. Various AM-produced patterns can be used as sand-casting patterns because they possess the strength to withstand the pressure of the moulded sand and can also tolerate the chemicals in the sand. Dimensional accuracy in rapid prototyping can easily be applied to a concept model for visualisation purposes [31]. When fabricating AM core boxes and pattern parts for sand casting, any fault or error in the casting tools will be carried through to the finished cast parts. Utela et al. [17] observed in their studies that some AM techniques can actually result in defects in the core box and sand-casting pattern. In addition, the thin wall-part geometry may not be suitable for rapid tooling for a particular AM technique. Globally, manufacturers have expressed a need for rapid casting that can fabricate (using patternless casting) ready-to-pour moulds. Currently, Zcast 501, ProMetal RCT and EOS DirectCast are being used to fabricate patternless castings using direct sand-casted cores and moulds from CAD designs [28, 32]. These mechanisms make the conventional physical patterns needed to develop sand moulds redundant. Using the rapid-casting mechanism, intricate and complex model parts can be rapidly cast at a minimal cost, unlike the conventional foundry method. This modern mechanism encourages foundries to fabricate spare parts made from any material, according to customer requests. Likewise, this mechanism makes typical job shop production feasible and economical for industries by fabricating diverse modelled parts at a rapid rate. The recent innovations in these devices that produce moulds and cores for sand casting include 3D-printed sand [33, 34]. The latest research has been carried out to determine how the chemical binder sand system used for 3D-printed sand can be altered when the liquid metal at high temperatures is poured into the moulds and cores.

Based on case studies of the different applications of rapid sand casting (RSC) elaborated above, the most important qualities of this technique to foundrymen, developers, researchers, and manufacturers are as follows:

- The cost is reduced because conventional casting tools needed to cast samples or small-volume manufacturing castings can be discarded. The costs of correcting badly designed parts and the concomitant repetitions needed prior to design completion are likewise decreased when using RSC.
- RSC optimises the sand-casting process because, prior to tool production, prototype casting enables the correct placement of parting lines and the ejection of inserts and pins. Mould and pattern evaluation and moulding parameter optimisation can also be carried out efficiently.
- Intricate cavities and complex geometry of cast parts are possible with RSC, unlike traditional casting, where it is either impossible or too expensive.
- There is gating system optimisation. One of the functions of the foundry is to develop the gating design and runner system. Before assigning the production tooling order, applying AM patterns for trial-run castings promotes gating-system optimisation.
- The application of RSC is feasible and economical in emergencies, specifically if the casting quantities are needed prior to the preparation of the production tool [35, 36].

2 THE DEVELOPMENT OF A CONCURRENT ENGINEERING MECHANISM TO MINIMISE THE CHALLENGES ENCOUNTERED IN RSC

For the production of functional parts, various steps are involved. The many approaches involved in these steps mean there is a great need to correlate these processes. In the past, communication between the pattern designer and the foundrymen, regarding the various steps involved in producing parts, has been lacking. This sometimes causes a disparity between the designed pattern and the finished product, resulting in variability in their properties. Hence, to nullify these challenges, concurrent engineering is being adopted to create a system of linkages in all the steps involved in producing the functional parts [52].

The concurrent engineering mechanism enables the normally chronological procedures, like pattern designing, material development, and manufacturing to occur simultaneously, thus decreasing the entire production time from start to finish, hence improving productivity and minimising costs [37-40].

Additionally, introducing a concurrent engineering mechanism in RSC ensures direct communication between the pattern developers, designers, foundrymen and end users (Figure 3).

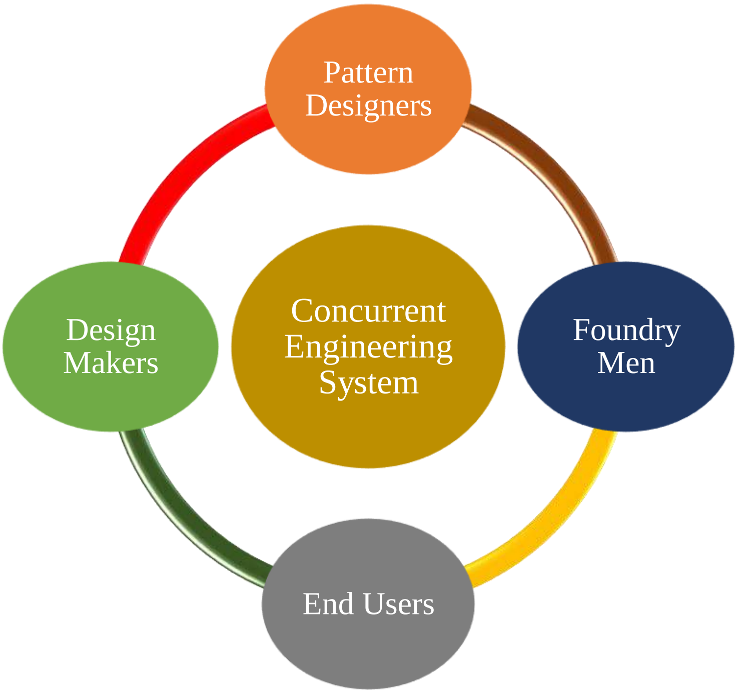

Figure 3: Concurrent engineering mechanism needed in RSC for fabrication of parts

This mechanism aids in evaluating the problems related to each step involved in casting the components. Also, it assists in examining the emergence of product variation through the application of CAD simulation and modelling. Consequently, this ensures quick detection of challenges and the easy provision of solutions along the production line, thus reducing the product manufacturing cycle; also, the mechanism fosters multi-disciplinary collaboration and quality maximization [41, 42]. The following subsections elaborate on how various approaches in concurrent engineering mechanisms can be applied to produce parts for high-tech applications.

2.1 Design justification and model verification

The unique parameters for a design and model can be validated in terms of the nature, size, structure, dimension, and performance of the moulds and cores; as well as the parts to be produced. To efficiently verify and justify the validity of such models and designs, it is expedient that each of the materials, and the parameters to be introduced, needs to be segregated so that each behaviour can be focused on, examined and validated separately [43, 44]. Figure 4 depicts the procedural routes for this mechanism.

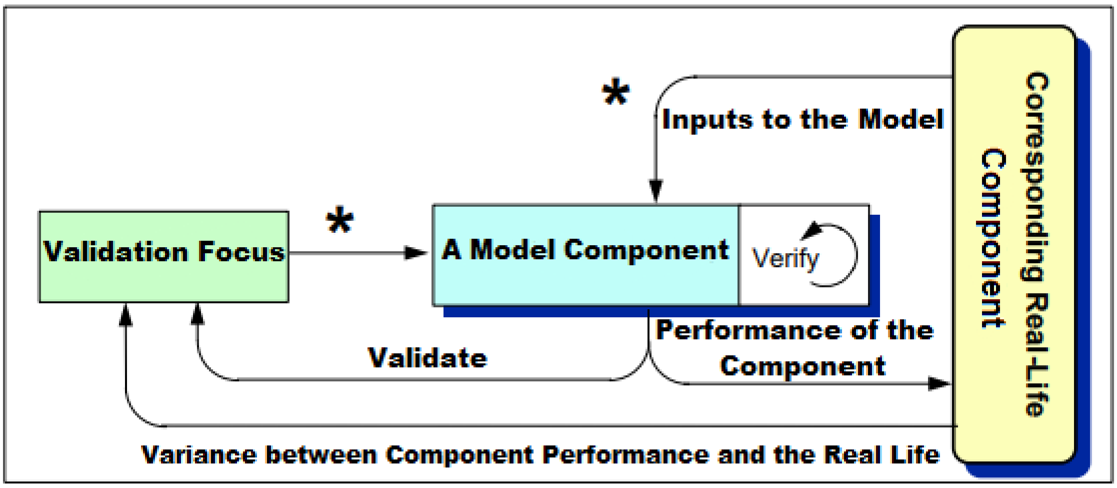

Figure 4: A procedural process for a design or model verification and justification [44]

2.2 Process validation, preproduction examination, and justification of manufacturing routes and tooling

Process validation can be described as an evidential standard that each step of the procedure, which is worked out within predetermined parameters, is behaving efficiently and effectively to manufacture parts that will match the pre-established model, specifications, requirements and qualities [45, 46].

Prior to producing the designs or models of the moulds and cores, the production and manufacturing steps are thoroughly examined. This minimises defects in the final products. The route justification should affirm that the control mechanism is sufficient for the process design and the product quality. The justification should encompass various fabricating phases and the strength needed for developing the final products [47]. The route justification is the documented approval indicating that the route functioned within the specified parameters and to specified standards, behaved efficiently and is repeatable, and will produce a product that meets the required standards of quality and specifications. In process validation, constant monitoring of manufacturing performance is required for verification purposes. This approach depends on the data and information from the product and procedural development examination and/or past manufacturing knowledge, product complexity, the employed analytical techniques, and the degree of automation. Constant process verification may require elaborate on-line, in-line, or at-line monitoring and/or controls to examine process rendition [48, 49].

It is neither practical nor feasible to introduce into the computer models the various influencing parameters that could occur in a realistic product. Therefore, the detection modules should be established not only to firmly dominate, but also to efficiently ascertain several outcomes using real circumstances. To prevent the computer regulating system from becoming outdated, the actual components of the mechanism monitoring modules should be constantly updated. This approach will sustain the reliability or integrity of the control mechanism in the computer model. The introduction of process validation in concurrent engineering mechanisms should not isolate each stage of the process [50], but should be a lifecycle routine (Figure 5) linking the model, process, and product establishment, as well as their justification, verification, and validation.

Therefore, in establishing the concurrent engineering mechanism, particularly in RSC interactive 3D CAD, simulations, kinematic modelling, solid modelling, virtual reality, etc, are the vital tools or software needed. These tools would ensure accurate simulation of the actual performances of the different procedures to produce the actual products. Then, introducing a control closed loop system with some sensors being integrated into the production structures can make the return of parts not produced according to desired design, specifications and properties feasible. Hence, making RSC a comparative technique that competes in the industrial world for part production in high-tech applications.

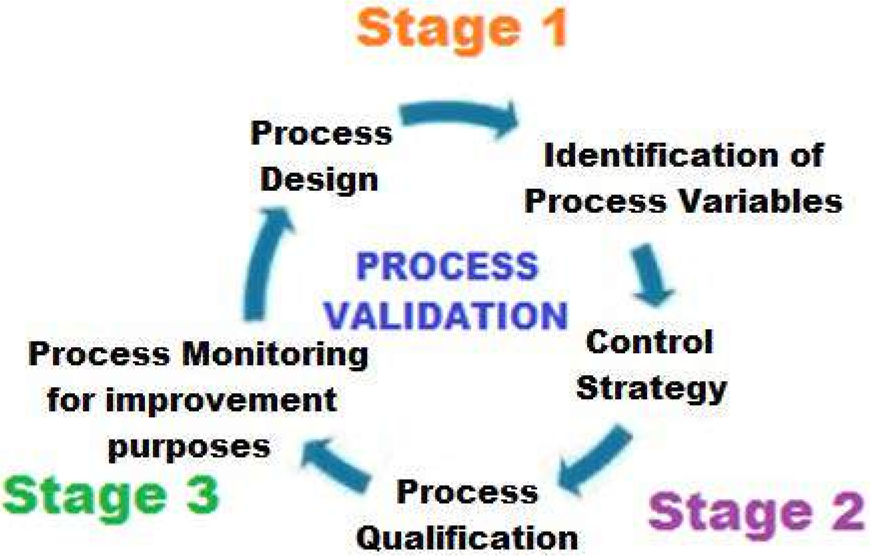

Figure 5: A diagrammatical representation of the process validation [48]

3 FUTURE DEVELOPMENTS IN RAPID CASTING TECHNOLOGY

Rapid casting techniques have gained recognition globally and are anticipated to be significant for foundries, developers, manufacturers and researchers. The mechanisms of rapid casting analysed above have constantly improved, and modern casting processes are likewise being developed. It is anticipated that some mechanisms will be developed along with it so that some casting solutions with no intermediary techniques can be initiated. However, the high cost of building components, AM devices, and other consumables are the challenges encountered when introducing rapid casting into foundries. Thus, when producing direct moulds or patterns for sand casting and investment casting in foundries, less expensive devices alongside low-cost consumables and building materials are needed.

It is well known that in rapid sand casting there is rapid production of sand cores and moulds and, consequently, the type of functional parts cast in the foundry. Recently, progress has been made to develop a process where the sand cores, moulds and component casts are made simultaneously. The lack of standardised mechanisms or devices that could undertake this procedure has been one of the limiting factors in achieving this process effectively. However, the establishment of modernised artificial intelligence (AI) is envisaged to be of enormous importance in this aspect of RSC innovation, since autonomous and monotonous work at the various production stages can be carried out collectively and promptly instead of relying on human labour for some of the operations.

Furthermore, the 3D printing of sand cores and moulds lacks the capacity to change the printed part’s dimensions as and when needed under unfavourable conditions. Four-dimensional (4D) printing overcomes this deficiency by adding the fourth dimension of time to enable physical features to be altered in the course of the part’s lifespan. With 4D printing, the printer is programmed to respond to stimuli, such as humidity, heat, pressure and temperature. Due to this shape-modification property, 4D printer systems can even be programmed for repair and self-assembly; and to envisage the performance and movements of the part to be manufactured.

Lastly, the continuous global research in different fields of AM and rapid casting will drive the following innovations:

- Development of materials with excellent strength for fabricating patterns, which will produce a large quantity of cores and moulds for the bulk production of parts.
- Material development to fabricate patternless sand cores and moulds to produce high-melting point ferrous and non-ferrous materials.
- The development of AM devices with excellent properties such as high resolution, fast build speed, and the ability to fabricate parts with thin layer thickness and bulk parts of intricate geometry.
- Modern AM devices, with efficient operational stages to fabricate enormous moulds and patterns for casting huge components, should soon be obtainable.

4 CONCLUSION

This review has elaborated on the importance of introducing concurrent engineering mechanisms in producing functional parts for high-tech applications, especially when applying RSC. The majority of the parts produced by RSC have had property disparities. Consequently, this has limited the use of RSC in high-tech practices such as in aerospace and biomedical industries. Thus, introducing concurrent engineering mechanisms to RSC is necessary to control design justification, model verification, process validation, preproduction examination and justification of manufacturing tooling. This mechanism minimises the property disparities between the designed pattern and the finished product, thus improving their appropriateness for high-tech industries.

Furthermore, this review also examines various global studies in different fields of AM and rapid casting, and some future approaches to the RSC technique, whereby a procedure that simultaneously incorporates the development of sand cores and moulds, and the casting of parts, can be developed. The emergence of modern AI techniques is envisaged to be significant for this innovation.

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QUALITY 4.0 MATURITY ASSESSMENT FOR SOUTH AFRICAN MANUFACTURING SECTORS

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ABSTRACT

This study assesses the maturity of South African manufacturers to transition to Quality 4.0, and aims to identify current strengths and weaknesses. An online survey was conducted among manufacturing practitioners to gather their perspectives on their organization's readiness, focusing on 'people', 'processes', and 'plant' aspects. Closed-ended questionnaires were distributed to participants using a snowball sampling technique. Most practitioners reported the unpreparedness of their manufacturing firm with respect to all three aspects. Based on the findings of the survey, the study recommends that organizations follow alleviating measures to enhance maturity to Quality 4.0, including recruiting and upskilling their workforce, establishing dedicated Quality 4.0 leadership for effective change management, conducting technology assessments for Industry 4.0 adoption, and aligning key performance indicators with business objectives. This paper provides practical guidelines for preparing South African organizations for Quality 4.0, which should result in improved productivity and economic growth.

Keywords: Industry 4.0, Quality Management, Quality 4.0

1 INTRODUCTION

The journey to achieving quality methods that suit the production challenges brought forth by the emergence of the fourth industrial revolution has seen quality-assurance professionals being met with several barriers, suggest Carvalho et al. [1] and Khourshed Gouhar [2]. The concept of Quality 4.0 has emerged as a transformative force in the manufacturing industry, leveraging digital technologies and data analytics to enhance quality management practises [3], [4]. As industries across the globe embrace digital transformation, it becomes essential to assess the readiness of manufacturers to transition to Quality 4.0 and to identify the challenges they face in this transition [4], [5], [6]. South Africa, as a prominent player in the manufacturing sector, is no exception to this trend.

In the pursuit of economic growth and societal progress, it is imperative for South Africa's manufacturing sectors to undertake rigorous assessments of their Quality 4.0 maturity. This strategic evaluation aligns seamlessly with the government's overarching commitment to leverage Industry 4.0 tools to enable economic growth, thus combatting the triple threat of unemployment, poverty and inequality by 2030. South Africa's ambitious vision, articulated in its National Development Plan, aims to expand employment opportunities from 10 million in 2010 to 24 million by the end of this decade [7], [8]. Notably, the plan underscores the pivotal role of the labour-intensive manufacturing industry in achieving this ambitious employment target, designating the industry sector as a significant generator of job opportunities. Recognizing the manufacturing sector as the economic backbone of the nation, testing Quality 4.0 maturity becomes not only a prudent business strategy, but a vital component in realizing the broader socio-economic objectives outlined by the South African government [9]. By aligning technological advancements with industrial processes, the manufacturing sector can catalyse job creation, economic development, and ultimately contribute to the nation's pursuit of a more equitable and prosperous future.

This study aims to assess the readiness of manufacturers to transition to Quality 4.0 based on the 3Ps of digital transformation (People, Process and Plant), utilizing the following readiness themes: technology, vision and strategy, culture, skills and competencies, resource allocation, compliance, collaborative networks, reliable connectivity infrastructure and performance measures as adapted from prominent Quality 4.0 researchers [3], [5], [10]. This study uses the 3P framework to assess the strengths and weaknesses of these organizations along their journey to Quality 4.0 and to recommend improvement measures to combat the weaknesses. In doing so, this study aims to contribute to a smooth transition to Quality 4.0, ensuring improved quality and production processes in manufacturing sectors, thereby promoting economic growth in South Africa.

2 LITERATURE REVIEW

2.1. South African manufacturing sector and quality management

The South African manufacturing sector has been identified by the current South African government as a key enabler of job opportunities, highlighting its potential to grow the economy and alleviate the triple threat of poverty, unemployment and inequality [8], [9], [11]. However, over the last few years, the sector has been struggling, as can be seen in the major, costly and persistent product recalls (Table 1) that have been attributed mainly to inadequate quality-control measures [12], [13], [14], [15], [16].

Table 1 Poor quality incidents in South African manufacturing

Incident	Impact	References
Asbestos contamination in Tiger Brands' baby powder	The announcement of the recall resulted in Tiger Brands' shares experiencing their most significant decline in two years, dropping by approximately 10% to ZAR154.02, reputational damage and concerns about the safety of baby powder products.	[17], [18], [19], [20]
Mercedes-Benz brake defect	Financial cost of recalling 13,159 vehicles, share price dropped by more than 4% and reputational damage.	[21], [22], [23], [24]
Enterprise cold meats Listeriosis outbreak	Public health impact with more than 1,000 confirmed cases and more than 200 deaths, product recalls and lawsuits against affected companies.	[25], [26], [27], [28], [29], [30]
McCain and Nestlé South Africa product recalls	Financial cost of ZAR33 million and ZAR15 million, respectively, and reputational damage.	[15], [16], [31], [32], [33], [34]
Toyota South Africa Motors recalls	Cost of recalling over 700,000 vehicles, reputational damage and initial drop in Toyota Motor Corporation's share price by around 1% to 2%.	[13], [14], [35], [36]
L'Oréal product recalls	Reputational damage and financial impact.	[37], [38], [39], [40]
Ford Kuga recall	Recall of 4,556 Kuga models, share price dropped by more than 4%, reputational damage, property damage, injuries and a fatality.	[12], [41], [42], [43]

These regimes have even been dubbed obsolete, outdated and unable to handle current complex production processes [44]. This has undermined the sector output over the years and, in turn, lessened the contribution to GDP of the sector to the economy of the country [45]. However, in recent literature, there has been a growing interest among quality practitioners in Industry 4.0 tools, and a consensus that integrating these tools into traditional quality management practices will revive these practices. This phenomenon has been called Quality 4.0 [45], [46], [47], [48], [49]. Quality 4.0 uses data insights and modern technologies to enable real-time quality inspection, ensuring that a product does not leave the shop floor with defects.

2.2. Quality through to Quality 4.0

Quality, as a concept, embodies the degree of excellence or 'fitness for purpose' in a product, service or process. It encompasses aspects such as performance, reliability, durability and customer satisfaction [50], [51]. The evolution from Quality 1.0 to Quality 4.0 represents the different stages of a quality management system. Quality 1.0, rooted in the early 20th century, focuses on inspection and defect detection, emphasizing post-production corrections [6], [51]. Quality 2.0, emerging in the 1950s, introduces statistical methods and proactive quality control, aimed at preventing defects during manufacturing [6], [52]. Quality 3.0, prevalent in the late 20th century, integrates quality management into organizational processes, emphasizing continuous improvement and customer satisfaction [6], [52], [53]. Quality 4.0, which integrates existing quality management practices with Industry 4.0 technologies, has been proposed to improve quality and performance in organizations [6], [53]. Quality 4.0 relies on data and utilizes technologies such as big data analytics, machine learning, artificial intelligence, the internet of things, and cyber-physical systems. By collecting and analysing data from sensors on shop floors, manufacturers can identify processing errors and rectify them before products reach customers. This approach enhances decision-making, operations and processes, ultimately improving overall quality [3], [4], [54].

Several studies have worked on Quality 4.0 and conceptualize it differently, for example: Sader et al. [52] described and conceptualized Quality 4.0 as an extension of total quality management by integrating it with Industry 4.0 technologies. This theory suggests that integrating the two will improve quality, improve processes and enhance overall business efficiency. This model is represented in Figure 1.

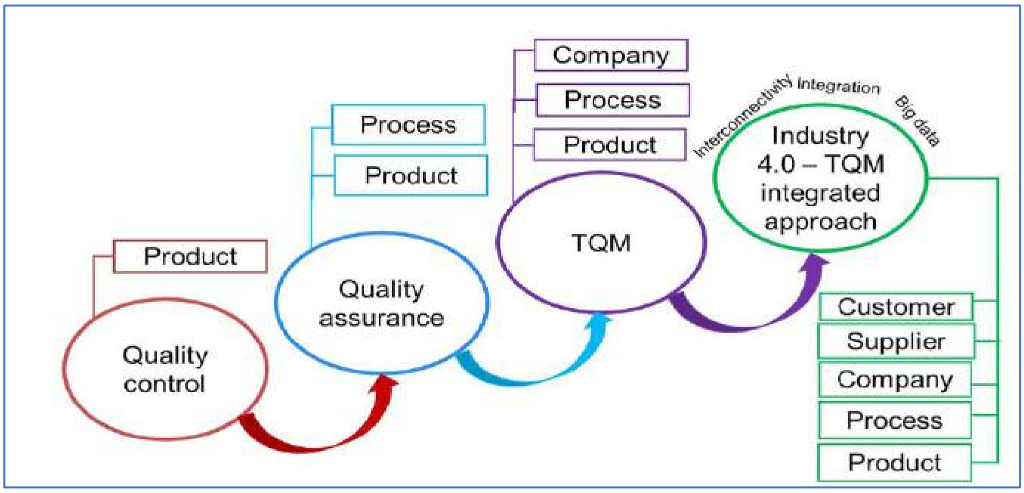


Figure 1 Conceptualization of Quality 4.0 by Sader et al. [52]

Lim [55] conceptualized Quality 4.0 as a modulation of information technology (IT) and operational technology (OT) through digital transformation, as seen in Figure 2. This concept emphasizes the importance of enabling and enhancing real-time data flow and usage, to improve decision making by modulating the two technologies – IT and OT.

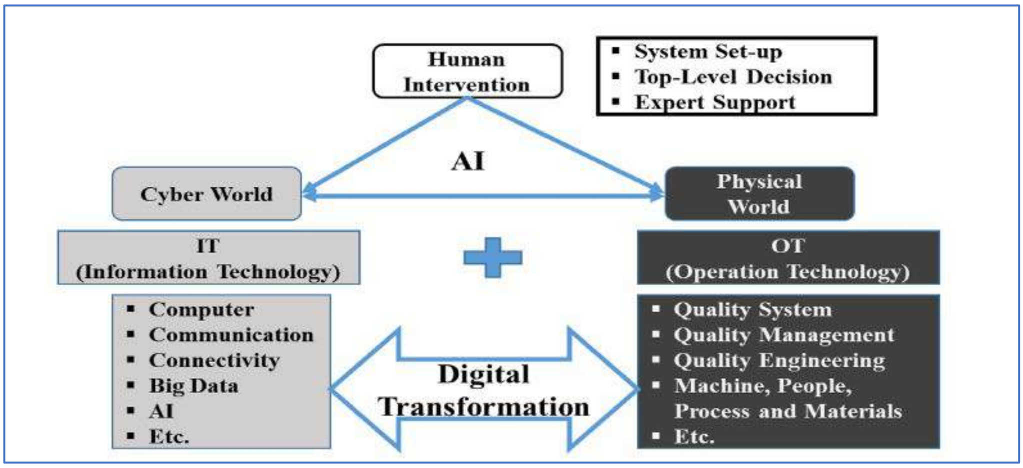


Figure 2 Conceptualization of Quality 4.0 by Lim [55]

Jacob [10] conceptualized Quality 4.0 as the LNS Quality 4.0 model as seen in Figure 3. This model aims to enhance efficiency and revive traditional quality management through interconnecting people, processes and technology. Alzahrani et al. [56] states that this model focuses on 11axis to achieve Quality 4.0, which are labelled in Figure 2 as analytics, management system, data, application, development, connectivity, compliance, culture, leadership, competency, collaboration and scalability.

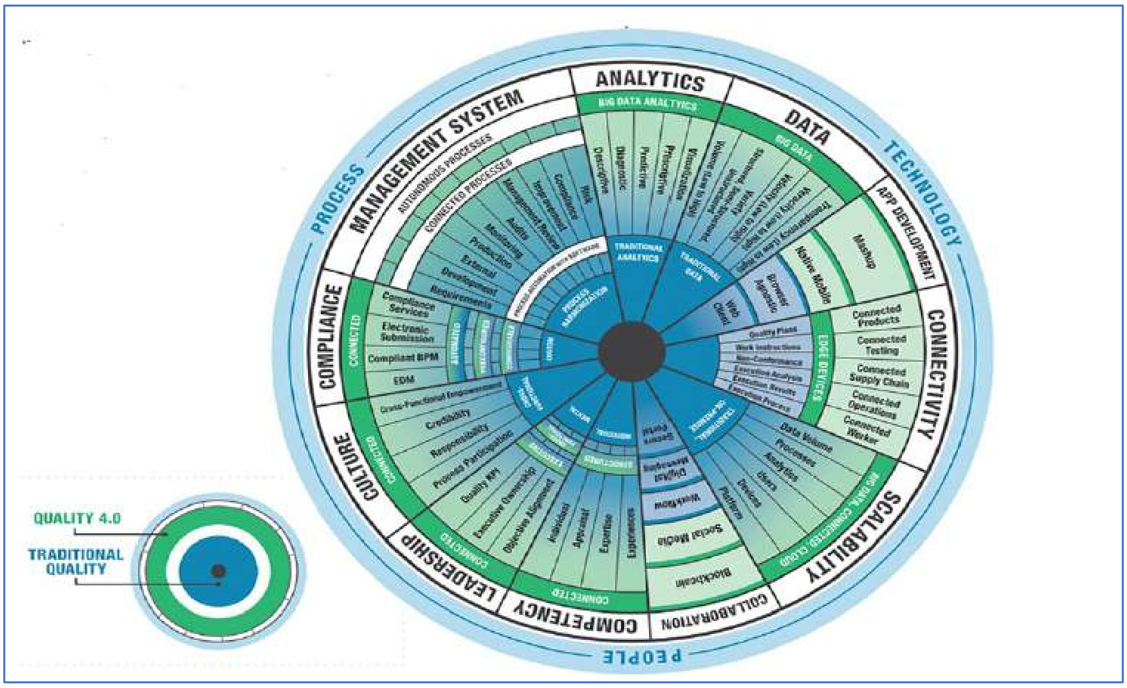


Figure 3 Conceptualization of Quality 4.0 by Jacob [10]

2.3. Quality 4.0 readiness

The concept of readiness encompasses both the willingness and state of preparedness for various situations [6], [53]. In the context of this study, readiness pertains to the comprehensive evaluation of preparedness for the adoption of Quality 4.0. This study identified a range of readiness factors by conducting a semi-systematic literature review. To thoroughly assess Quality 4.0 readiness, this study identified multiple crucial aspects, including the level of awareness regarding Quality 4.0, readiness factors, challenges associated with its adoption and the corresponding benefits [3].

Numerous authors emphasize the significance of establishing Quality 4.0 infrastructure, which encompasses crucial elements such as enabling technologies, integration capabilities, connectivity, reliable electricity supply and a skilled workforce [3], [4], [54]. These factors play a critical role in facilitating successful implementation of Quality 4.0 practices (as illustrated in Table 2). Table 2 presents a compilation of insights derived from analysed articles, providing a deeper understanding of how researchers interpret the various factors contributing to Quality 4.0 readiness. The literature highlights a range of factors that influence readiness, including visions and strategies, awareness of Quality 4.0, customer- and supplier-centric approaches, training and skills, financial considerations, fostering an organizational quality culture, garnering support from top management and leadership, promoting teamwork, vision alignment, and implementing actionable strategies. Establishing and effectively implementing such strategies is of paramount importance for driving enhanced productivity within the manufacturing industry.

Table 2 Quality 4.0 maturity factors

Readiness factor	References
Top management support	[4], [6], [46], [54], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66]

Infrastructure	[1], [6], [48], [56], [57], [61], [67], [68], [69], [70], [71], [72], [73], [74]
Quality 4.0 leadership	[1], [6], [48], [56], [57], [61], [67], [68], [69], [70], [71], [72], [73], [74]
Trainings and rewards	[1], [6], [46], [48], [54], [56], [57], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78]
Quality 4.0 vision and strategy	[4], [5], [6], [57], [58], [59], [76], [79], [80], [81], [82], [83]
Customer readiness	[4], [5], [6], [57], [62], [84], [85], [86]
Knowledge and awareness of quality	[4], [5], [6], [10], [46], [54], [57], [58], [59], [60], [62], [63], [66], [87], [88], [89], [90], [91]
Supplier centredness	[4], [5], [6], [54], [57], [59], [62]
Quality 4.0 culture	[3], [4], [5], [6], [10], [46], [54], [57], [58], [59], [60], [61], [62], [63], [76], [78], [88], [89], [90], [91], [92], [93], [94]
Resource allocation	[6], [56], [57], [58], [62], [64], [74], [76]
Leveraged technology	[1], [3], [6], [46], [48], [57], [60], [61], [63], [64], [66], [69], [70], [71], [72], [73], [74], [78], [95], [96]
Data-handling capabilities	[6], [56], [60], [63], [64], [66]
Collaboration	[6], [62], [63], [64], [76]
Governance compliance	[6], [46], [61], [62], [63], [65], [81], [82], [83]

2.4. 3Ps of continuous improvement

This study employed the 3Ps strategy framework, as seen in Figure 4, to assess the maturity of South African manufacturing firms to transition to Quality 4.0. This framework, consisting of plant, process and people dimensions, defines what an organization must effectively have in place to be considered adequately mature or ready for the adoption of a new initiative [97].

The ‘plant’ dimension within the 3Ps framework emphasizes that, to successfully implement and sustain an initiative, the essential infrastructure must be established and prepared [6], [97]. In the context of Quality 4.0, the plant must be deploying cutting-edge technologies associated with Industry 4.0, such as the internet of things, additive manufacturing, big data and analytics, cyber-physical systems, artificial intelligence, machine learning, virtual reality and more. This extends to the connectivity infrastructure, ensuring the availability of reliable internet access and stable electricity [10], [57], [58]. Additionally, the plant must consider the financial resources allocated for upgrading technology and capabilities, thereby guaranteeing the dependability of the overall infrastructure.

The 'people' dimension within the 3Ps framework underscores the vital role of human resources in the success of an initiative. It necessitates the integration of personnel into the change management process, involving recruitment, training and workshops that help to instil the Quality 4.0 culture [10], [97]. This dimension places importance on support and engagement from top management and stakeholders. Moreover, it highlights the need for effective Quality 4.0 leadership, guiding the organization and steering it through transformative changes. Key aspects within this dimension include evaluating and enhancing skills and competencies, gauging the effectiveness of leadership, fostering a conducive workplace culture, and securing support from top management and stakeholders [54], [58].

The 'process' component within the 3Ps framework underscores the necessity for effective change management processes to drive the success of any initiative. In essence, this dimension encapsulates a series of steps and activities that convert inputs into outputs to realize organizational goals [3], [98]. In the case of Quality 4.0, it includes processes for introducing employees to the initiative; for presenting the vision to top management to secure buy-in; for evaluating current systems in comparison to Quality 4.0; for identifying bottlenecks; and for strategizing to enhance existing processes [3], [10], [97]. Additionally, it requires processes to uphold data governance, compliance and cybersecurity, thereby ensuring the management of data quality, security and adherence to regulations [6].

Figure 4 3Ps Framework adapted from Jacob [10]; Nkomo and Kalisz [97]

Table 3 groups readiness factors identified from a systematic review of literature on the 3Ps. The table illustrates the conceptual framework foundational to this research, which is based on current theories of Quality 4.0.

Table 3 Conceptual framework: Grouping of maturity factors into 3Ps

3Ps aspects	Readiness measurement factor
People	Top management support
	Knowledge and awareness of Quality 4.0
	Quality 4.0 leadership
	Quality 4.0 culture
Process	Quality 4.0 vision and strategy
	Trainings and rewards
	Customer readiness
	Supplier centredness
	Resource allocation
	Collaboration

	Governance compliance
Plant	Infrastructure
	Leveraged technology
	Data-handling capabilities

3 METHODOLOGY

This study utilizes an online survey to collect the views of South African manufacturing stakeholders. The survey instrument consisted of a closed-ended questionnaire. The questionnaire was designed and organized to follow the readiness factors that were identified at the literature review stage of this study, organized according to the aspects of people, process and plant. As seen on Table 3, the 3Ps framework defines what an organization must effectively have in place to be considered adequately mature or ready for the adoption of a new initiative. Previous researchers such as Jacob [10] and Nkomo and Kalisz [97] in industrial transformation asserted that for firms to be considered ready for new initiatives, in this case Quality 4.0, they must link their readiness factors to the 3Ps framework.

The plant aspect in the framework involves implementing cutting-edge Industry 4.0 technology while assuring reliable electrical and internet access. The people part of the framework emphasizes the importance of human resources in an initiative's success. It necessitates the inclusion of workers into the change management process, which includes recruitment, training, and workshops to help instil the Quality 4.0 culture. The 'process' component emphasizes the importance of good change management methods to ensure the success of any effort. In essence, this dimension encompasses a set of actions and activities that convert inputs into outputs to achieve corporate goals [10], [97].

Many of the questions were adapted from seasoned researchers in the quality management field such as Sony et al. [46], Cudney et al. [5], Maganga and Taifa [6], and Khourshed and Gouhar [2].

The study used snowball sampling to identify survey participants, starting with eight (8) manufacturing practitioners who were known to the researchers and who were able to refer other practitioners. Snowball sampling is advantageous as it can reach a wider audience that understands the subject due to reliable referrals, it is also considered a cost-effective sampling method. The study reached 44 participants comprising entry-level to seasoned researchers, quality practitioners, engineers and managers.

Data was collected using an online tool called Microsoft Forms, and organized and analysed using Excel packages. The participants rated each aspect's maturity on a 5 Point Likert scale (1- Initial Stage, 2- Developing Stage, 3-Intermediate Stage, 4-Advanced Stage, and 5-Leading Stage), modified from Cosby's quality management maturity model, cited by Makhanya et al. [99] and the Quality 4.0 maturity model by Nenadál et al. [100] , with the initial stage indicating extremely poor knowledge of digitization of quality, no basic skills and little to no processes aimed at digitization of quality, and the leading stage indicating world class technology adoption, highly skilled staff and leading processes.

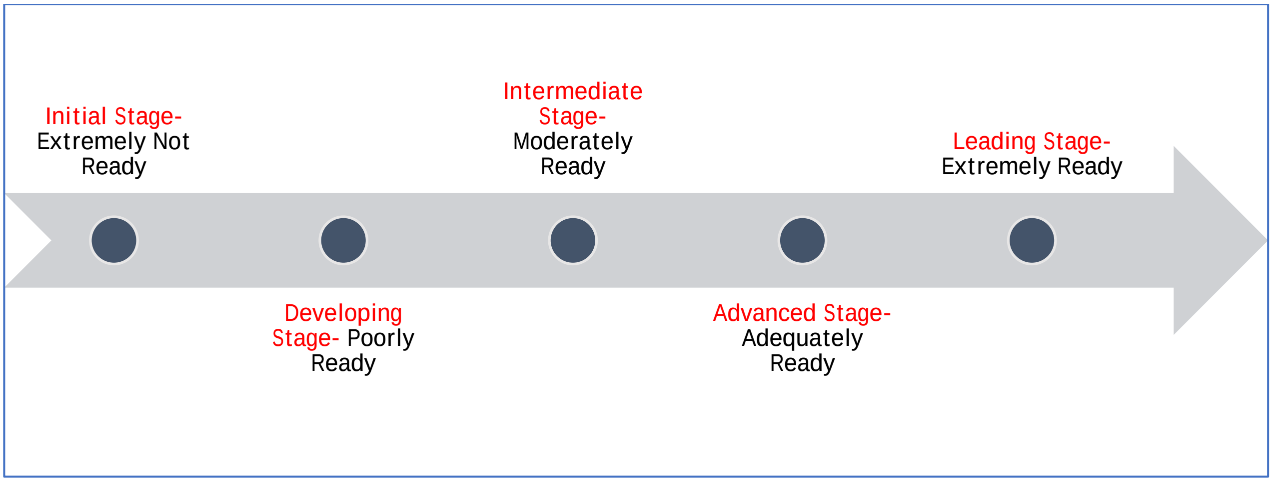


Figure 5 Maturity Levels

The study used quantitative methods (frequency and the aggregate median) to analyse the collected data. To test for the internal consistency of the instrument, the study utilized Cronbach's alpha, which was calculated to be 0.83.

4 RESULTS

The sections below present the results of the study.

4.1. Demographics

Below are the results of demographic analysis showing educational and employment levels.

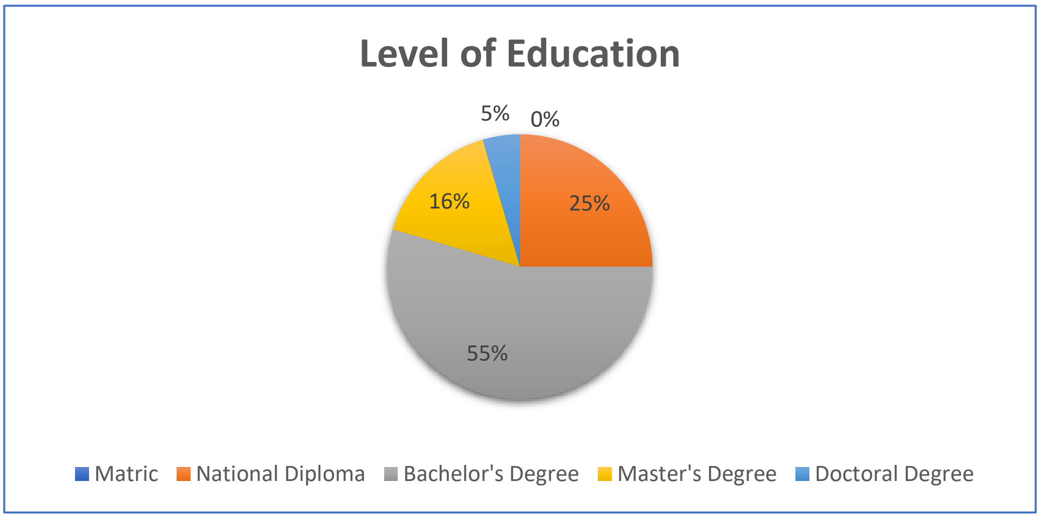


Figure 6 Level of education

Figure 6 shows that the respondents possessed at least a National Diploma, and Figure 7 show that there was a wide range of employment levels from entry- to senior-level management.

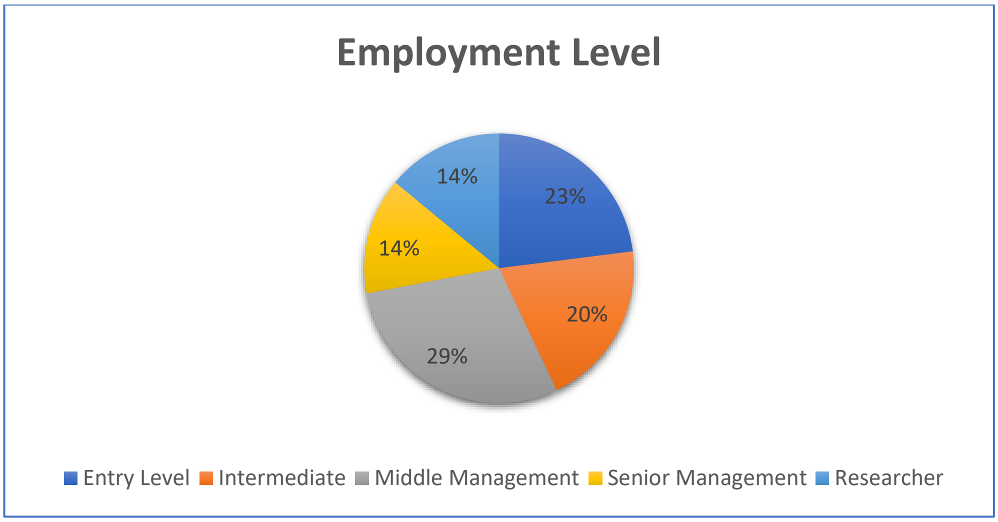


Figure 7 Employment level

4.2. Quality revolution adoption level

Figure 8 shows that at least 60% of the respondents indicated that their organizations had adopted Quality 3.0 (ISO standards, TQM, Lean and Six Sigma). Additionally, 15% and 10% of the respondents indicated that they utilized quality assurance and quality control (Quality 2.0 and 1.0, respectively). Only 15% of respondents indicated that their organizations had adopted Quality 4.0 methodologies.

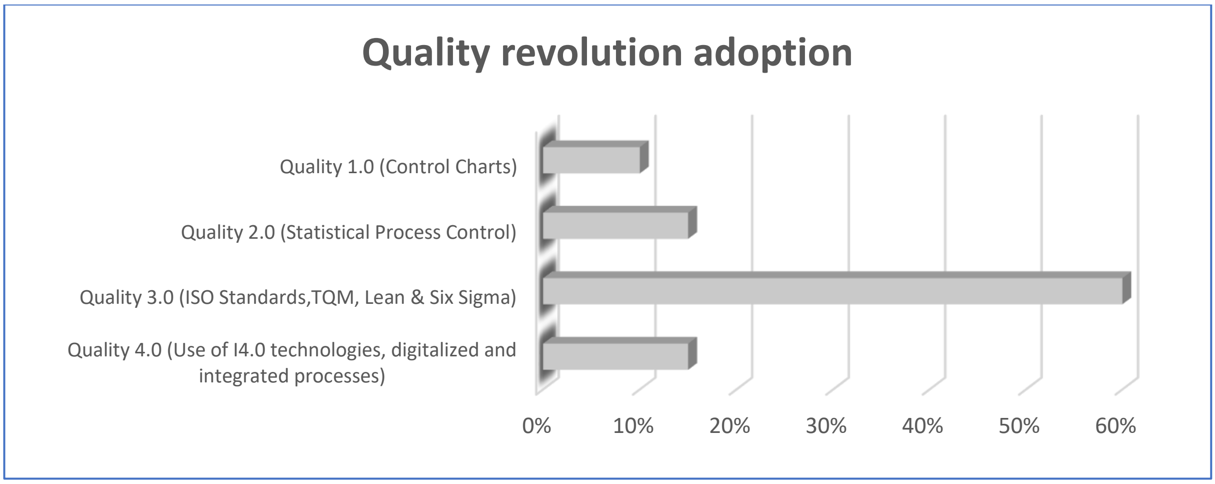


Figure 8 Quality revolution adoption

These insights are important as they illustrate that some organizations have already adopted Quality 4.0, while others are yet to embrace it. It is also important to note that all these organizations recognized the importance of quality management regimes, making the goal of transitioning to Quality 4.0 more achievable.

4.3. Maturity based on the people aspect

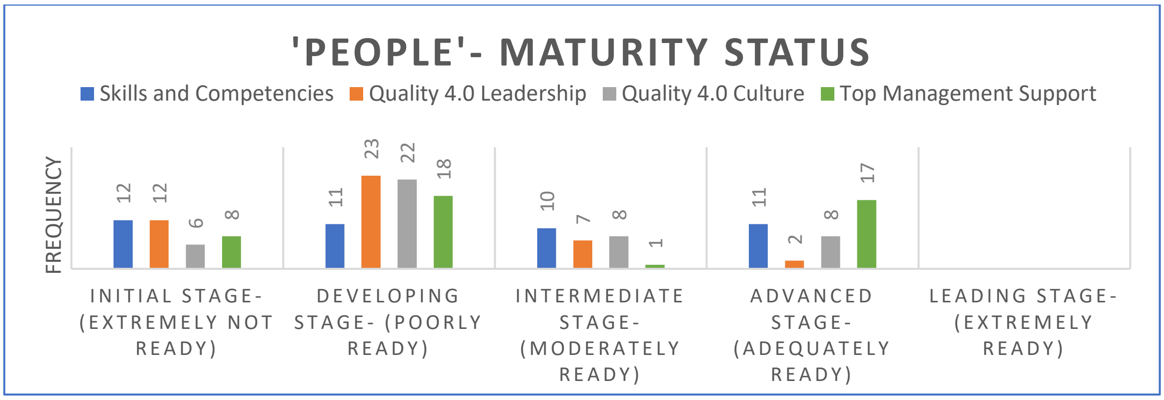


Figure 9 People aspect readiness

Figure 9 shows the collective evaluations of manufacturing stakeholders regarding the readiness of South African manufacturing firms to transition to Quality 4.0, specifically focusing on the people aspect. The figure illustrates the aggregated results of the Likert scale themes.

The histogram is mostly skewed to the ‘Developing stage’, highlighting that most respondents considered their organisations to be poorly prepared when looking at skills, leadership, quality 4.0 culture and top management support. Notably, most respondents, numbering 23, 22 and 18, perceived their organizations as poorly ready in crucial factors like Quality 4.0 leadership, Quality 4.0 culture and top management support, respectively. A noteworthy finding is that 23 respondents, when assessing the skills and competencies factor, considered their organizations to be poorly and extremely poorly ready to handle Quality 4.0 initiatives.

Nevertheless, some organizations exhibited an adequately ready people aspect, as indicated by 17 respondents, who expressed satisfaction with their organization's adequate top management support. Additionally, 11 respondents mentioned that their organization provides training for Quality 4.0, with their skills and competencies deemed moderately ready for Quality 4.0 initiatives. Moreover, 8 respondents highlighted the presence of an adequate Quality 4.0 culture among their employees. The factors of Quality 4.0 leadership, Quality 4.0 culture and top management support emerge as pivotal, with a significant portion falling within the poorly and extremely not ready categories. The data suggests that organizations have yet to enforce a Quality 4.0 culture, and that skills and competencies also present an opportunity for improvement.

4.4. Maturity based on the plant aspect

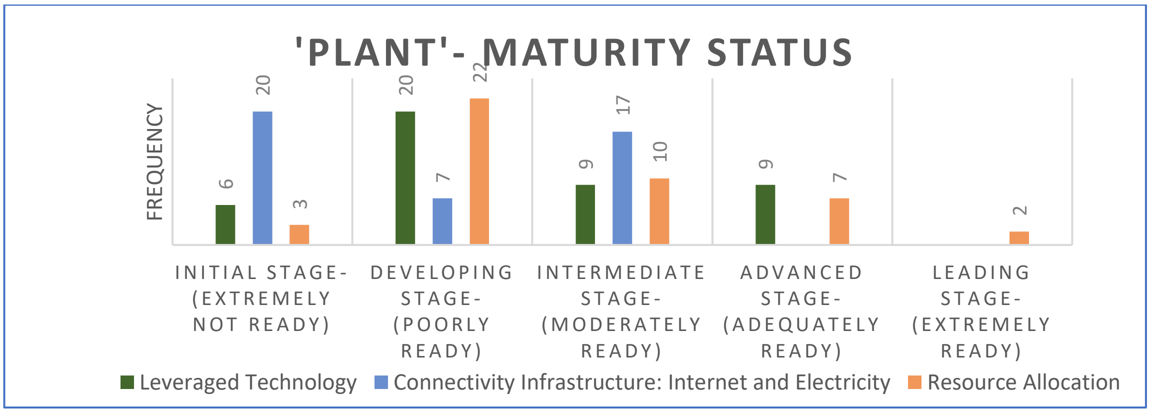


Figure 10 Plant aspect readiness

Figure 10 illustrates the readiness status of the plant aspect. Notably, a substantial majority of respondents (22) perceived their organizations as poorly ready in terms of making resources available for upgrading and maintaining the plant for Quality 4.0 initiatives. Another noteworthy observation is that 20 respondents indicated that their firms had not adequately leveraged modern technology, deeming their technology status as poorly ready for Quality 4.0.

Regarding connectivity infrastructure, a significant number of respondents (20) expressed that their organizations were extremely not ready for adopting Quality 4.0, possibly due to issues like unreliable internet access and electricity. Conversely, 17 other respondents reported that their firms had implemented measures to ensure a moderate level of maturity in connectivity infrastructure. Only 7 respondents indicated adequate readiness, assuring that their firms had implemented measures to allocate resources effectively for Quality 4.0 plants to be both effective and sustainable.

The factors under the plant category exhibit diverse levels of readiness. Connectivity infrastructure emerges as a critical consideration, with the majority falling into the extremely not ready and poorly ready categories. This suggests that although some work has been done, there is much room for improvement to ensure readiness in this aspect.

4.5. Maturity based on the ‘process’ aspect

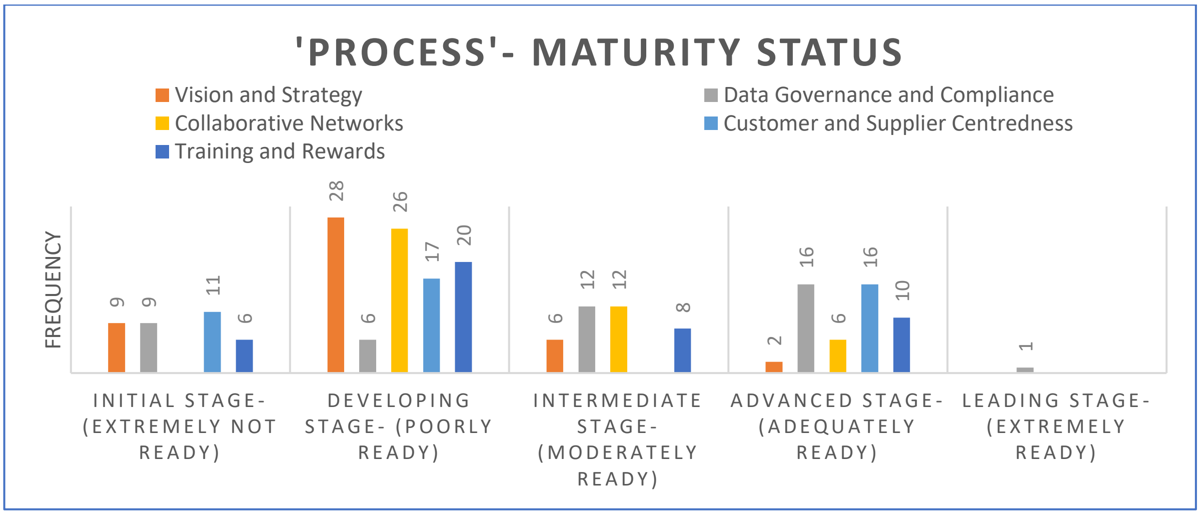


Figure 11 Process aspect readiness

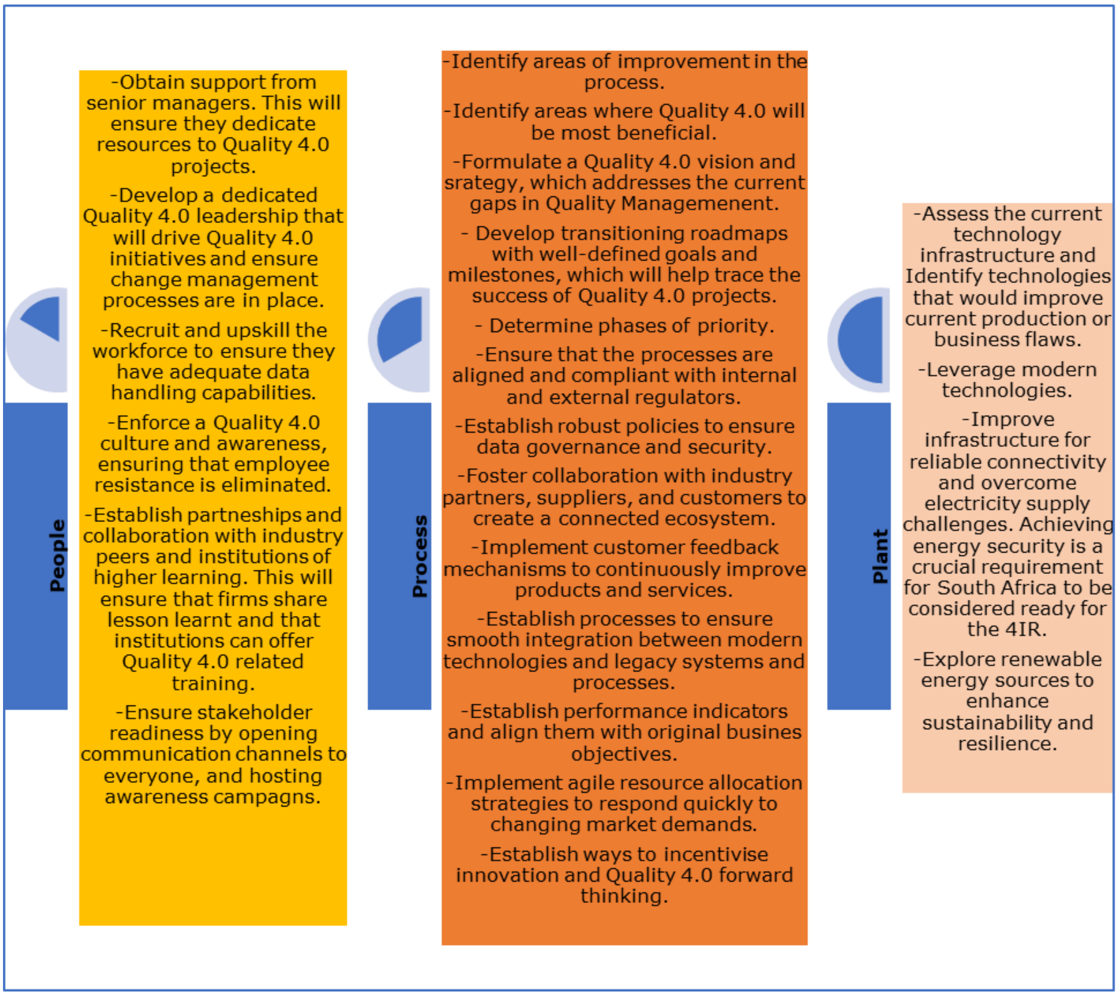
Figure 11 depicts the status of readiness for the process aspect for Quality 4.0 among South African manufacturing organizations. The figure illustrates that most themes tended towards the poorly ready measure. The data reveals that most respondents (37) believed that their organizations have a poorly and extremely poorly ready Quality 4.0 vision and strategy, contrasting with 6 respondents who indicated a moderately ready status. This suggests that the majority of organizations in South Africa have not identified the gaps between their legacy processes and where Quality 4.0 could take them. Without a clear vision and strategy, senior management will not be responsive to change, and the initiative may experience poor outcomes. Following closely, 26 respondents indicated that the existing collaborative networks were poorly ready to accommodate Quality 4.0 initiatives, against 12 respondents who indicated a moderately ready status. This is a major weakness since, without stringent collaborative network with industry peers, lessons learned cannot be shared, resulting in the same mistakes being repeated. Additionally, without these networks, organizations may not have access to external funding and external skills development programs. Furthermore, 26 respondents expressed dissatisfaction with the readiness of processes in place for training and rewarding employees, stating that they are poorly or extremely poorly ready. However, 8 and 10 respondents indicated moderately and adequately ready status, respectively. Customer and supplier-centred approaches were also considered poorly and extremely poorly ready for Quality 4.0 by a total of 28 respondents, contrasting with 16 respondents who found them adequately ready in their firms. This indicates that some organizations have started teaching their stakeholders about Quality 4.0 and have assessed the readiness of their stakeholders to support their transition.

Conversely, 12 and 16 respondents regarded their data governance and compliance processes as moderately and adequately ready, respectively. In contrast, 9 and 6 respondents indicated an extremely poor and poorly ready status, respectively, for this measure. This suggests that the majority of organizations show awareness and have measures in place to protect their data and that of their stakeholders, and that their processes are fairly compliant with regulations.

The results of this process analysis indicate that there are more weaknesses than there are strengths regarding this aspect, and it is necessary to build capabilities and ensure readiness before transitioning.

5 RECOMMENDATIONS

The previous section discussed the results of the survey, and identified all the factors that are a cause for concern per aspect. This section provides recommendations for ensuring that Quality 4.0 maturity is achieved in South African firms. Figure 12 captures all the actions to be followed to ensure Quality 4.0 readiness in all three aspects.



People

-Obtain support from senior managers. This will ensure they dedicate resources to Quality 4.0 projects.

-Develop a dedicated Quality 4.0 leadership that will drive Quality 4.0 initiatives and ensure change management processes are in place.

-Recruit and upskill the workforce to ensure they have adequate data handling capabilities.

-Enforce a Quality 4.0 culture and awareness, ensuring that employee resistance is eliminated.

-Establish partneships and collaboration with industry peers and institutions of higher learning. This will ensure that firms share lesson learnt and that institutions can offer Quality 4.0 related training.

-Ensure stakeholder readiness by opening communication channels to everyone, and hosting awareness campagns.

Process

-Identify areas of improvement in the process.

-Identify areas where Quality 4.0 will be most beneficial.

-Formulate a Quality 4.0 vision and srategy, which addresses the current gaps in Quality Management.

- Develop transitioning roadmaps with well-defined goals and milestones, which will help trace the success of Quality 4.0 projects.

- Determine phases of priority.

-Ensure that the processes are aligned and compliant with internal and external regulators.

-Establish robust policies to ensure data governance and security.

-Foster collaboration with industry partners, suppliers, and customers to create a connected ecosystem.

-Implement customer feedback mechanisms to continuously improve products and services.

-Establish processes to ensure smooth integration between modern technologies and legacy systems and processes.

-Establish performance indicators and align them with original busines objectives.

-Implement agile resource allocation strategies to respond quickly to changing market demands.

-Establish ways to incentivise innovation and Quality 4.0 forward thinking.

Plant

-Assess the current technology infrastructure and Identify technologies that would improve current production or business flaws.

-Leverage modern technologies.

-Improve infrastructure for reliable connectivity and overcome electricity supply challenges. Achieving energy security is a crucial requirement for South Africa to be considered ready for the 4IR.

-Explore renewable energy sources to enhance sustainability and resilience.

Figure 12 Recommendations for improvement

6 CONCLUSION

This study provides a comprehensive assessment of Quality 4.0 maturity within South African manufacturing organizations, employing the insightful 3Ps framework to scrutinize process, plant, and people aspects. The findings reveal nuanced insights into the current state of readiness for Quality 4.0 adoption. The results show that 60% of the organizations represented by respondents have adopted Quality 3.0; and only 15% are already embracing Quality 4.0. Notably, while the process dimension emerges as the most challenging area, with several key elements flagged for improvement, the plant aspect holds promise for transformative advancements. The people dimension presents both challenges and opportunities, emphasizing the critical role of human capital in digital transformation.

The identified areas of concern within process, including the poorly ready vision and strategy, collaborative networks, and training and rewards, underscore the necessity for strategic interventions in change management, collaboration, and employee development. Concurrently, the plant dimension's potential, particularly in leveraging modern technology, calls for proactive measures to bridge the current gaps and position organizations for Industry 4.0 success. The people aspect necessitates a dual focus on enhancing skills and competencies while cultivating effective leadership and top management support.

The study modified the 3Ps framework to assess maturity highlighting that as organizations embark on the journey toward Quality 4.0, it is imperative to consider the interconnected nature of these dimensions. A holistic approach that aligns strategic vision, technological infrastructure and workforce development is essential. Recommendations provided for process improvement, plant enhancement and people development offer actionable steps to navigate the challenges and capitalize on the opportunities identified in this study.

The successful transition to Quality 4.0 among South African manufacturing firms requires a strategic blend of process optimization, technology adoption and people-centric initiatives. Organizations are encouraged to embrace change, invest in advanced technologies and foster a culture of continuous learning and innovation. By addressing the specific areas identified in this study, South African firms can position themselves as resilient and adaptive entities in the rapidly evolving landscape of Quality 4.0.

Future studies could focus on utilizing the study's results and recommendations to develop a migration framework to guide manufacturing firms towards digital quality transformation.

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DEVELOPMENT OF A DATA ANALYTICS TOOL FOR INTERNAL AUDITING PRACTICES: THE CASE STUDY OF A HARNESS-MAKING COMPANY IN SOUTH AFRICA

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ABSTRACT

This study develops a data analytics tool to improve internal quality auditing within a South African harness-making company, enhancing decision-making processes. It analyses process audits and non-conformances from 2019 to 2023 using a mixed-method approach, combining quantitative data from the company's database with qualitative insights from interviews with internal quality auditors and auditees. Business Intelligence (BI) tools and Atlas Ti 23 software facilitated comprehensive analysis. Findings reveal that BI tools significantly improved risk management by identifying departmental strengths and weaknesses, prioritising audits, and optimising resource allocation. A BI-developed non-conformance dashboard provided valuable insights for strategic planning and employee performance evaluations, serving as a visual tool for corrective actions. Interviews confirmed that the company's adherence to the standard known as *Verband der Automobilindustrie*(VDA) 6.x standard, enhance audit effectiveness and readiness for external evaluations.

Keywords: Data Analytics, Internal quality auditing practices, Business intelligence (BI)

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1 INTRODUCTION

In today's fiercely competitive business landscape, maintaining top-notch quality standards is no longer an option but a necessity. Companies are striving to meet customer expectations and stay ahead in the competitive race. For a company seeking to supply the automotive industry, compliance with IATF 16949:2016 standards is a non-negotiable requirement. [1, 2].To meet this requirement, internal quality audits emerged as indispensable tools for businesses to measure the efficacy of their quality management systems and to identify areas for improvement[3].

1.1 The Significance of Internal Quality Audits

Nowadays, where we are experiencing advanced digital revolution and widespread adaptation of data analytics in many industries, most processes and applications generate data that can be leveraged to drive decision-making. Internal process audits create data that can be processed and analyzed using data analytics [4]. However, some organizations remain entrenched in traditional methods, where auditors analyze data and generate reports that address non-conformances and other opportunities for improvement. This method has several disadvantages, including tediousness, resource inefficiency, and low effectiveness. These challenges stem from the lack of utilization of data analytics and other technologies to enhance processes [5].

Furthermore, research shows that problems repeat and increase in the automotive industry. This leads some people to view internal quality audits as non-value-adding activities [3]. However, studies by Tulus and Dana [6] show the significance of weighted scores of internal audit outcomes in gauging compliance with automotive standards. Conducting a thorough analysis of these results is essential in informing decisions that safeguard companies against failing external audits. The issue lies not in the audit processes, but in how audit results are handled and how identified problems are communicated and addressed within the company.

1.2. Data Analysis

John [4] emphasized the critical role of effective communication when presenting data analysis results. This is particularly important when considering humans' cognitive limitations in processing vast information. When humans are bombarded with enormous amounts of information, they find it challenging to understand issues from written reports or numerical data. John argues that humans excel at understanding interrelationships between data sets through visual representations [5]. Visual representations facilitate better comprehension and retention of complex issues, thereby providing an in-depth insight into the daily operations of the business [4, 7].

This study presents a data analytics tool using visuals to aid decision-makers in making prompt decisions and help auditees understand deviation reports after audits. Focusing on internal process audits and non-conformances, the study employed Business Intelligence (BI) for quantitative analysis and Atlas.ti version 23 for qualitative analysis. The primary objective was to enhance the efficiency and effectiveness of internal audits using a BI dashboard, improving how participants prepare for audits and handle non-conformances, benefiting auditors, auditees, and stakeholders.

1.3 Case Company

Company X, a South African branch of a global firm since 1998, specializes in manufacturing vehicle cable parts, particularly wiring harnesses for bodies, cockpits, and audio systems. By 2024, it employed 615 people and supplied a specific harness type to an automotive client, adhering to VDA 6.X standard internal process audits since 2000. Due to a shortage of in-house auditors, the company relies on costly external auditors and managers. Challenges include unresolved non-conformances and limited proactive problem identification, compounded by inadequate technology use. This study aims to improve audit efficiency, optimize staff and technology utilization, ensure timely resolution of non-conformances, and promote proactive issue management.

1.4 The structure of the paper

The overall structure of this paper is presented as follows: section 2 provides the literature review, section 3 outlines our research methodology, section 4 presents the findings, section 5 discusses the results, and lastly, section 6 provides the conclusion.

2 LITERATURE REVIEW

ISO 9000, established by the International Organization for Standardization (ISO) in 1987 [8], sets the global standard for Quality Management Systems (QMS). It outlines five key principles: establishing a quality policy, documenting processes, defining roles and responsibilities, implementing control measures, and fostering continuous improvement with a focus on customer satisfaction [9].

This framework is universally applicable but industries like automotive and aerospace have developed standards that are more specific. For instance, ISO/TS 16949, now known as IATF 16949:2016, was created by the International Automotive Task Force (IATF) for the automotive sector, adding industry-specific requirements beyond ISO 9000's general guidelines [6, 10, 11].

This standard is mandatory for many automotive Original Equipment Manufacturers (OEMs) to ensure supplier quality. Another automotive industry standard is VDA6.x, originating in Germany and known for its detailed requirements [10, 14]. While VDA6.x was once prevalent, IATF 16949:2016 has become the global standard in the automotive industry [15].

Yulia [9] suggests that the VDA6.x standard was widely adopted in the automotive industry; however, IATF 16949 has now replaced it. Implementation and adherence to these standards not only enable companies to supply automotive parts but also offer benefits such as improved organizational practices tailored to customer needs [16].

2.1 Quality Audits

The necessity for independent verification to mitigate record-keeping errors, misappropriation, and fraud within the business prompted the establishment of audits [8]. ISO 9001:2018 defines a quality audit as a systematic and autonomous evaluation conducted to assess the conformity of quality activities and their outcomes with planned arrangements [9].Organisations can conduct three types of ISO 9000 audits: first-party, second-party, and third-party audits [7].

An organisation conducts a first-party audit to assess and improve its processes, systems, and compliance with internal and external policies and procedures. On the other hand, a second-party audit is conducted on a supplier by a customer to evaluate the supplier's capability to meet the customer's specific quality requirements and contractual obligations [3]. A third-party audit is an audit that a certification body auditor conducts[10]. A third-party audit is conducted to verify compliance with specific standards or regulations relevant to the industry or sector in question. Examples include ISO standards, industry-specific regulations, or legal requirements [3].

Of the three types of ISO 9000 audits mentioned above, first-party audits (internal audits) will be discussed in depth as this is the focus of this study. Internal audits can improve a company's performance [11].

The Institute of Internal Auditors [12] articulated the mission of internal audits as "to enhance and protect organisational value by providing risk-based and objective assurance, advice, and insight". Internal audits also serve as a cornerstone in ensuring the effectiveness of a company's Plan-Do-Check-Act (PDCA) cycle[13]. By providing independent and objective assessments, internal audits help validate the efficacy of each stage of the PDCA cycle, ensuring that processes are continuously monitored, improved, and aligned with organisational goals [1].

The automotive industry has three primary categories of internal audits: product, system, and process. Product audits assess samples of products in production or finished to determine if they meet the necessary criteria [9]. A system audit assesses a company's implementation of controls to govern a business process over extended durations [10]. A process audit involves analysing outcomes to assess whether the activities, resources, and behaviors that contribute to those outcomes are efficiently and effectively managed [14]. Process audits are often conducted on higher-risk processes to optimise operations, improve performance, and ensure alignment with strategic objectives[9].

2.1.1 Internal Quality Audits

Historically, internal audits aim to evaluate internal policies and procedures to ensure they adhere to the standards and expectations set by an organisation's customers [3]. They are also conducted to effect continuous improvement. Internal audits have long been recognised as a valuable aid to external auditing by verifying the internal control processes within an entity. According to Melinda and Szabolcs [11], they also assist management in understanding the entity's risks. Another noted benefit of these audits is that companies can offer guidance, recommendations, and value-added support based on the audit results [15]. The audit results consist of conformances and non-conformances identified during the audits. Deviations found during the audits are reported as non-conformities[9]. Conversely, conformance indicates that the organisation is adhering to the stipulated guidelines and regulations outlined in its internal procedures, policies, and guidelines and to external requirements specified by the industry, customers, and relevant standards [3].

2.1.2 Impact of Internal Quality Audits

Substantial efforts have been undertaken to incorporate best practices in internal quality audits and understand the implications of compliance, continually evolving standards, auditing methods, and the influence of technology on audits.

Researchers like Faudziah *et al.*,[16] sought to examine the extent of the internal audit department's auditing practices and the effects of the practices on the quality of the internal control. Their study suggested that internal auditing practices should comprise nine functions instead of the five functions suggested by the IIA (2000). The additional functions identified are objectivity, audit reviews, audit programs, and audit reporting.

Joe *et al.*[17] analyzed the independence of internal audit functions in Australian companies. They found that the freedom of internal audits is threatened by management, as management approves the budget for internal audits, and auditors depend on management for career growth. Stamatis [3] mentioned that the extent to which internal audit objectives are met depends on the maturity of management. The author added that there is sometimes mistrust towards auditing and its benefits to the company [3].

Chiarini *et al.*,[18] investigated the factors that are important for improving quality performance in Small medium Enterprises through internal audits. Their findings indicate that improving quality performance hinges on auditing key performance, economic, and financial indicators and controlling improvement initiatives. Top-management commitment and applying Lean Six Sigma and Total Quality Management (TQM) principles are also crucial.

2.2 Internal audit and technological advancement

Over the years, businesses have experienced numerous challenges, including labour shortages and the ever-evolving skill sets required of their workforce[19]. This scarcity of internal auditors can be attributed to several factors, including increased audit thresholds and greater scrutiny from regulators, which make the career path less attractive to high-quality candidates. Additionally, technological changes have prioritised IT skills, disqualifying many traditional auditors who are accustomed to paper-based audits and now need to utilise spreadsheets, audit software, and data analytics tools[20].

In response, efforts have been made to optimise labour across departments and introduce technology to assist humans in handling repetitive and time-consuming tasks [5]. The labour shortage in internal audit departments was initially addressed by integrating internal control systems. Auditors were certified to conduct audits under ISO 9000 and ISO 14000 simultaneously [21, 22]. Another way was using managers for internal audits [18]. These challenges are mitigated today through various technologies such as data analytics, machine learning, predictive analytics software, business intelligence platforms, big data, cloud computing, and artificial intelligence[5].

However, according to Zhou [5], the scarcity of labour and skills is not the sole problem confronting internal audits. There are inherent issues with the traditional audit process itself. These include tool limitations, low sampling accuracy, challenges in resource sharing, and overall low efficiency [5]. Recognising the weaknesses of traditional auditing methods, research has been directed towards exploring ways to enhance internal audits. For instance, Marcela's[23] research demonstrated how implementing robotic internal audits could streamline production, reduce operating costs, and prevent fraud opportunities in industrial beer production, leading to significant cost savings and reduced labour costs. Similarly, Toshiyuki et al. [15] developed a multi-criteria decision-making aid to help internal auditors prioritise high-risk business units within a corporation during an audit.

2.3 Data Analytics

In today's rapidly evolving landscape, decision-making necessitates the backing of either comprehensive knowledge or the utilisation of data analytics [24-26]. With the exponential growth of information and the increasing complexity of challenges, relying solely on intuition or traditional methods may no longer suffice [19]. Embracing data analytics empowers decision-makers to extract valuable insights from vast volumes of data, enabling them to make informed decisions grounded in evidence and analysis.

Data analytics can be divided into 4 categories: descriptive analytics, diagnostic analytics, predictive analytics and prescriptive analytics [27, 28] Descriptive analytics refers to the use of statistics and exploratory techniques to summarise and understand data, the analyses give answers about what happened [29]. Diagnostic analytics offers essential insights into the reasons behind a trend or relationship, helping professionals make data-driven decisions[30]. Predictive analytics forecast future values with the help of data mining methods and statistics to describe what may happen[29]. Prescriptive analytics employ statistical methods and quantitative analysis to data analytics to answer the questions of “What should I do?” and “Why should I do it?”[31].

Previous research findings suggest that data-driven decision-making results in better decisions, which ultimately leads to an increase in business performance [32-34]. To facilitate this process, various technologies are implemented, including machine learning algorithms, data visualisation tools, predictive analytics software, and business intelligence platforms. Among these technologies, Business Intelligence (BI) and analytics have gained popularity with many organisations because they provide technological capabilities for data collection, integration, and analysis [24]. Additionally, BI is preferred because it provides easily accessible and understandable insights to decision-makers through visuals.

2.3.1 Data Analytics Application in Internal Quality Auditing

In recent years, many companies have recognised the benefits of utilising data analytics in auditing. Data analytics and auditing technologies are being adopted to improve efficiency, effectiveness, and cost reduction [35]. These technologies are primarily used for data analysis and technology-based audits. In the early 2010s, commonly used technologies included software packages such as Microsoft Excel, Access, and Structured Query Language (SQL), as well as generalised audit software like Audit Command Language (ACL), IDEA, and Oversight[36] . Nowadays, more advanced technologies are being introduced, including data mining, data science, and robotic process automation for internal audits[19, 36, 37].

These advancements enable auditors to extract valuable insights from complex data sets, automate repetitive tasks, and enhance the overall audit process[19]. By leveraging data analytics, organisations can gain a competitive advantage through improved risk management, efficiency and audit quality[5]. Other benefits include avoiding manual errors and addressing the shortage of human resources. However, fully utilising these technologies requires auditors to have IT knowledge as an additional skill to use audit tools and techniques effectively[36]. It also demands significant investment in training auditors and implementing the necessary systems[23].

2.4 The research contribution

The study investigated the impact of data analytics, specifically business intelligence (BI), on improving internal audits and decision-making processes within a harness-making company in South Africa. The research was motivated by findings from Leticia, Guangxiu, and Hradecká[5, 23, 36], who stated that most exploration and research on the impact of new technologies on internal audits had been conducted by large auditing firms such as PWC and Ernst & Young. Recognising the lack of research and exploration of new technologies on internal audits in other firms, the aim was to enhance auditing practices and decision-making processes by utilising business intelligence technologies in a manufacturing environment. This is also supported by the Institute of Internal Auditors, who advocate adopting technology-based audits and other data analysis techniques [19]. To this end, Power BI was employed to analyse and visualise internal quality audit findings, enhance communication with auditees and enable stakeholders to make informed decisions promptly. The primary objective was to enhance the efficiency and effectiveness of internal audits using a BI dashboard, improving how participants prepare for audits and handle non-conformances, benefiting auditors, auditees, and stakeholders.

3 METHODOLOGY

A South African harness manufacturer with extensive internal audit experience was studied to improve auditing practices and decision-making. Qualitative and quantitative data were collected in parallel, enabling a comprehensive understanding of audit practices and identifying areas for improvement. The mixed-methods approach provided deeper insights into the company's auditing processes and decision-making strategies.

3.1 Quantitative Study

Quantitative data was extracted from 14 audit reports and 5 non-conformance log sheets from 2019-2023 were sampled via census, providing a large enough data pool. Data was extracted and organized into a new Excel table with columns including audit type, date, category, department, conformances, and non-conformances. Results were classified into critical, major, minor, and conforming categories using a scoring system and color-coding, with evaluation criteria presented in Table 1.

Table 1: Evaluation criteria for classifying audit results

Score Range	Category	Colour
0 to 4	Critical	Red
5 to 6	Major	Orange
7 to 8	Minor	Yellow
9 to 10	Conforming	Green

A similar approach for the non-conformance log sheets to extract the necessary information for our analysis. An Excel spreadsheet was created with the following columns: raised by, list of open points (LOP) date, LOP category, responsible, department, deadline, date completed, and date completed vs. deadline.

An Excel formula (formula 1) was used to classify the non-conformance completion notes as "Completed before the deadline," "Not completed on time," "Completed on time," or "In progress." This classification allows us to understand and evaluate how quickly the company addresses raised non-conformances.

IF(H3=0,"In progress",IF(H3>0,IF(I3<G3,"Completed before deadline!!",IF(I3=G3,"Completed on time",IF(I3>G3,"Not completed on time"))))) **(1)**

3.2 Data Analysis

After creating the spreadsheets in Excel, they were imported into Microsoft Power BI to clean and transform the data and make it suitable for visualisations. From the internal audits, all the conformances and non-conformances for all audits were summed up to provide an overview of the findings.

Using Power BI, visuals were created to communicate the audit results to management and auditees for decision-making. This helped them understand the findings through the emphasis on visuals. Slicers were used to filter the data based on the user's selection, allowing for dynamic data exploration. The same method was followed to develop the non-conformance dashboard, using visuals to communicate non-conformances to management, auditors and auditees.

3.3 Qualitative study

Qualitative data was collected through interviews with two internal auditors and four auditees using purposive sampling based on their roles. Auditees answered 10 questions about audit preparation and non-conformance handling, while auditors answered 12 questions on the same topics. The interviews provided insights into their perspectives and experiences, complementing the quantitative analysis of audit reports. This qualitative data helped identify where Business Intelligence (BI) can enhance auditors' and auditees' efficiency and ease their work

3.4 Data Analysis

The interviews were recorded and transcribed using Otter AI, an AI-powered meeting note-taker and real-time transcription service. After transcribing and editing the interviews, the transcriptions were imported into Atlas-ti version 23 software for analysis. Content analysis was used to analyse the qualitative data. The analysis allowed the researchers to quantify, categorize, and establish relationships within the qualitative data. Codes were created based on the two research objectives:

1. To understand the practices of auditees and identify areas where BI can help them prepare for audits and handle non-conformances.
2. To understand the practices of auditors and identify areas where Bi can help them prepare for audits and handle non-conformances.

The data was labelled using these codes and analysed to determine relationships between codes and frequencies within the categories. This systematic approach to content analysis enabled us to extract meaningful insights from the interview data, providing a comprehensive understanding of the auditors' and auditees' perspectives and experiences regarding internal audit practices.

4 FINDINGS

4.1 Quantitative results

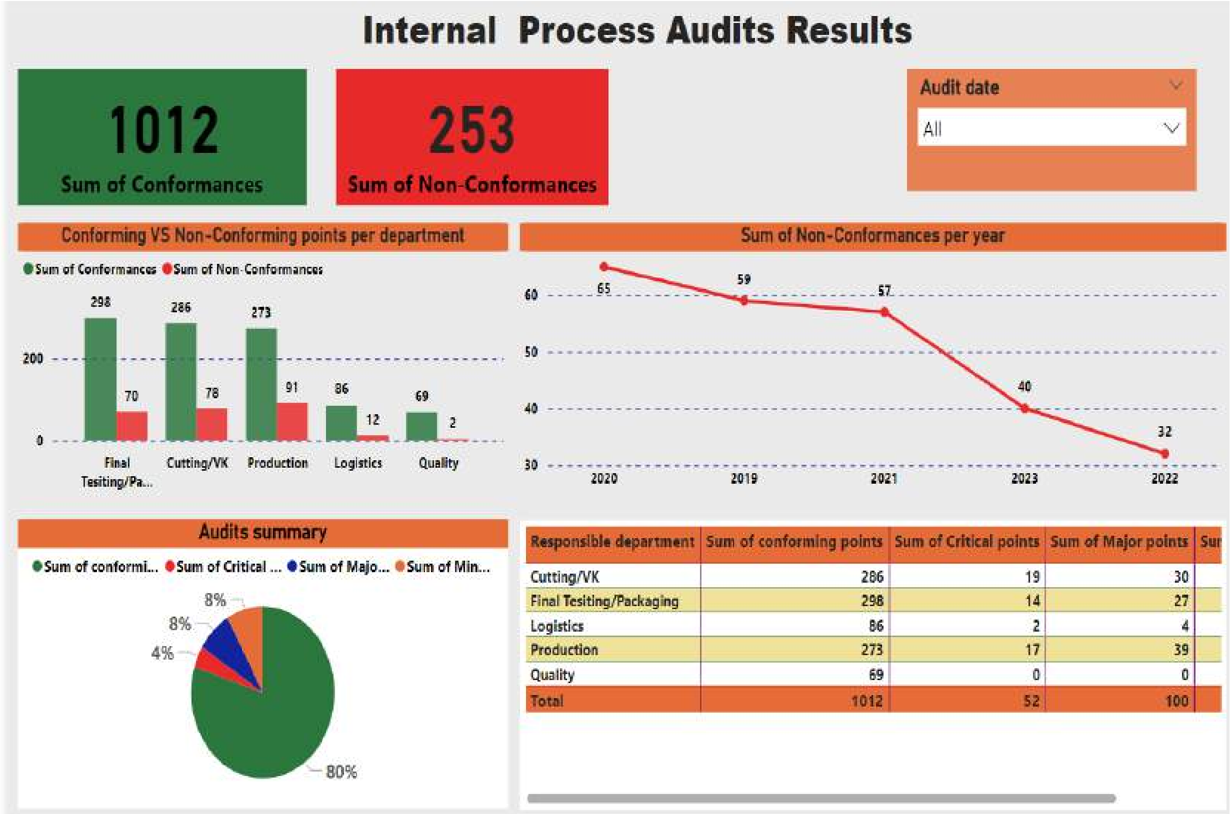
The company conducts internal process audits thrice yearly, except for 2020 when only two audits were performed. Thus, 14 internal process audits were analysed between 2019 to 2023. These audits covered three key areas: supplier management, process analysis, and customer care. The supplier management section had seven questions, the process analysis section had 28 questions, and the customer care section had five questions. The audit followed the VDA6.x standard, a customer requirement in the automotive industry.

During internal process audits, five departments were audited: logistics, cutting area, assembly, testing, and quality. The analysis showed that 80% of the audited points conform, and 20% are non-conforming. This indicates that the company's overall performance in internal process audits was good, according to the evaluation matrix shown in Table 2. This qualifies the company to obtain a certificate of cooperation and a permit to supply in the automotive industry[38]. The dashboard clarified where the company stands according to the matrix, allowing managers to take corrective measures quickly. These results demonstrate that business intelligence can improve the presentation of audit results and enable data-driven managerial decisions.

Table 2: Matrix for evaluation of the audit process

Result	Condition for the assessment of individual requirements	Corrective actions
“Green”	70% of individual questions were rated as satisfactory (marked in green)	Optimisation of selected areas should be self-performed
“Yellow”	At least 50% of individual questions were rated satisfactory (marked in yellow). None of the questions were assessed as unsatisfactory (marked in red)	Deviations or corrective actions will be described in the corrective action program
“Red”	At least 50% of individual questions were rated as satisfactory (marked in yellow), and / or at least one question was assessed as not satisfactory (marked in red).	Corrective actions are not sufficiently formulated.

Source: Materials of the enterprise



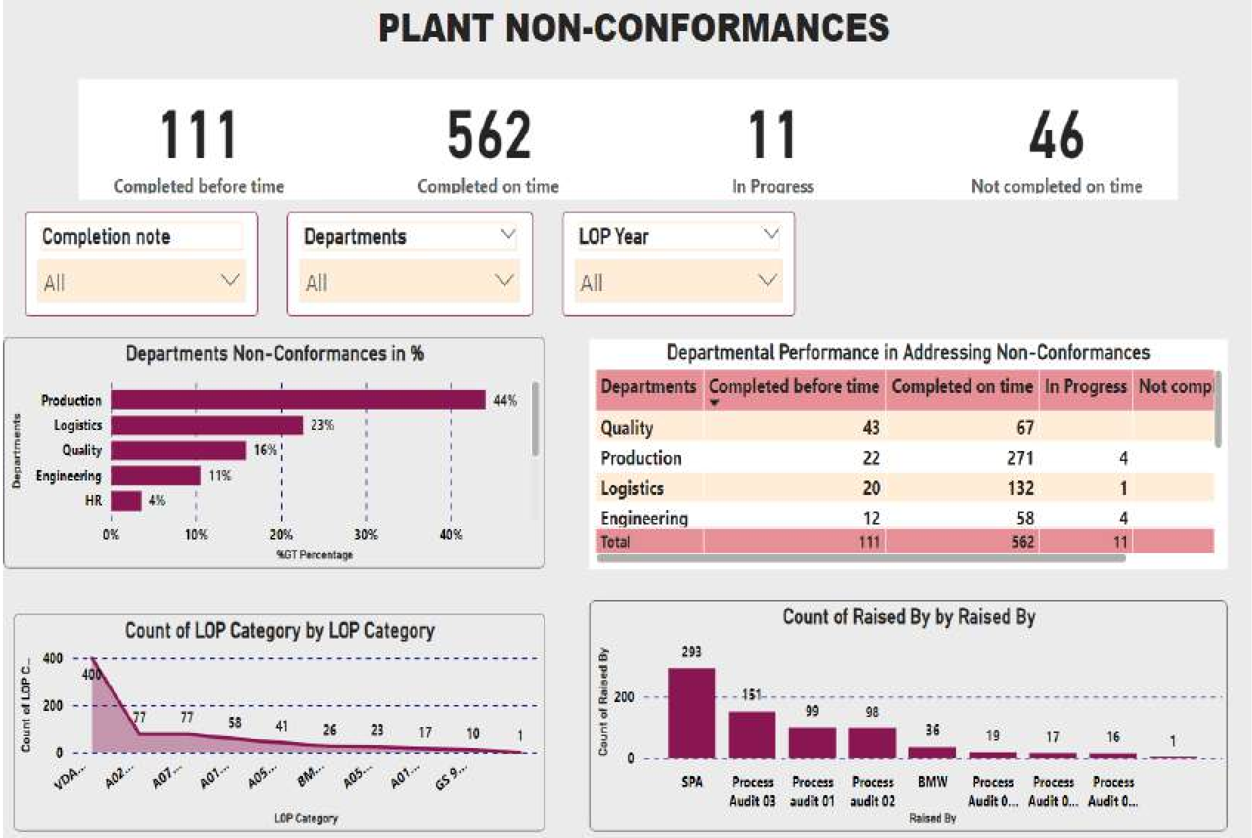
Responsible department	Sum of conforming points	Sum of Critical points	Sum of Major points	Sur
Cutting/VK	286	19	30	
Final Tesiting/Packaging	298	14	27	
Logistics	86	2	4	
Production	273	17	39	
Quality	69	0	0	
Total	1012	52	100	

Figure 1: Visual presentation of audit results

The detailed analysis revealed that the production department had the highest non-conformances (25%), followed by Cutting (21%) and Testing (19%). Yearly comparisons indicated that 2020 had the highest non-conformances with 65, followed by 2019 with 59, and 2022 with the lowest at 32. This fluctuation points to failure to follow FIFO principles, improper material storage, damaged and unidentified materials, failure to adhere to manufacturing processes, poor housekeeping, and employees' negligence or lack of understanding of 6S principles.

The inconsistent trend shows that current corrective actions may not be consistently effective, necessitating a re-evaluation of quality management processes and more robust strategies. After investigating the root causes, managers enforced employee discipline and recognised departments with improved housekeeping to drive improvement. The dashboard helps managers identify improvement areas and make data-driven decisions, while auditors can focus on critical issues in future audits to enhance their effectiveness in managing risk.

Based on the dashboard results, management decided to investigate the contributors to the highest non-conformances and assign special process auditors to departments lagging in addressing issues. Auditees could compare their results with other departments, facilitating prompt issue resolution. The production supervisor's lack of knowledge in conducting root cause analysis was a key contributor to high non-conformance. Figure 2 highlights that production had the highest non-conformances at 44%, while HR had the lowest at 4%.



Departmental Performance in Addressing Non-Conformances

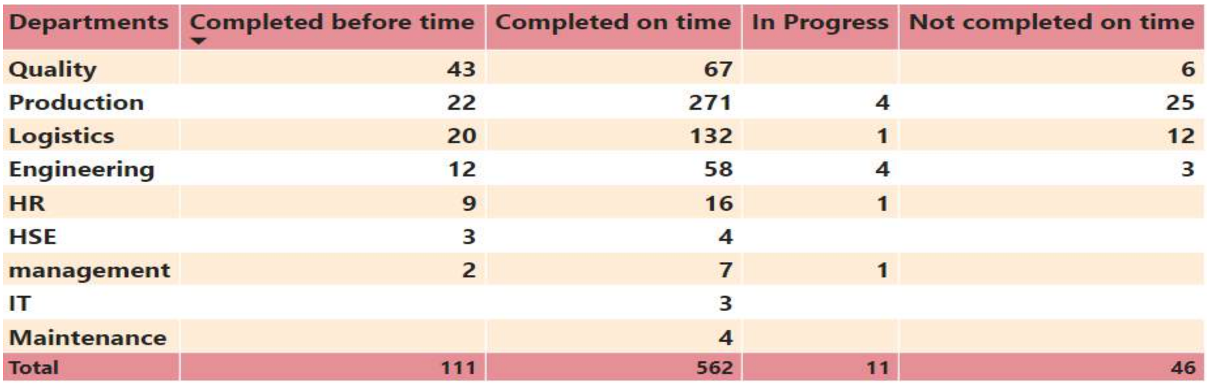
Departments	Completed before time	Completed on time	In Progress	Not comp
Quality	43	67		
Production	22	271	4	
Logistics	20	132	1	
Engineering	12	58	4	
Total	111	562	11	

Figure 2: Dashboard for overall non-conformances in a plant

Figure 2 dashboard offers insightful statistics on the sources of non-conformances within the plant, revealing which internal controls are most frequently associated with these issues. This information is invaluable for managers, as it highlights which audits are more effective in identifying problems. Consequently, it helps them discern between value-adding audits and those that do not contribute significantly, potentially leading to a reduction in the number of unnecessary audits.

The dashboard also provides a comprehensive overview of the status of non-conformances. It categorises them into those that are in progress, completed on time, ahead of schedule, or not on time. This clarity enables management to pinpoint departments requiring attention and support, recognise efficient teams in resolving issues, and provide targeted assistance to those falling behind. Table 3 further details these findings, emphasising the actionable insights drawn from the dashboard.

Table 3: Department Performance in Handling Quality Issues



Departments	Completed before time	Completed on time	In Progress	Not completed on time
Quality	43	67		6
Production	22	271	4	25
Logistics	20	132	1	12
Engineering	12	58	4	3
HR	9	16	1	
HSE	3	4		
management	2	7	1	
IT		3		
Maintenance		4		
Total	111	562	11	46

4.2 Qualitative results

The study included 6 participants - 4 production supervisors and two internal auditors. The supervisors had over two years of experience in their roles. The auditors were VDA 6.3 certified, qualifying them to conduct audits. Their expertise and certifications ensured that the perspectives and insights gathered from the interviews were well-informed and relevant to the study's objectives.

*4.2.1 **Auditor's** response on how they prepare and handle deviations.*

The audits are planned according to a schedule provided by the head office, and auditees receive email invitations well in advance. In preparation, auditors consider various factors, including management views, previous audit results, and customer complaints, to determine focus areas beyond the standard VDA 6.3 questions. Both auditors emphasized that recurring issues during audits were notably minimal and that internal process audits played a pivotal role in preparing them for external audits, which was commendable

This positive result can be attributed to the diligent efforts of auditees in addressing identified findings and the auditors' roles in verifying the effectiveness of corrective actions within 15 days. However, this process relies heavily on Excel spreadsheets. Auditors and auditees constantly check the spreadsheet to see if deviations have been closed and whether any new deviations have appeared. The interview also revealed that auditors often need to remind managers to implement corrective actions when the stipulated period has passed.

The use of spreadsheets to enter and track deviations was identified as an area where business intelligence could be utilized. Relying on spreadsheets posed risks of missing deviations and was time-consuming. Implementing a dashboard would allow deviations to be tracked in real-time, reducing the risk of oversight, and centralize all relevant data, making it easily accessible to all stakeholders. Figure 3 shows the network diagram of the analysis results.

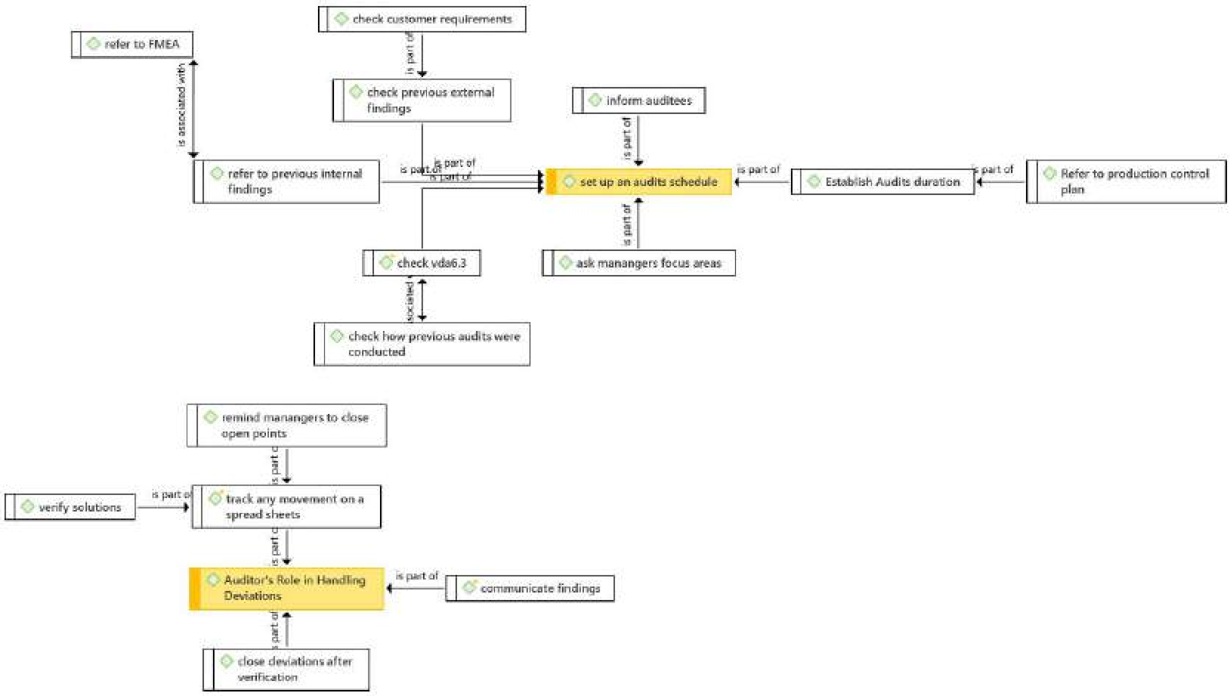


Figure 3: Auditors Analysis Results

*4.2.2 **Auditee’s response on how they prepare for audits and handle non**-conformances*

In audit preparation, participants checked staff qualifications, provided training, reported potential findings, informed teams, validated documents, closed past findings, and maintained housekeeping standards. From the auditees' perspective, the area identified for improvement was closing past findings. A dashboard was created to help the auditees understand and address deviations faster than going through detailed deviation reports. For handling non-conformances, all four auditees conducted root cause analyses, communicated findings to teams, shared responsibilities with leaders, and evaluated outcomes. Their dedication to continuous improvement contributed to the company's quality enhancement.

5 DISCUSSIONS

This study aimed to examine how data analytics can improve internal audit practices and the decision-making processes in which stakeholders are involved. Business intelligence (BI) was utilised to analyse audit results and communicate findings to stakeholders and auditees. Additionally, the study explored how BI tools can enhance the company's management of non-conformances, thereby effectively managing risk. Building upon the work of Leticia [36], this study established new value-added aspects of BI in internal audits, specifically in improved decision-making supported by data visualisations. The author identified the value proposition of internal audit's business intelligence to include risk management, cloud computing, data warehousing, operations, and balanced scorecards, all of which our study confirms as valid. These findings underscore the potential of BI to transform internal audit practices and support more informed decision-making across various organisational functions.

The results demonstrated the unique benefits of BI in the risk management process. The BI tool gave the company valuable insights, revealing that some departments excelled in handling non-conformances and quickly addressing them, while others struggled. This exposure enabled management and auditors to prioritise departments facing higher risk in their audits. The quality manager utilised these findings for objective resource allocation. These results can then be used for internal audit prioritisation and resource allocation. This expands and contributes to the study of Toshiyuki *et al*. [15]. This is another BI method in addition to data envelopment analysis (DEA) and analytic hierarchy process (AHP) that determines which business units require audit. The guidance from the analysis on prioritising departments for audits can enhance the effectiveness and efficiency of the audit process. Consequently, auditors can allocate more time to evaluate the effectiveness of corrective actions, as noted by Yining and Chen [19].

The results align with the findings of Marc *et al*.[35], who examined technology-based audit techniques' effectiveness, efficiency, and costs. They found that higher usage of Technology-based audit techniques is associated with improvements in the effectiveness and efficiency of audit work. Other researchers, such as [5, 19, 37] , also confirmed that applying technologies can effectively improve the efficiency and quality of internal audits. Therefore, the study contributes to the research concerning the use of technologies in internal audits and expands knowledge about BI and audits.

The results showed that the non-conformance dashboard can be used to gain business insights during annual meetings, as it shows quality performance yearly, thus helping management to set Annual Objectives Plans (AOP). The study results demonstrate that managers can use the dashboard to assess and reward high-performing departments, enhancing the company's Total Quality Management (TQM). The dashboard also served as a constant reminder for auditees to close non-conformances in their departments quickly. Different managers use dashboard visuals to communicate non-conformances to their staff and as a visual management tool. The study results proved that BI tools can be used to manage plant quality performance, thus contributing to manufacturing quality management research[39, 40]

The auditors and auditees were interviewed to understand how the studied company performs internal process audits and handles non-conformances. It was found out that VDA 6.x is the standard used in the company for internal process audits, following a process approach, and it is a customer requirement used to improve the firm's auditing system, conforming to previous finding [1]. Even though the process approach is not emphasised in the VDA series, the studied company followed it.

Previous researchers [22, 41-43] highlighted that internal audits prepare the company for external audits, and the study results confirmed the same. A recent study on automotive quality standards and their advantages has added to the body of knowledge on how internal audits enhance compliance and operational efficiency. This is consistent with findings that internal audits not only evaluate internal controls but also ensure organizations are well-prepared for external audit scrutiny, thereby improving the overall governance and risk management framework of the company [44, 45].

5.1 Implications for Practice

The study has considerable practical importance and makes several contributions. Business intelligence (BI) tools can significantly reduce the time needed to prepare presentations by revealing departmental strengths and weaknesses for stakeholders and utilising audit results for decision-making and employee feedback. The proposed data analytic tool can also serve as a criterion for employee appraisals. For auditors, using technology in auditing can save time when analysing and reporting findings. Dashboards help visualise plant performance, allowing auditors to prioritise areas during audits and ensure effective risk mitigation.

The study suggests evaluating the effectiveness of proposed solutions for non-conformances over 15 days to prevent recurring issues. Other auditors can adopt this practice. Additionally, BI tools improve resource allocation and audit planning by providing real-time data and insights, leading to more strategic audit scheduling and better risk management. Enhanced communication across departments fosters transparency and continuous improvement, promoting a proactive approach to quality and risk management.

5.2 Limitations and Future Research

The study's limitations offer opportunities for future research. Although the analysis of five years of internal audit data from a single company met sampling criteria, future studies could compare results across multiple companies to validate our findings. The developed decision-making tool lacks prescriptive analytics and root cause identification. This suggests an area that can be studied in future. In addition, integrating data analysis directly with auditing sheets could streamline visual creation. Beyond Power BI, exploring other technologies such as robotic process automation, Artificial Intelligence (AI), and machine learning may improve internal auditing practices across industries.

Future research could investigate the effectiveness of various BI tools, integrate machine learning algorithms to predict non-conformances, and suggest preventive measures. Studies could also examine the impact of BI tools on auditor training and performance, thereby enhancing analytical skills. Cross-industry research may reveal best practices and innovative approaches adaptable to different sectors, broadening the understanding of technological advancements in audit efficiency and effectiveness.

6 CONCLUSIONS

This study investigated the impact of business intelligence (BI) on internal audits and decision-making in a harness-making company. It found that BI tools significantly enhanced risk management by improving the identification of departmental strengths and weaknesses, prioritising audits, and optimising resource allocation. A non-conformance dashboard developed with BI provided valuable insights for strategic planning and employee performance evaluations, serving as a visual management tool for corrective actions. Interviews confirmed the company's adherence to the VDA 6.x standard, enhancing audit effectiveness and readiness for external evaluations.

The study's practical implications suggest that BI have a potential of saving time and improving decision-making by streamlining audit preparations and analyses. Limitations include the single-company focus and time-specific data, suggesting future research should explore broader applications. Enhancements to the BI tool could consist of prescriptive analytics and root cause analysis. Overall, the study underscores the potential of BI in improving audit processes and risk management, contributing to theoretical and practical advancements in the field.

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SOUTH AFRICA'S MINING INDUSTRY EXPERT'S OPINION ON TECHNOLOGY IMPLEMENTATION STEPS

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ABSTRACT

SA's mining industry is moving towards implementing Industry 4.0 technology. As a developing country, circumstances surrounding the implementation of this technology need to account for the unique circumstances of developing countries. While also learning relevant lessons from developed countries. Considerations required for developing countries are how the move to Industry 4.0 technology will affect people, including addressing workers' concerns and the broad communities the mines affect. Concerns include job security, worker safety and the environmental impact of mining. This study used a survey to solicit responses from SA's mining industry experts on a technology implementation roadmap. SA's mining industry was the basis for the roadmap development. The survey measured the experts' satisfaction levels with the roadmap. Results reinforced inclusions on the roadmap that experts agree with. While also shedding light on topics the experts disagreed with. Experts also provided additional areas the roadmap needed to cover.

Keywords: technology implementation, mining, South Africa, roadmap

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1 INTRODUCTION

The mining industry is increasingly embracing technology, which offers benefits such as money-saving, time-saving and reduced risks. Adopting technological innovations minimises waste and provides a competitive edge, as noted by [1]. Despite these benefits, there has been limited research on the challenges and facilitators of technology adoption in mining, highlighting the importance of such studies.

According to [2], there has been a rapid increase in digital twin technology use, which is transforming business operations to cut costs. A 2019 survey found that 75% of companies using the Internet of Things (IoT) have adopted digital twin technology [3]. Additionally, 13% were implementing this technology already, and 62% planned to do so within a year. Digital twin technology can simulate every product, process, or service aspect, enabling faster decision-making against traditional methods.

Developing countries like South Africa are seeking the benefits of implementing these new technologies in the mining industry. This paper used a survey on the steps necessary for applying these new technologies in the South African mining context. The survey questions were from the literature from other countries with similar experiences and those leading in this pursuit.

The study aims to develop a roadmap that South African mining companies can use when introducing new technologies, accounting for the unique circumstances specific to the country.

2 LITERATURE REVIEW

2.1 Pakistan's implementation

2.1.1 Awareness of Autonomous Mining Systems

Awareness of autonomous mining systems in Pakistan primarily comes from social networks, word of mouth, and academia [4].

2.1.2 Stakeholder preparedness

Pakistan's mining industry supports semi-autonomous and fully autonomous systems due to safety improvements, productivity, and cost reductions. However, concerns about knowledge gaps and unemployment persist. Many feel prepared for autonomous systems employment, though some do not. Most are willing to undergo training, but it is currently unavailable in Pakistan [4].

2.1.3 Impact of implementing autonomous mining systems

The main concern is unemployment. Proponents believe the government will support new technology due to its positive effects on GDP and productivity. Sceptics cite potential unemployment, political risks, labour unrest, and health and safety concerns [4].

2.2 India's implementation

The study, based on [5], identified several themes for technology adoption in India's mining industry:

1. Technology adoption must be an organisational initiative.
2. Reliable emerging technology providers are crucial.
3. Mining companies seek partnerships with proven technology providers.
4. The initial step is the digitalisation of mining data.
5. Public sector companies are slow to adopt technology due to job creation goals.
6. Strategies for long-term goals and technology implementation are misaligned.

7. Difficult geographical and geological conditions hinder technology adoption.
8. A shortage of skilled employees is a barrier.
9. Improved legal environments could expedite technology adoption.
10. Natural factors limit economies of scale in the Indian mining industry.
11. Bureaucracy and legal restrictions impede new technology implementation.
12. Data analytics and cloud computing are the most feasible technologies.
13. Solutions from developed countries often do not suit India, requiring unique solutions.
14. Managers prefer extracting total value from current technology before upgrading.
15. New technology affects the entire organisation.
16. New technology requires significant initial investments.
17. New technology must enable mining activities.
18. Technology providers must understand the economic context of mining companies.
19. Providers need to comprehend the geological and geographical conditions of mining.
20. The benefits of new technology are often unclear and need a better definition.
21. Organisational culture plays a critical role in technology adoption.
22. Mining managers often lack awareness of emerging technologies.
23. If new technologies solve current problems, adoption will increase.
24. Benefits like cost reduction, faster delivery, and better quality enhance adoption likelihood.

2.3 South Africa’s implementation

Key factors enabling technology implementation in South Africa include powerful political will, supportive culture, adequate funding, effective Intellectual Property Laws (IPL), robust partnership networks, market competition, high market demand, substantial R&D capacity, solid engineering capacity and access to natural resources. The absence of these factors hinders implementation [6].

2.4 Technology implementation roadmaps

Technology road mapping is identified as a well-known technique yet infrequently applied [7]. Technology implementation roadmaps are visual tools that align an organisation's technology strategy with its business strategy [8]. Successful implementation of these roadmaps requires setting clear, organisation-specific objectives that align with the company's culture [8]. The development process has three phases: Initial, Development, and Integration.

1. **Initial phase**: This phase involves gathering information for subsequent stages. Key stakeholders form a team to develop the organisation's technology implementation roadmap. Measure success by stakeholder acceptance of the customised roadmap.
2. **Development phase**: Data from internal and external sources is collected and analysed by stakeholders, who then present it in a roadmap format. This phase often requires multiple iterations. Measure success by the quality of roadmap content and the expertise contributed by stakeholders.
3. **Integration phase**: The roadmap integrates with business operations. Success measure is the roadmap's alignment with the business strategy, quality, and ongoing development.

Technology road mapping helps build consensus on technological needs, forecast technology developments, and plan future technology implementations [9]. A roadmap for Industry 4.0 technology in manufacturing with seven phases as follows [10]:

1. **DEFINE**: Identify problems and resource limitations. Develop a scope for Industry 4.0. Involve stakeholders and develop a transition team. Create detailed project plans and identify long-term, mid-term, and short-term strategies. Define skills and training needs and establish a change management strategy. Adapt the supply chain and legal framework to the new technology, including risk management strategies.

2. **MEASURE**: Gather data to understand and address the company's requirements using Quality Function Deployment (QFD) and Measurement System Analysis (MSA) to capture realistic views of process variations.
3. **EVALUATE**: Benchmark the readiness for Industry 4.0 technology, compare quality processes with market leaders, and develop new concepts using methods like FMEA and TRIZ. Use the Pugh matrix to identify the best design.
4. **OPTIMISE**: Build a detailed design using performance analysis software such as Anylogic and CAD tools like Autodesk.
5. **DEVELOP**: Build a prototype, evaluate hardware and software needs, and develop the prototype based on previous simulations without disrupting the production line.
6. **VALIDATE**: Test the prototype against the simulation model to mitigate risks and confirm expectations. Gather stakeholder feedback and conduct risk assessments.
7. **IMPLEMENT**: Implement the system, making adjustments where necessary. Focus on cost-saving, standardise processes and create a training plan for users. Continuously improve the system.

2.4.1 Roadmap of technology implementation in a generic industry

[11] developed a generic roadmap for technology adoption and divided it into three phases: analysis, goal setting, and implementation, which split further into six steps addressing production, purchasing, intralogistics, human resources, and sales.

1. Create Awareness: Involve employees and conduct a SWOT analysis.
2. Gather Data: Assess the company's capabilities to implement Industry 4.0 technologies.
3. Define Target States: Use techniques like morphological analysis and brainstorming with industry experts.
4. Draw Documents and Measure Evaluation: Evaluate differences between expectations and results, rating efforts and benefits.
5. Define Objectives: Establish the relevance and impact of objectives on the organisation.
6. Connect Projects with Budgets: Use pilot projects to gain experience and address early issues before full-scale implementation.

2.4.2 South African roadmap for Industry 4.0 implementation

[12] developed a roadmap for technology implementation in South African mines through a case study at the Wits Mining Institute (WMI). The roadmap's three phases with various challenges are as follows:

1. Pre-installation Challenges:
    - Identifying and selecting appropriate technologies
    - Budget overspending
2. Installation Phase Challenges:
    - Overspending
    - Delays in civil works
    - Poor system compatibility
    - System malfunctions
    - Unreliable communication systems
    - Faulty hardware design
    - Remote access restrictions
    - System integration issues
3. Post-installation Phase Challenges:
    - Poor after-sales support
    - Inadequate maintenance and upgradability provisions

The literature review covers technology implementation in Pakistan, India, and South Africa's mining sectors, with technology road mapping for Industry 4.0. Pakistanis and Indians show support for autonomous systems but face challenges like training availability and bureaucratic hurdles, respectively. South Africa benefits from political will and strong R&D, but some regions lack these advantages. Highlighted as critical was technology road mapping for aligning strategies and engaging stakeholders. Challenges include complex implementation phases and issues like budget overspending and system compatibility. Overall, the review stresses adapting global solutions to local contexts and continuous alignment with business strategies to maximise technology adoption benefits.

From the literature review on Industry 4.0 technology implementation and roadmaps, the researcher compiled a survey to be assessed by participants. The participants had experience with approaches suitable for South African mines. Therefore, they quantified whether the new roadmap would succeed in this context. A Appendix A: Survey questions shows the survey, and the methods used for designing this study's survey are in subsection 3.1 below.

3 METHODOLOGY

3.1 Survey design

Why surveys? Over the past 50 years, online surveys have become the most popular method for data collection in research, aligning with the rise of the internet [13]. This method is more convenient for gathering information, especially when surveyors and respondents are geographically distant. Online surveys allow respondents to participate at their convenience. This study used Google Forms for the survey, which stores responses in real-time, is free, and allows easy data export [14] - [17].

Surveys collect primary data through direct questions to respondents, measuring attitudinal data such as opinions, preferences, awareness, perceptions, and motivations. E-surveys are popular due to their autonomous data collection, low cost, wider reach, and current data [18]. They eliminate interviewer bias, give respondents more time, and ensure anonymity, resulting in more honest answers [15]; [16]; [18].

However, e-surveys have drawbacks, such as the lack of personal communication between respondents and researchers, no control over the collection procedure, low response rates, and no provision for clarity for respondents. Surveys must be simple and short, limiting the amount of data collected. There's also no control over who the final respondent is, increasing bias, and no opportunity for further probing [18]. Surveys need thorough testing before use. Researchers must ask only relevant questions, carefully considering the form, wording, and sequence of questions [13]. This study included Likert scale questions to assess respondents' views on a topic [19]. The survey was on a roadmap developed through the literature on adopting Industry 4.0 technology in the mining industry. The researcher aimed to test whether this new roadmap was sufficient for the South African mining industry. Google Forms online decimated the survey. Appendix [1] A. Ediriweera and A. Wiewiora, “Barriers and enablers of technology adoption in the mining industry,” Resources Policy, vol. 73, no. 1, pp. 1–14, Oct. 2021, doi: 10.1016/J.RESOURPOL.2021.102188.

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A Appendix A: Survey questions shows the questions in the survey. Based on the literature, the recurring subdivisions were three phases in the technology implementation. The three phases were pre-installation, installation, and post-installation. These three phases also had their subdivisions that the survey roadmap was quantifying. The survey amalgamated all the roadmaps in the literature survey and redesigned them into the new roadmap.

3.2 Sampling

The study used purposive sampling, a non-random (or non-probability) sampling method based on experience, common sense, expertise, and researcher intention [20]. The study used purposive sampling because it allows the extraction of information from a particular group of individuals, in this case, people familiar with technology implementation in the mining industry.

3.2.1 Type of purposive sampling

The study employed expert sampling, which gathers data from individuals with specific expertise. This sampling is helpful in situations involving high uncertainty [20]. Participants were experts familiar with implementing new mining industry technology (all respondents worked at a single mine). The experts chosen in this study varied in professions, from plant engineers, mining engineers, managers, artisans, supervisors, superintendents and health and safety officers. Their experience ranged from 0 to more than 40 years of experience. Additional information on the participant's demographic information, such as gender, age groups, years of experience in the mining sector and type of position held, can be found in B Appendix B: Respondents demographics information.

3.2.2 Snowball sampling

Snowball sampling supplemented the purposive sampling. This study applied the s-stage k-name Snowball sampling method by asking individuals identified in the purposive sample to name k additional individuals with the necessary expertise (technology implementation in mining). This process continued in stages until an adequate sample size was reached [21].

3.3 Strategies for survey validation and verification

Emphasising validity, generalisability, and reliability ensures that observed effects honestly reflect the causes. Valid results accurately represent the phenomenon under study, reliable results remain consistent across different contexts, and generalisable results hold across various conditions [22].

3.3.1 Survey pre-testing

Environmental triangulation involves testing findings across different settings to establish validity [23]. A pilot study pre-tested the survey with a smaller participant set [19]. The pre-test confirmed the survey's clarity, readability, and consistency. It also identified grammatical or punctuation errors [24]. Five participants unfamiliar with the study were used in the pre-testing to ensure the survey's validity and reliability [15]; [17]; [25].

3.3.2 Identifying outliers in multivariate analysis

The Mahalanobis measure calculates the distance from the mean centre of the overall observations in a multidimensional space used to identify outliers in the data [26]. The levels of significance chosen were 0.05 (5%). For small samples, the $\frac{D^2}{df}$ value should be 2.5, while for larger samples, it should be between 3 and 4 [26].

3.3.3 Statistical assumptions in multivariate analysis

In multivariate analysis, the crucial assumption is normality, which compares the distribution shape to the normal distribution [26]. Examining graphed plots and statistical normality tests, namely Kurtosis and skewness, were conducted. The $z_{skewness}$ statistic calculation follows the formula:

$$z_{skewness} = \frac{skewness}{\sqrt{\frac{6}{N}}} \quad , \tag{1}$$

The used $z_{critical}$ values are ± 1.96 for a 0.05 significance level. Similarly, $z_{kurtosis}$ is determined by:

$$z_{kurtosis} = \frac{kurtosis}{\sqrt{\frac{24}{N}}} \quad , \tag{2}$$

Homoskedasticity assumes equal variance levels across predictor variables [26]. Linearity, assessed with scatter plots, is essential for correlation-based measures.

3.3.4 Measuring internal consistency: The Cronbach Alpha

Cronbach's alpha measures internal consistency in multi-item scales [27]. The alpha calculation follows the formula:

$$\alpha = \frac{N}{N-1}\left(\frac{\sigma_X^2 - \Sigma_{i=1}^{N}\sigma_{Y_i}^2}{\sigma_X^2}\right) \quad , \tag{3}$$

where N is the number of surveys in the scale, σ_X^2 is the variance of the observed total scores and $\sigma_{Y_i}^2$ is the variance of items i for person y [27].

3.4 Factor analysis

Assumptions that go along with factor analysis include linearity, no outliers in the data, no multicollinearity, homoscedastic data, interval data and correlation between variables [26]; [28].

3.4.1 Determining the number of factors to extract

In **Kaiser's Criterion**, the eigenvalue of a factor indicates the amount of variance it explains. The study retained factors with eigenvalues greater than one as they signified a more common variance than the factors' variance. This method requires careful judgment due to potential sampling errors [26]; [28]. Factor loadings with values above 0.4 represent influence considered to meet the minimum levels to represent structure [26]. **The Scree test** graphically determines factors, with eigenvalues on the vertical axis and factor numbers on the horizontal. Factor extraction stops where the plot levels off or forms an elbow [26]; [28]. Rotating Factors and Interpretation Initial factor extraction is often complex due to cross-loading. Orthogonal rotation simplifies interpretation. Varimax reduces the number of variables with high loadings on each factor [26]; [28].

3.4.2 Factor analysis

Factor analysis extracts critical factors from a large set of variables. Confirmatory Factor Analysis (CFA) and Exploratory Factor Analysis (EFA) are the main factor analysis methods. EFA, used in early research stages, examines the interrelationships among variables [26]; [28]. Steps include assessing data suitability, extracting factors, and rotating factors for interpretation. Measures like the Kaiser-Meyer-Olkin (KMO) test and Bartlett's test for sphericity evaluate data adequacy for factor analysis [28].

$$KMO_j = \frac{\Sigma_{i\neq j} R_{ij}^2}{\Sigma_{i\neq j} R_{ij}^2 + \Sigma_{i\neq j} U_{ij}^2} \quad , \qquad (4)$$

where R_{ij} is the correlation matrix and U_{ij} is the partial covariance matrix.

$$\chi^2 = -\left(n - 1 - \frac{2p+5}{6}\right) \times ln|R| \quad , \qquad (5)$$

where p is the number of variables, n is the total number of sample sizes, and R is the correlation matrix.

3.4.3 Average Variance Extracted (AVE) and Composite Reliability (CR)

AVE measures the variance a construct explains versus measurement error, indicating convergent validity. CR assesses the correlation between multiple indicators of the same construct. AVE values ≥ 0.5 confirm convergent validity, and CR values > 0.6 are acceptable. If AVE < 0.5 but CR > 0.6, convergent reliability remains adequate [28].

$$AVE = \frac{\sum_{i=1}^{n} \lambda_i^2}{n} \quad , \qquad (6)$$

where λ_i are the loadings, and n is the number of items.

$$CR = \frac{\left(\Sigma_{i=1}^{n} \lambda_i\right)^2}{\left(\Sigma_{i=1}^{n} \lambda_i\right)^2 + \Sigma_{i=1}^{n} Var(e_i)} \quad , \qquad (7)$$

where $var(e_i)$ is the variance of error terms in the i^{th} item.

4 RESULTS

4.1 Likert scale responses

Figure 4-1 - Figure 4-3 show the respective summarised responses from the survey.

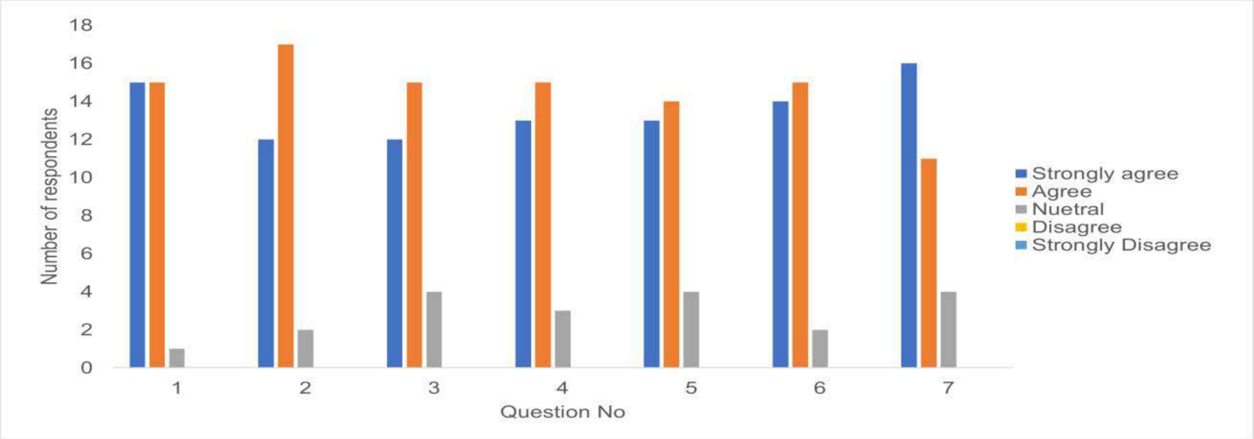

Figure 4-1: Responses to questions on the pre-installation phase.

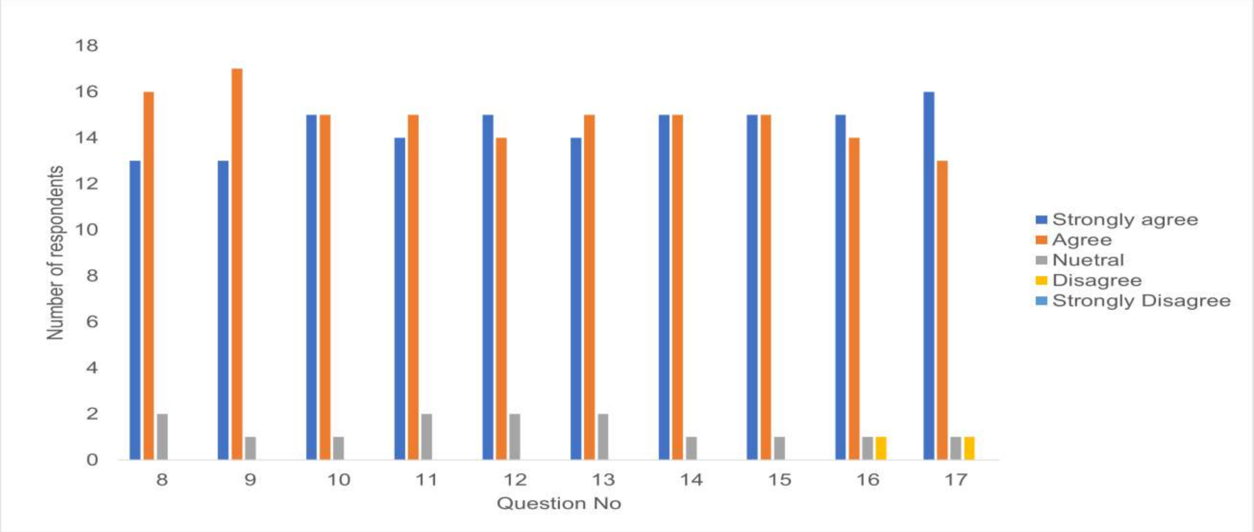

Figure 4-2: Responses to questions on the installation phase.

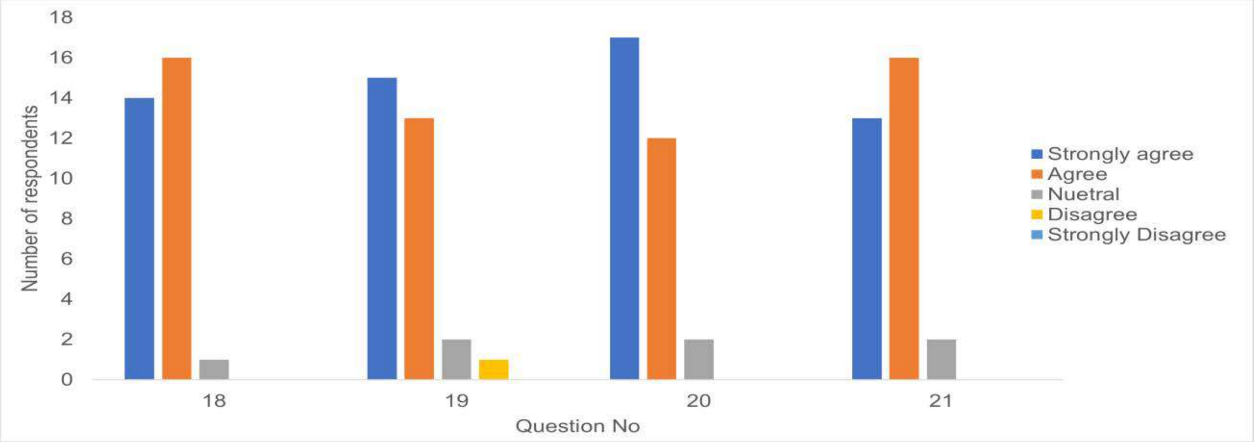

Figure 4-3: Responses to questions on the post-installation phase.

4.2 Identifying outliers in multivariate analysis

Results for the test for outliers in the survey responses are detailed in Figure 4-4 and Figure 4-5.

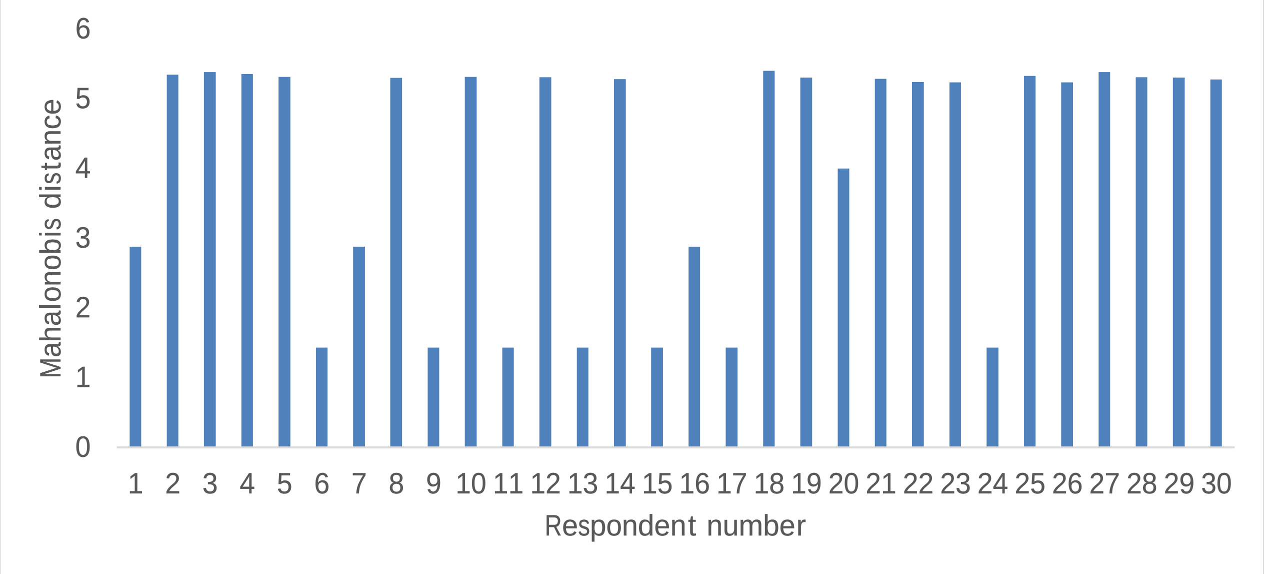

Figure 4-4: Mahalanobis Distance test for outliers.

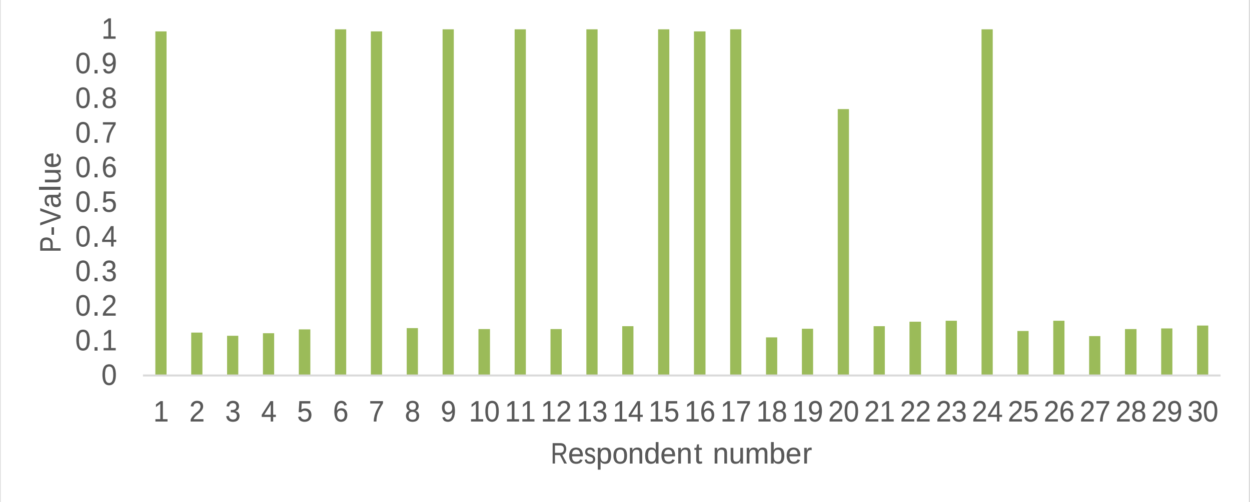

Figure 4-5: Corresponding P-values of respondents Mahalanobis Distance

Figure 4-4 and Figure 4-5 illustrate the Mahalanobis Distance and p-values of the respondents, respectively. All p-values were > 0.05, so the null hypothesis was false for all respondents.

4.3 Measuring internal consistency: The Cronbach Alpha

Table 1 lists the Cronbach Alpha values for the overall survey responses, responses relating to the pre-installation phase questions, responses relating to the installation phase questions and answers to the post-installation phase questions, respectively. The table details the confidence interval of Cronbach Alpha values at α = 0.05.

Table 1: Cronbach alpha test for internal consistency of survey.

	Cronbach Alpha	**Cronbach Alpha for pre-installation questions**	**Cronbach Alpha for installation questions**	**Cronbach Alpha for post-installation questions**

Alpha value	0.976	0.944	0.970	0.874
Confidence interval	[0.961, 0.987]	[0.907, 0.970]	[0.951, 0.984]	[0.781, 0.934]

4.4 Factor analysis

4.4.1 Skewness, Kurtosis, Spearman Average correlation, Mean and Standard deviation.

Table 2 details the results for the normality in the survey responses as Kurtosis. The skewness also shows how skewed the answers were around the mean. The average correlation details the average Spearman correlation coefficients between the Likert scale question responses.

Table 2: Summary statistics for all survey question results.

Question No	Skewness	Kurtosis	Z-Skewness	Z-Kurtosis	Average correlation	Mean	Standard deviation	Variance
1	-0.433	-0.822	-0.968	-0.920	0.709	4.467	0.571	0.326
2	-0.280	-0.656	-0.625	-0.734	0.663	4.333	0.606	0.368
3	-0.307	-0.800	-0.686	-0.895	0.670	4.233	0.679	0.461
4	-0.366	-0.706	-0.818	-0.789	0.708	4.300	0.651	0.424
5	-0.474	-0.851	-1.060	-0.951	0.653	4.300	0.702	0.493
6	-0.383	-0.670	-0.857	-0.749	0.600	4.367	0.615	0.378
7	-0.657	-0.781	-1.468	-0.873	0.668	4.367	0.718	0.516
8	-0.280	-0.656	-0.625	-0.734	0.641	4.333	0.606	0.368
9	-0.070	-0.863	-0.156	-0.965	0.727	4.367	0.556	0.309
10	-0.309	-0.882	-0.691	-0.986	0.755	4.433	0.568	0.323
11	-0.383	-0.670	-0.857	-0.749	0.722	4.367	0.615	0.378
12	-0.491	-0.643	-1.098	-0.719	0.761	4.400	0.621	0.386
13	-0.383	-0.670	-0.857	-0.749	0.757	4.367	0.615	0.378
14	-0.309	-0.882	-0.691	-0.986	0.669	4.433	0.568	0.323
15	-0.309	-0.882	-0.691	-0.986	0.713	4.433	0.568	0.323
16	-1.224	2.004	-2.738	2.241	0.654	4.367	0.718	0.516
17	-1.309	2.102	-2.926	2.351	0.732	4.400	0.724	0.524

18	-0.188	-0.896	-0.421	-1.002	0.573	4.400	0.563	0.317
19	-1.109	1.200	-2.480	1.342	0.590	4.433	0.758	0.575
20	-0.720	-0.463	-1.609	-0.518	0.641	4.467	0.629	0.395
21	-0.280	-0.656	-0.625	-0.734	0.649	4.433	0.606	0.368

4.4.2 Linearity of the data

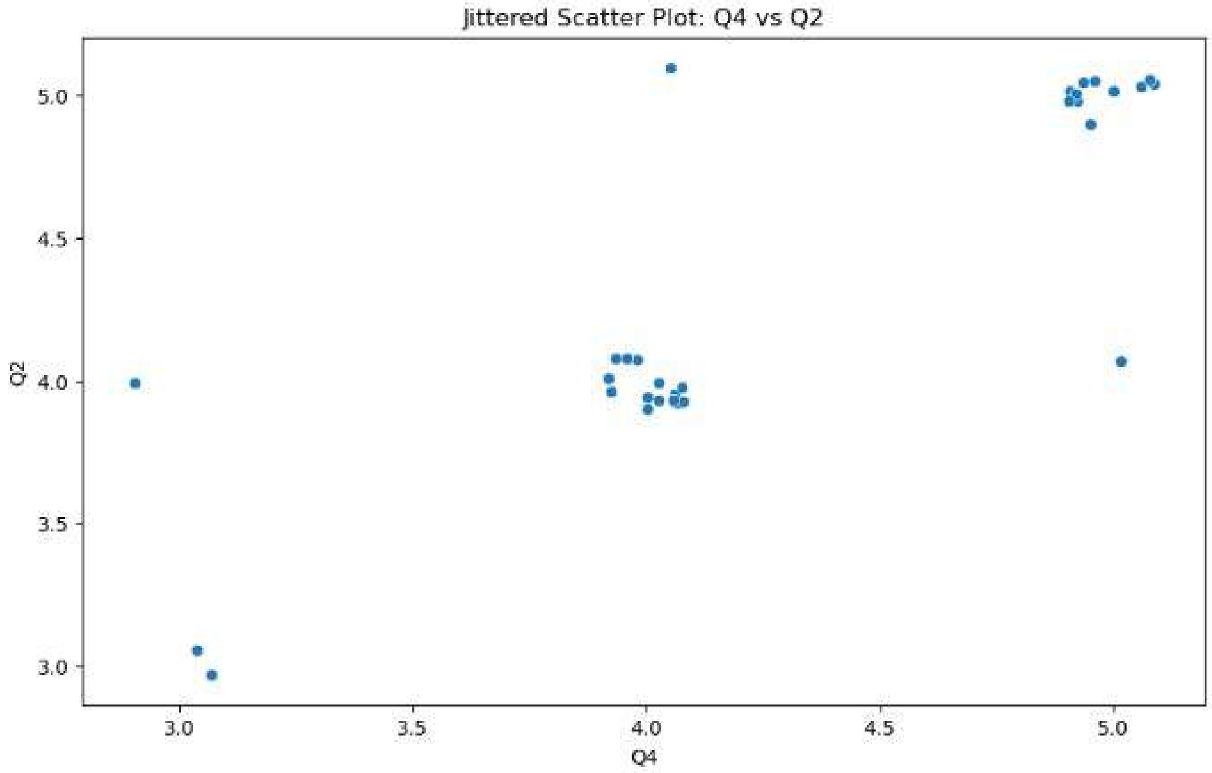

Figure 4-6: Jittered scatter plot for Q2 vs Q4.

Figure 4-6 above shows the Jitters scatter plot of Question 2 against Question 4 of the Likert survey responses. Many other plots similar to the above are available (not included because of space constraints), and the plots displayed above were selected randomly for analysis.

4.5 Factor analysis

4.5.1 KMO measure of sampling adequacy and Barlett test for sphericity

The Kaiser-Meyer-Olkin (KMO) value for the Likert scale questions in the survey, their corresponding chi-square statistic value and their p-value are in Table 3.

Table 3: KMO value for the model and significance.

KMO model value	**Chi-Square value**	**p-value**	**Is p-value < 0.05**
0,716	696.110	2.060×10^{-53}	Yes

4.5.2 *Scree Test for Eigenvalues*

The Scree plot of Eigenvalues of all factors is in Figure 4-7. This figure shows eigenvalues for each question, with questions having eigenvalues greater than 1 being influential factors.

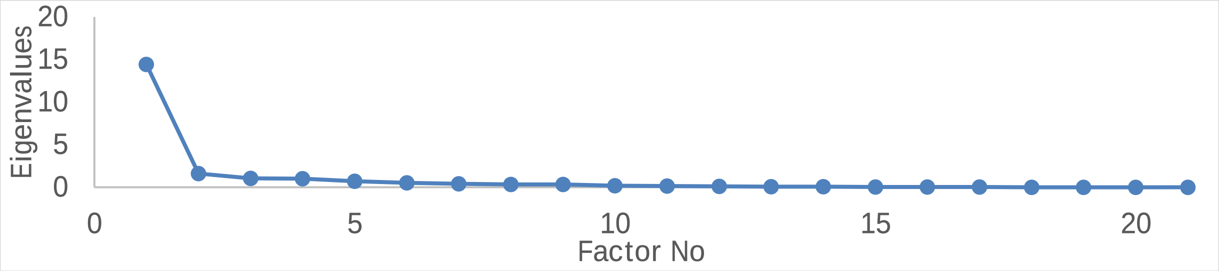

Figure 4-7: Scree plot of Eigenvalues of all factors.

4.5.3 *Factor loadings*

The factors loadings for Likert-scale responses having eigenvalues of more than one (>1) are detailed in Table 4 below.

Table 4: Factors, their corresponding loadings and influence on each question.

Question No	Factor1	Factor2	Factor3	Factor4	Factor 1 affects question	Factor 2 affects question	Factor 3 affects question	Factor 4 affects question
1	0.365	0.478	0.409	0.496	Yes	Yes	Yes	Yes
2	0.650	0.186	0.394	0.443	No	Yes	Yes	Yes
3	0.799	0.358	0.285	0.049	Yes	No	No	Yes
4	0.739	0.304	0.447	0.177	Yes	No	No	No
5	0.918	0.172	0.200	0.204	Yes	No	Yes	No
6	0.655	0.281	0.002	0.413	Yes	No	No	No
7	0.613	0.310	0.252	0.347	Yes	No	No	Yes
8	0.207	0.879	0.225	0.090	Yes	No	No	No
9	0.462	0.787	0.186	0.263	No	Yes	No	No
10	0.387	0.684	0.350	0.379	Yes	Yes	No	No
11	0.379	0.552	0.526	0.310	No	Yes	No	No
12	0.539	0.464	0.516	0.326	No	Yes	Yes	No
13	0.377	0.736	0.480	0.227	Yes	Yes	Yes	No
14	0.214	0.688	0.305	0.424	No	Yes	Yes	No
15	0.430	0.592	0.454	0.179	No	Yes	No	Yes
16	0.497	0.345	0.679	0.029	Yes	Yes	Yes	No

17	0.532	0.317	0.692	0.188	Yes	No	Yes	No
18	0.291	0.277	0.180	0.787	Yes	No	Yes	No
19	0.108	0.320	0.675	0.242	No	No	No	Yes
20	0.355	0.213	0.576	0.553	No	No	Yes	No
21	0.092	0.575	0.535	0.483	No	No	Yes	Yes

4.5.4 Average Variance Extracted (AVE) and Composite Reliability (CR)

Table 5 shows the variance, proportional variance, CR and cumulative variance of the factors with factor loading eigenvalues of more than one in the Scree plot.

Table 5: Factors, their variance and composite reliability.

	Factor 1	Factor 2	Factor 3	Factor 4
Variance	5.361	5.207	4.034	2.749
Proportional Variance	0.255	0.248	0.192	0.131
Cumulative Variance	0.255	0.503	0.695	0.826
Composite Reliability (CR)	4.397	4.397	4.397	4.397

5 DISCUSSION

5.1 Identifying outliers in multivariate analysis

None of the respondents were outliers because the Mahalanobis distances P-values (significance values) were all > 0.005. That meant all responses were suitable for use in the analysis. The Mahalanobis distances divided by the degree of freedom ranged between 0.068 and 0.257. That is lower than the threshold of 2.5 used to determine outliers for small samples [26].

5.2 Measuring Internal Consistency: The Cronbach Alpha

The overall Cronbach Alpha value for this study was 0.976. That meant the Likert scale questions responses internal consistency in the survey were internally consistent. In addition to the internal consistency of the overall Likert questions, the three sections, namely pre-installation, installation and post-installation, were also checked for internal consistency. Their Alpha values were 0.944, 0.970 and 0.874, respectively and were considered internally consistent.

5.3 Linearity of the data

One of the assumptions made for the factor analysis was a linear relationship between the Likert scale results. This assumption was tested by visually comparing the Jitter plots of the different questions. For example, in Figure 4-6, most of the answers were the same in Q2 and Q4, with only two exceptions where a respondent gave a 4 for Q2 and a 5 for Q4 and vice versa, leading to the assumption that a linear relationship existed between the two questions. Similar Jitter plots of a combination of questions all indicated linear relationships. It was, therefore, concluded that the Likert question in the survey had a linear relationship.

5.4 Factor analysis

5.4.1 Normality of the data

The following is a summary of the results for the normality and skewness test of the Likert scale questions in the survey. Testing was at significance values at $p < 0.05$.

- Q1 - Q6, Q8 - Q 15, Q18, Q21: Approximately symmetric. Kurtosis indicates approximately normal.
- Q7, Q20: Moderately skewed. Kurtosis indicates approximately normal.
- Q16 - Q17, Q19: Highly skewed. Kurtosis indicates a high deviation from normality.

That confirms normality for all the questions except Qs 16, 17 and 19. These questions also showed high skewness. It is safe to assume that the data follows a normal distribution.

5.4.2 KMO measure of sampling adequacy and Barlett test for sphericity

The KMO value calculated was 0.716, meaning the survey responses had adequate sampling [26]; [28]. Since the p-value corresponding to Bartlett's Test of Sphericity in Table 3 was less than 0.05, confirming Homoskedasticity, factor analysis was worth pursuing [26];[28].

5.4.3 Scree Test for eigenvalues

From Figure 4-7, only four factors had Eigenvalues > 1. That meant these four factors affected Likert scale responses significantly. Subsubsection 5.4.4 below lists the four factors.

5.4.4 Factor loadings

In factor analysis, appropriate names should reflect the underlying theme or concept that groups the questions. Based on the questions and their associated factors, the following four were the names of the factors chosen:

- Strategic Planning and Management;
- Technological Assessment and Implementation;
- Stakeholder and Expectation Management; and
- Legal and Contractual Compliance.

The reasoning behind these names is based on Table 4 factor loadings:

- **Strategic Planning and Management**: This factor encompasses questions affecting the overall planning and management processes required to ensure the project's success. The tasks involve high-level strategic decisions, risk management, and continuous oversight of the project.
- **Technological Assessment and Implementation**: This factor includes questions focusing on the technical aspects of the project, such as identifying technological needs, evaluating technical options, and implementing technology solutions.
- **Stakeholder and Expectation Management**: This factor is centred around understanding and managing the expectations and needs of various stakeholders, ensuring their requirements are met, and maintaining effective communication and support throughout the project.
- **Legal and Contractual Compliance**: This factor pertains to the legal and contractual obligations fulfilled throughout the project. It involves drafting agreements, ensuring compliance with legal requirements, and managing contracts.

These names succinctly captured the essence of the grouped questions, making it easier to understand the focus areas of each factor in the factor analysis.

5.4.5 *Average Variance Extracted (AVE) and Composite Reliability (CR)*

The four factors listed in the factor analysis above, accounted for 82,6% of the variance in responses.

The AVE values were 0.255, 0.248, 0.192 and 0.131 respectively. Their respective CR values were 4.397, 4.397, 4.397 and 4.397. Since all the AVE values for the factors were < 0.5, but their respective CR values were > 0.6, convergent reliability was adequate.

5.5 Likert scale responses

From Figure 4-1, Figure 4-2 and Figure 4-3, the respondents mostly agreed or strongly agreed with the implementation steps outlined on the survey's new proposed roadmap. That is also confirmed by Table 2 where the means for responses to each question range from 4.300 to 4.467, which are between agree (4) and strongly agree (5) on a Likert scale. The standard deviations also had a low range between 0.556 and 0.758 (less than a standard deviation from the mean). The variance ranged from 0.309 to 0.575, confirming the Homoskedasticity assumption.

The study conducted a rigorous analysis of data related to technology implementation in the mining sector, covering various aspects such as outlier identification, internal consistency, data linearity, and factor analysis. The Mahalanobis distances confirmed no outliers, ensuring the robustness of the dataset. High Cronbach Alpha values (0.976 overall and ranging from 0.874 to 0.970 across the three phases of Likert scale questions) indicated internal consistency among Likert scale questions. Visual inspections and statistical tests affirmed the linearity of Likert questions, supporting the assumption of a linear relationship. Factor analysis revealed four significant factors—Strategic Planning and Management, Technological Assessment and Implementation, Stakeholder and Expectation Management, and Legal and Contractual Compliance, explaining 82.6% of variance with good reliability. Most respondents agreed or strongly agreed with the implementation steps outlined, backed by low standard deviations and variance, suggesting consistent perceptions among respondents. These findings underscore the reliability and comprehensiveness of the study's data analysis methods in assessing technology adoption in the mining industry.

5.6 Limitations of the study

- A small sample size from a single mine was used for the analysis, limiting the generalisability of the findings across South African mines.
- The high Cronbach Alpha values suggest internal consistency, but they do not account for the possibility of overly homogeneous responses that might not truly reflect the diverse views of the population.
- Confirming the linearity assumption was through visual inspection of Jitter plots. However, visual inspection can be subjective and may not be as reliable as more rigorous statistical tests for linearity.
- While most questions showed approximately normal distributions, questions 16, 17, and 19 exhibited high skewness and Kurtosis deviations from normality. That indicates that the assumption of normality might not hold for all data points, potentially affecting the validity of factor analysis results.
- The study does not delve into demographic differences that could influence responses, such as gender, age, years of experience, and type of mining experience, limiting the generalisability of the findings across different demographic groups within the mining industry.
- The study relies heavily on self-reported data from survey respondents. This data type can be subject to biases such as social desirability bias, where respondents may answer in a manner they believe is more socially acceptable or favourable rather than

providing their actual opinions or experiences. That can potentially skew the results and affect the accuracy and reliability of the findings [29].

6 CONCLUSION AND RECOMMENDATIONS

6.1 Conclusions

The study utilised quantitative methods for data collection and analysis. The survey consisted of questions based on the literature on roadmaps for technology implementation in the mining or similar industry. An online Google Form collected data. The participants purposively sampled with expertise in implementing technology in the mining industry. To ensure data validity and reliability, triangulation, pre-testing, and constant comparisons were pursued through the data collection. The researcher tested statistical assumptions made for analysis, such as linearity, normality, no outliers and correlation between the data. Statistical testing and visual inspections confirmed all assumptions. Internal consistency was measured using Cronbach's alpha. Factor analysis was employed to refine survey questions and ensure the robustness of the findings. The factor analysis yielded four factors which each question in the survey fell under, namely:

- Strategic Planning and Management
- Technological Assessment and Implementation
- Stakeholder and Expectation Management
- Legal and Contractual Compliance

These factors accounted for a majority of the variance. The actual means of the Likert scale responses ranged from 4.300 to 4.467 (four on the Likert scale meant the participant agreed with the step in the survey roadmap, and five on the Likert scale meant they strongly agreed with the step).

6.2 Recommendations

- Develop a new roadmap that includes the four identified factors (Strategic Planning and Management, Technological Assessment and Implementation, Stakeholder and Expectation Management, and Legal and Contractual Compliance). Highlight critical elements within each factor and integrate qualitative responses from experts to include necessary additional steps.
- Analyse demographic data collected from the survey, including gender, age, years of experience, and type of mining experience. Check for differences in these demographics not included in this initial study.
- Expand the participant pool to include representatives from multiple mining companies in South Africa. Ensure that the new data collection supplements the existing dataset and aims to generalise the study's conclusions to the entire South African mining industry.

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A APPENDIX A: SURVEY QUESTIONS

The following was the survey used for data collection for this study. The three sections that subdivided the survey were pre-installation, installation, and post-installation phase questions. These phases had steps that the respondents quantified by the survey respondents in terms of their applicability in the South African mining industry context. The survey consisted of 5-point Likert scales with responses allowed from strongly agree, agree, neutral, disagree, and strongly disagree. The questions were as follows.

- **Pre-installation phase (gathering and evaluating implementing entity's capacity and potential partners) questions**
  1. Define the business problem
  2. Identify the technological gap
  3. Identify the commissioning entity's expectations and capacity
  4. Evaluating information on the necessary technology and vendors
  5. Assessment and selection procedure for vendor and technology selection
  6. Compiling short-term, medium-term, long-term and risk management strategies
  7. Drafting agreements and contracts

Do you agree with the listed checklist items and their order for gathering and evaluating the information above?

- **Installation phase questions**
  8. Design and evaluate concepts for a simulation, create a numeric simulation of the technology scenario
  9. Evaluate the numeric simulation against expectations

10. Prepare prototype designs for possible implementation based on simulation separated from normal operations
11. Validate the prototype against simulation expectations, choosing optimal (if the results of the prototype are unfavourable terminate the project)
12. Gathering system requirement documents from the vendor
13. Gathering system requirements for infrastructure upgrade
14. Ensure implementation of legal agreements
15. Implement budget control measures
16. Constant checks of design and quality of civil works
17. Provide support and cooperation (communication)

Do you agree with the listed checklist items for developing a detailed project plan above?

- **Post-adoption phase (System calibration, testing, integration and after-sale service) questions**

18. System calibration, testing and integration
19. Providing training services
20. Activities required to maintain continuous system functionality
21. Exit strategy

Do you agree with the listed checklist items for system calibration, testing and integration above?

B APPENDIX B: RESPONDENTS DEMOGRAPHICS INFORMATION

There were multiple different age groups, experience levels and gender. Table 6 shows these differences among the participants.

Table 6: Sample characteristics table (demographics)

Gender	Age group						Experience level									
Male	18 - 20 years	20 - 29 years	30 - 39 years	40 - 49 years	50 - 59 years	60 years or older	0 - 2 years	3 - 5 years	6 - 10 years	11 - 15 years	16 - 20 years	21 - 25 years	26 - 30 years	31 - 35 years	36 - 40 years	More than 40 years
	0	2	9	3	3	2	2	1	1	5	1	3	4	1	1	0
Female	18 - 20 years	20 - 29 years	30 - 39 years	40 - 49 years	50 - 59 years	60 years or older	0 - 2 years	3 - 5 years	6 - 10 years	11 - 15 years	16 - 20 years	21 - 25 years	26 - 30 years	31 - 35 years	36 - 40 years	More than 40 years
	0	1	7	2	2	0	1	1	2	5	2	1	0	0	0	0

Table 7 below shows the different types of work the participants had undertaken in the mining industry.

Table 7: Sample characteristics table (types of work experiences)

Type of work experience in the mining industry	Number of respondents
General work	6
Manager or supervisor	19
Engineer	7
Senior manager	3
Junior manager	2
Specialist (e.g., boiler maker)	4
Intern	1
Professional	1

DEVELOPING A DYNAMIC NEXT PURCHASE DATE PREDICTOR FOR INDIVIDUAL CUSTOMERS IN THE FAST-MOVING CONSUMER GOODS RETAIL SECTOR

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ABSTRACT

Amid increased competition in the retail industry due to globalisation, deregulation, and diversification, retailers urgently need to secure a competitive edge to ensure their survival. Embracing digital direct-marketing advancements is pivotal to enhancing promotional effectiveness and gaining a competitive advantage. This paper introduces a study on the development of a dynamic next purchase date predictor, aiming to forecast the timing of future repurchases of specific products by individual customers in the retail sector. The dynamic aspect of the predictor reflects its adaptability based on the latest customer behaviour data. The scope encompasses employing discrete-event simulation for dynamic customer purchase data generation and utilising machine learning techniques for analysis, focusing on fast-moving consumer goods in the business-to-customer sector. These predictions inform personalised discount offers ahead of repurchases, facilitating direct delivery of tailored promotions to individual customers. Seven prospective models were evaluated, with the artificial neural network emerging as the best predictor.

Keywords: Machine Learning, Marketing, Retail, Fast Moving Consumer Goods.

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1 INTRODUCTION

This paper illuminates the development of a Dynamic Next Purchase Date (DNPD) predictor for individual clients within the fast-moving consumer goods sector. It addresses the question "What is this?" by introducing the DNPD predictor as a system and explores "How is it done?" by demonstrating the application of industrial engineering principles in its development.

Amidst increased competition in the retail industry driven by globalisation, deregulation, and diversification, retailers must secure a competitive edge for survival. Embracing digital direct-marketing advancements is pivotal for enhancing promotional effectiveness and gaining this competitive edge [1].

Central to the digitalisation of marketing strategies is the transition from a product-centric to a customer-centric approach [2]. This shift requires the acquisition of customer data, including personal information, engagement insights, behavioural records, and attitudinal data [3]. While collecting such data is time-consuming, loyalty programmes serve as effective platforms for its aggregation. With sufficient customer data, organisations can predict various events, enabling customised marketing strategies that confer a competitive advantage.

The direct correlation between customer satisfaction, loyalty, and retention underscores the importance of marketing strategies aimed at attracting and retaining profitable clientele [4]. Particularly relevant are approaches focusing on cross-selling and up-selling. In the pursuit of enhancing cross-selling and up-selling effectiveness, attention is drawn to the feasibility of dynamically predicting the next purchase date for individual customers. This paper details the conceptualisation of the DNPD predictor, aimed at forecasting the dynamic next purchase date of specific retail products by individual customers. Information systems, discrete event simulation (DES), and machine learning (ML) are fundamental industrial engineering principles central to this research.

The paper is organised as follows: Section 2 outlines the conceptual framework of the study. Section 3 reviews prior studies and relevant literature. Section 4 describes the methodology. Section 5 presents the experimental results and evaluation. Finally, Section 6 concludes the paper and explores future research directions.

2 CONCEPTUAL FRAMEWORK

This section presents the conceptual framework for the DNPD predictor. The term “dynamic” implies that these predictions will be informed by the latest updates on customer behaviour data. Figure 1 showcases recent purchase transactions over time of several retail customers denoted by C_i, where $i = 1, 2, 3, \dots, n$; $n \in \mathbb{Z}^+$.

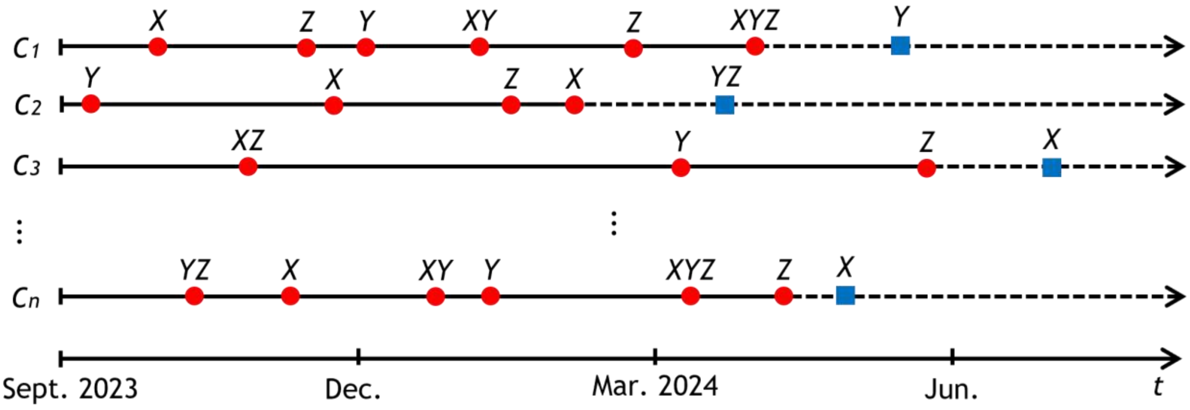


Figure 1: Recent purchase behaviour for some customers

The timelines shown above highlight the most recent interactions between customers and the retailer, focusing solely on recent transactions rather than their complete purchase history.

Each red dot corresponds to a recent historic purchase made by Customer C_1 to C_n. These purchases take place at random time intervals and with varying frequencies. The symbols X, Y, and Z label the products purchased by each customer at specific instances, representing independent or combined purchases in varying quantities. The timeline at the bottom of the figure provides the exact timing, t, for each transaction.

The purchase history of each customer is stored in a database and undergoes data preparation procedures before being analysed by a variety of ML algorithms. Next, a DNPD is generated for each customer, ranging from C_1 to C_n, as illustrated in Figure 2. This DNPD prediction is represented in Figure 1 by blue squares on each customer's timeline, along with the associated products for upcoming purchases. Each timeline is divided into a solid and a dashed segment. The solid segment represents past customer interactions with the retailer, displaying known historic transactions. Conversely, the dashed segment represents future customer-retailer interactions, featuring the predicted DNPD.

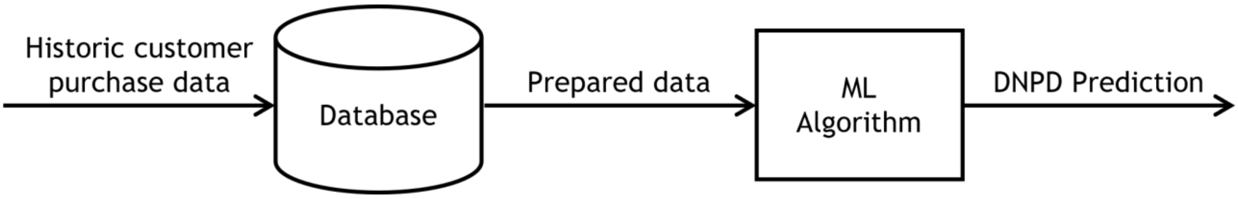


Figure 2: Dynamic Next Purchase Date (DNPD) predictor implementation

This iterative process benefits from accumulating more historical purchase data over time, enhancing model adaptability and accuracy. Leveraging a dataset encompassing n customers and a range of FMCGs (XYZ), this simulated model proves scalable for retailers of varying sizes. Once the DNPDs for individual customers have been determined, a range of promotional strategies can be implemented to boost purchase frequency and quantity.

Retailers and individual customers are required to subscribe to the DNPD predictor system. This system, which is based on an information system and ML algorithms, will predict the next purchase date of products for individual customers. Leveraging this predictive capability, personalised marketing initiatives can be tailored to customer needs and preferences.

3 LITERATURE REVIEW

This section provides an overview of the key principles and concepts of this study. It begins with a review of previous work relevant to the study, followed by an evaluation of important marketing principles. Finally, it investigates ML techniques for future event prediction.

3.1 Previous Work

Traditional marketing has relied on probabilistic models to extract implicit customer features from historical purchasing patterns, treating observed behaviour as originating from stochastic processes [6]. Recent academic efforts have emphasised predicting future purchases in the FMCG sector. Examples include an “Intelligent Shopping Assistant” proposed by Cumby *et al.* [7], and a “Personalised Discount Offer (PDO) System” developed by Els [8]. Moreover, market basket analysis (MBA) has emerged as a popular avenue for shopping list prediction.

Market baskets refer to the set of products or categories purchased together within a single transaction [9]. Analysing these correlations enables profitable category management through marketing strategies [10]. Loyalty programs and point-of-sale systems provide transaction data for analysing cross-category behaviour. Integrating purchase histories with store-specific data may further enable tailored cross- and up-selling campaigns [10].

This research aligns closely with the framework introduced by Droomer [11], termed the “Next Purchase Date (NPD) predictor,” which focuses on predicting the NPD of individual customers using static, pre-existing data. Training and test sets were constructed for sequence- and non-sequence-based ML techniques, with the NPD for user-product pairs as the target variable. Various combinations of the ML models were explored to assess if integrated strategies could improve prediction accuracy. The Artificial Neural Network (ANN) emerged as the selected model, accurately predicting the NPD within a day for 31.8% of the testing data and within three days for 55% of the data.

In contrast, this study employs ML to analyse data generated through DES to examine customer behaviour. The aim is to develop a scalable and adaptable DNPD predictor capable of handling diverse data inputs within an extensive database, tailored to individual customers. Various ML techniques are explored and evaluated in the study, with the aim of developing a sufficiently accurate DNPD predictor.

3.2 Basic Principles of Marketing

Mass marketing targets the entire customer base, which can be subdivided into niche- and micro-markets [12]. This segmentation allows for personalised marketing efforts, catering to individual customer preferences and needs. The evolution of marketing away from a "one-size-fits-all" model to a more customer-centric approach underscores the importance of recognising and catering to individual customer preferences [13][14].

Cross- and up-selling are effective marketing strategies that boost customer engagement and profitability, both with existing and prospective customers [5]. While these terms are often used interchangeably, they are distinct concepts. Cross-selling offers complementary products alongside the primary purchase, while up-selling promotes superior product variants [15]. Figure 3 illustrates this distinction, portraying up-selling as the promotion of a premium cell phone model and cross-selling as the concurrent purchase of headphones and a cell phone.

Figure 3: Up-selling vs. cross-selling

Organisational success relies on delivering value to customers before gaining value from them, highlighting the pivotal role of marketing in this value exchange [16]. Customer Lifetime Value (CLV) is a key metric for quantifying captured customer value, estimating the total net income an organisation anticipates from individual customers throughout their patronage [14][16].

CLV models, like the Recency, Frequency, and Monetary (RFM) strategy, facilitate the efficient allocation of marketing resources for customer acquisition, customer retention, as well as up- and cross-selling objectives [17]. Within an organisational setting, the elements of RFM are defined as follows [16]:

- Recency (R) assesses the time since an individual last made a purchase.
- Frequency (F) quantifies how often a customer makes purchases within a given period.
- Monetary (M) reflects the total monetary value of an individual's transactions.

The RFM model utilises data mining techniques to gain insights into customer attributes and purchasing behaviours, enabling the identification of potentially lucrative customers [18]. This technique is frequently employed in the retail industry to adapt marketing strategies based on customer behaviour changes. Moreover, RFM models are commonly employed for customer segmentation analysis, as well as individual-level examination.

3.3 Machine Learning Techniques for Future-Event Prediction

Time-series forecasting techniques predict future variable values by analysing historical data. In this study, historical purchase transactions are leveraged to forecast the DNPD for individual customers. Forecasting methods are broadly classified into two categories: statistical models and machine learning-based approaches.

This paper explores four ML techniques for developing the DNPD predictor: linear regression, extreme gradient boosting, artificial neural networks, and recurrent neural networks. These techniques are briefly described in Table 1.

Table 1: Selected machine learning techniques to realise the DNPD predictor

Technique	Description
Linear Regression (LR)	LR models the relationship between dependent and independent variables by fitting a linear equation to observed data, estimating coefficients through the method of least squares to determine the best-fitting line and minimise the sum of squared errors [20][23].
Extreme Gradient Boosting (XGBoost)	XGBoost is a scalable method based on decision trees and gradient boosting [21]. It minimises a loss function to construct an additive expansion of the objective function [22]. Unlike traditional gradient boosting, it exclusively uses decision trees for base classification and modifies the loss function to control tree complexity. It also integrates randomisation techniques to reduce overfitting and expedite training.
Artificial Neural Networks (ANNs)	ANNs mimic the functionality of biological neural networks present in the human brain for pattern recognition and prediction [19][20]. They comprise interconnected nodes in input, hidden, and output layers.
Recurrent Neural Networks (RNNs)	RNNs, a specialised type of ANN, process sequential data and are used in tasks such as language translation and speech recognition [24]. They feature recurrent loops for data propagation and retain memory by considering prior inputs [25].

4 METHODOLOGY

This section describes the methodology employed for the development of the DNPD predictor. The Cross-Industry Standard Process for Data Mining (CRISP-DM) methodology is recognised for its comprehensive approach to data mining project management. It comprises six primary steps: Business Understanding, Data Understanding, Data Preparation, Modelling, Evaluation, and Deployment. CRISP-DM facilitates a structured and holistic approach to this study.

This paper discusses the development of a predictor to forecast the DNPD for individual customer-product pairs by analysing historical purchases and behavioural patterns. Unlike traditional approaches using static datasets, it leverages dynamic data from DES, which provides a realistic basis for modelling customer behaviour. The scalable predictor will process diverse inputs from a vast database, creating a dynamic testing environment for ML techniques to capture customer behaviour intricacies across various scenarios.

Initially, the database structure and simulation model workflow will be described. This will provide an understanding of the data generation process and the underlying logic behind the DES model. Subsequently, the CRISP-DM methodology will be applied and discussed.

4.1 Database Structure

The database structure is crucial for generating and analysing the simulated retail data. The structure, illustrated in Figure 4, comprises multiple tables organised to capture aspects of customer attributes, customer behaviour, product attributes, and transactional details.

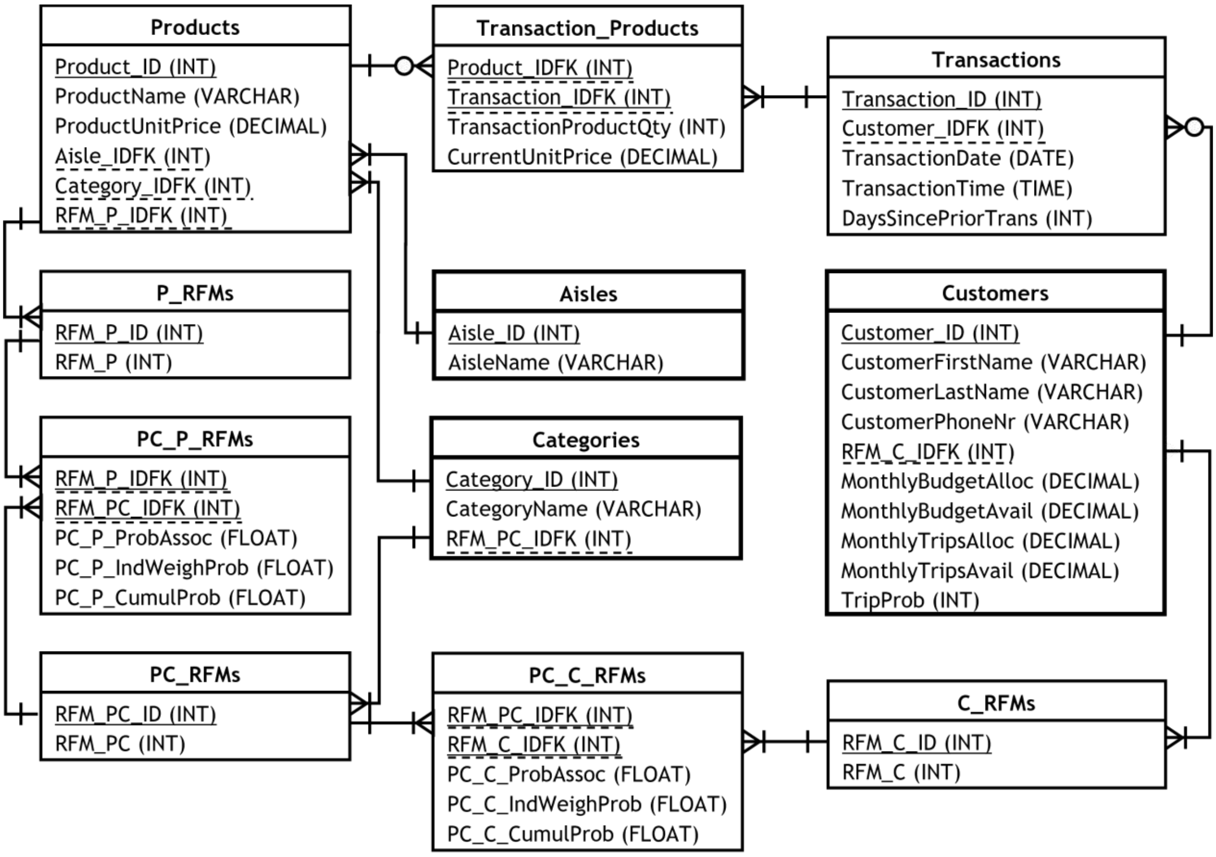


Figure 4: Extended entity relationship diagram

The database includes tables for Customer RFMs (‘C_RFMs’), Product RFMs (‘P_RFMs’), and Product-Category RFMs (‘PC_RFMs’), containing unique identifiers and RFM categorisations. Associations between these tables are managed by the ‘PC_P_RFMs’ and ‘PC_C_RFMs’ tables.

The ‘Products’ table consolidates all product-related information, including unique product identifiers, names, unit prices, associated aisle and category identifiers, and assigned product RFM categorisations. The ‘Aisles’ and ‘Categories’ tables provide the necessary contextual product data. All customer data is stored in the ‘Customers’ table, featuring unique customer identifiers, names, contact information, allocated and available monthly budgets and trips, trip probabilities, and customer RFM categorisations.

Transactional details are recorded in the ‘Transactions’ table, comprising unique transaction identifiers, associated customer identifiers, transaction dates and times, as well as the days since the prior transaction associated with the customer. The product quantities and current unit prices of the purchased products are detailed in the ‘Transaction_Products’ table, which links each transaction to the products associated with it.

4.2 Data Generation Utilising Discrete-Event Simulation

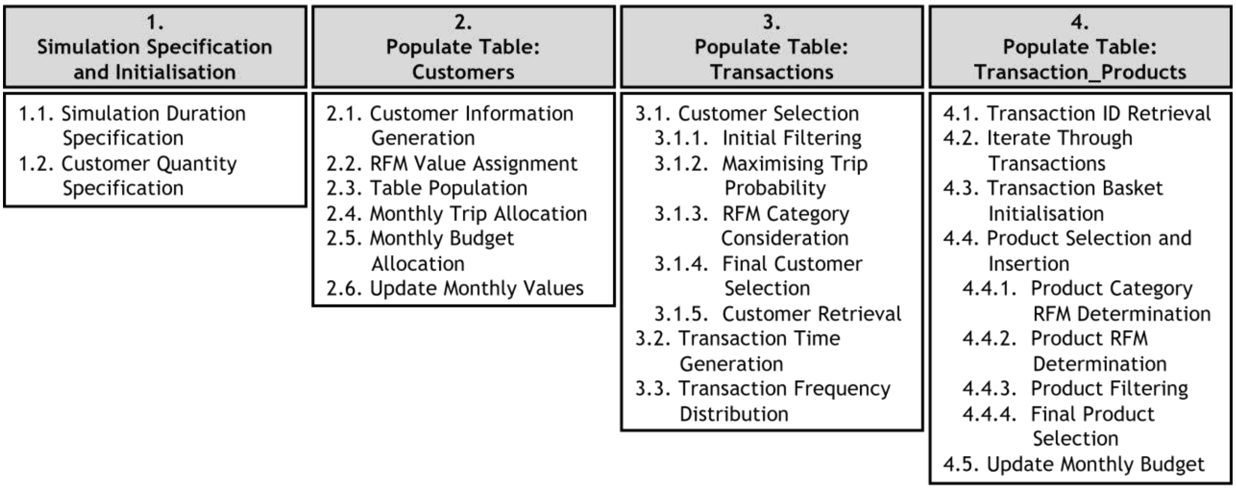
Predictive models rely on extensive datasets for accurate predictions, and DES emerges as a valuable strategy for generating such data. The simulation model employed generates data for developing the DNPD predictor, focusing on customer transactions in a retail setting. The model aims to create realistic datasets that mimic customer behaviour within a retail context.

RFM is central to the simulation as it offers a recognised method to categorise customers in a retail environment. The modelling of complex customer-product interactions is facilitated by leveraging RFM metrics to determine probabilities and preferences, resulting in convincing representations of real-world buying patterns and market dynamics. Moreover, the simplicity and effectiveness of RFM provides a good foundation for constructing a flexible and adaptable simulation model that can be tailored to diverse scenarios and market conditions.

Building upon the previously described reference database, the DES model integrates customer and transactional data for analysis and prediction using ML techniques. It can also assimilate extra data for deeper analysis with ML, resulting in a dynamic system. This section discusses the general workflow, detailed processes, and assumptions underlying the simulation model.

4.2.1 Simulation Model Components: General Workflow

The model comprises four elements: simulation specification and initialisation, customer data generation, transaction simulation, and product selection. These components are illustrated in Figure 5, with element descriptions corresponding to the numbered steps therein.



1. Simulation Specification and Initialisation

- 1.1. Simulation Duration Specification
- 1.2. Customer Quantity Specification

2. Populate Table: Customers

- 2.1. Customer Information Generation
- 2.2. RFM Value Assignment
- 2.3. Table Population
- 2.4. Monthly Trip Allocation
- 2.5. Monthly Budget Allocation
- 2.6. Update Monthly Values

3. Populate Table: Transactions

- 3.1. Customer Selection
  - 3.1.1. Initial Filtering
  - 3.1.2. Maximising Trip Probability
  - 3.1.3. RFM Category Consideration
  - 3.1.4. Final Customer Selection
  - 3.1.5. Customer Retrieval
- 3.2. Transaction Time Generation
- 3.3. Transaction Frequency Distribution

4. Populate Table: Transaction_Products

- 4.1. Transaction ID Retrieval
- 4.2. Iterate Through Transactions
- 4.3. Transaction Basket Initialisation
- 4.4. Product Selection and Insertion
  - 4.4.1. Product Category RFM Determination
  - 4.4.2. Product RFM Determination
  - 4.4.3. Product Filtering
  - 4.4.4. Final Product Selection
- 4.5. Update Monthly Budget

Figure 5: Workflow of the simulation model

1. Simulation Specification and Initialisation

This element involves specifying the simulation duration and customer quantity.

1.1. Simulation Duration Specification

The user specifies the simulation duration with explicit start and end dates, ensuring accuracy and consistency to meet simulation requirements.

1.2. Customer Quantity Specification

The user specifies the number of customers present in the system, enabling analysis of scenarios with varying customer base sizes.

2. Table Population: Customers

Populating the 'Customers' table involves generating *faux* customer information.

2.1. Customer Data Generation

Realistic customer details - including their name, surname, and phone number - are generated. Moreover, a unique identifier is assigned to each customer.

2.2. Recency, Frequency, and Monetary Value Assignment

Random recency, frequency, and monetary values, ranging from 1 to 3, are generated randomly for each customer. The RFM categorisation of each customer is determined by the combination of these values.

2.3. Monthly Trip Allocation

Customers are assigned monthly trip allocations according to their RFM frequency category, which classifies purchasing behaviours into three groups: infrequent (few trips), moderate (moderate trips), or frequent (many trips).

2.4. Monthly Budget Allocation

Customers are assigned monthly budget allocations according to their RFM monetary category. The budget is a percentage of income dedicated to FMCG purchases, with low-, moderate-, and high-income customers allocating high, moderate, and low percentages, respectively.

2.5. Table Population

Customer data is inserted into the 'Customers' table. An initial trip probability of 1.0 (100% likelihood of visiting the store) is given to each customer, which gets adjusted throughout the simulation based on remaining trips relative to the initial allocation.

2.6. Updating Monthly Values

Trip and budget allocations are recalculated monthly for each customer based on their RFM categorisation, accounting for any profile changes.

3. Table Population: Transactions

Populating the 'Transactions' table involves simulating the shopping events of each customer over the specified simulation period.

3.1. Customer Selection

Customers are filtered based on their shopping likelihood, available monthly trips, and RFM categories, facilitating realistic customer selection by prioritising high-probability shoppers. Subsection 4.2.2 provides a detailed process explanation of this process.

3.2. Transaction Time Generation

Random transaction times within store operating hours are generated, considering the day of the week. This distributes transactions throughout the day.

3.3. Transaction Frequency Distribution

All transactions are distributed across the month using a truncated multimodal Poisson distribution to accommodate both busy and slow days.

4. Table Population: Transaction_Products

Populating the 'Transaction_Products' table involves assigning products in various quantities to each transaction, ensuring the transaction reflects realistic purchasing behaviour.

4.1. Transaction ID Retrieval

Transaction IDs from the 'Transactions' table are retrieved and iterated over.

4.2. Transaction Iteration

For each transaction, the customer details - including their available budget, allocated trips, and RFM category - are retrieved from the 'Customers' table.

4.3. Transaction Basket Initialisation

For each transaction, a basket is initialised to hold the selected products. The budget for the transaction is calculated based on the customer's allocated budget and trips.

4.4. Product Selection and Insertion

Products are selected and added to the transaction basket using the product selection process described in Subsection 4.2.2. It continues until either the maximum number of products has been reached, or the transaction budget is exhausted.

4.5. Updating Monthly Budget

The value of the transaction basket is deducted from the available monthly budget.

4.2.2 Simulation Model Components: Detailed Process Explanation

Due to their complexity, the customer and product selection processes are detailed further in this subsection, corresponding to Figure 5.

3.1. Customer Selection Process

The customer selection process ensures transactions are allocated to the most appropriate customers based on their likelihood to shop and their available trips. By selecting customers probabilistically to reflect the distribution of RFM categories within the eligible customer pool, this process sensibly represents real-world customer behaviour.

3.1.1. Initial Filtering

Customers with a positive trip probability and monthly budget are retrieved and sorted.

3.1.2. Maximising Trip Probability

The customers with the highest trip probability are identified and prioritised.

3.1.3. RFM Category Consideration for Customer Selection

Customers are filtered based on their RFM categorisation. If only one unique category is present, a customer is randomly selected from this group. If multiple categories are present, a random number is generated and compared to a truncated cumulative Poisson distribution, determining the suitable RFM customer category for the specific simulation scenario. A random customer is selected from this refined list.

3.1.4. Customer Retrieval

The information of the selected customer - including their unique identifier, name, available trips and budget, and RFM category - is retrieved for transaction generation.

4.4. Product Selection and Insertion Process

The product selection process is a critical aspect of generating realistic transactional data. It involves multiple steps to ensure that the products chosen for each transaction align with the customer's purchasing behaviour, as indicated by their RFM profile. This process ensures that products are added to each transaction in a realistic and probabilistic manner by combining random number generation with cumulative probability comparisons.

4.4.1. Product-Category RFM Determination

A random number ('U_pc') is generated to select an appropriate RFM product-category profile, which introduces variability and probabilistic selection into the process.

The model fetches rows from the 'PC_C_RFMs' table, mapping customer and product-category RFM profiles with associated cumulative probabilities. These probabilities represent the likelihood of a customer from a specific RFM category purchasing from a particular product-category based on its RFM category.

'U_pc' is subsequently compared to these probabilities. The product-category RFM profile with a cumulative probability closest to 'U_pc' is identified, facilitating a probabilistic approach to product-category selection.

4.4.2. Product RFM Determination

A random number ('U_p') is generated to select an appropriate RFM product profile. This step introduces further variability and probabilistic selection into the process.

The model fetches rows from the 'PC_P_RFMs' table, mapping product and product-category RFM profiles with associated cumulative probabilities. These probabilities represent the likelihood of a product from a specific RFM category being selected from a particular product-category based on its RFM category.

'U_p' is compared to these probabilities to identify the product RFM profile with the closest cumulative probability, enabling a probabilistic approach to product selection.

4.4.3. Product Filtering

The model filters products to ensure they match both the determined product-category and product RFM profiles obtained in steps 1 and 2, respectively. This filtering process narrows down the available product options to those most likely to be purchased by the customer, based on their RFM profile and the probabilistic selection process.

4.4.4. Final Product Selection

In the final step, the model retrieves the customer's purchase history and categorises the filtered products as previously purchased or not. Random selection determines if the final product comes from the previously purchased or non-purchased list.

For previously purchased items, a weighted selection process computes cumulative purchase probabilities for each item, with a random number determining the final choice. Conversely, non-purchased items are chosen randomly. Details of the selected product are subsequently populated in the 'Transaction_Products' table.

4.2.3 Key Simulation Model Assumptions

The DES model incorporates the following assumptions, subject to future research review, to generate data that realistically imitates customer behaviour in a retail environment:

- All customers make monthly purchases during the simulation period, reflecting their assigned RFM categorisation.
- The customer base remains fixed, with no customer dropouts or additions.
- The product base remains fixed, with no product discontinuations or additions.
- Product availability remains consistent, with no stockouts or supply chain disruptions.
- Customer preferences are uniform within each RFM categorisation.
- All RFM categorisations remain fixed during the simulation.
- Market conditions remain stable, unaffected by external factors like seasonal variation and economic fluctuations.
- Pricing remains static throughout the simulation, unaffected by promotional activities.
- Product returns and exchanges are not considered.

4.3 Business Understanding

The DNPD predictor aims to improve marketing strategies for retailers and customers alike. Through the integration of information systems and ML algorithms, this tool enables retailers to predict the future purchasing behaviour of individual customers. By leveraging predictive data analytics, retailers can anticipate customer needs, implement personalised marketing strategies, and promote organisational growth in a competitive market.

4.4 Data Understanding

The DNPD predictor is developed using a dataset derived from the DES simulation, outlined in Subsection 4.2, comprising over 1.1 million transactions from 1,000 customers. Subsection 4.1 discusses the relational structure of the dataset. Each customer contributes a minimum of 12 transactions, each comprising a sequence of purchased products. Approximately 6,500 unique products are contained within the 'Products' table.

4.5 Data Preparation

Feature generation is an important aspect of data preparation. The methodology detailed in Droomer [11] guides the feature generation and Analytical Base Table (ABT) creation in this study. For a more detailed understanding, readers are referred to this prior work. Since this study uses time-series data, both sequential and non-sequential features are generated.

4.5.1 *Sequential Features*

Sequence-based features focus on the temporal dynamics of customer transactions, providing insight into purchasing patterns, which is crucial for predictive modelling. However, these features are not directly available in the dataset and need to be derived. In this study, two such features are developed and presented in Table 2.

Table 2: Sequential feature descriptions [11]

Feature	**Description**
Days Between Transactions per Product (Feature 1)	This feature tracks the time elapsed between successive transactions per customer-product pair. It describes the recency of customer purchases for specific products and facilitates the prediction of the DNPD per customer-product pair, which serves as the target feature in this study.
Days Since Prior Transactions per Product (Feature 2)	This feature tracks the time elapsed since a customer's last transaction, regardless of the product(s) purchased. It gives insights into customer activity patterns, indicating the frequency of transactions.

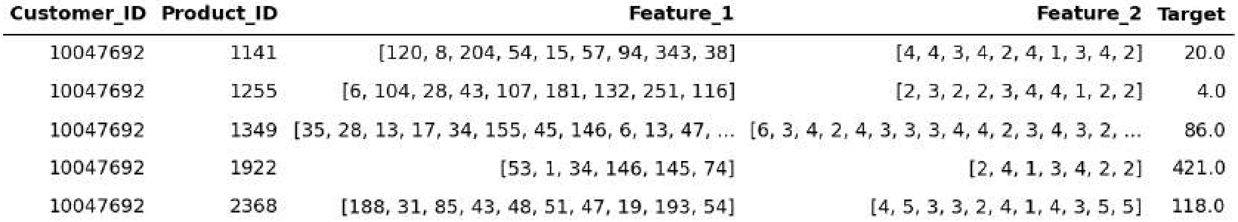
These sequence-based features are important for capturing customer-product dynamics and are crucial for subsequent modelling phases. Figure 6 presents the ABT for the models solely utilising sequential features.

4.5.2 *Non-sequential Features Informing Sequence Dynamics*

Non-sequence-based features offer a comprehensive view of customer-product interactions. Each feature, detailed in Table 3, is constructed based on the characteristics of customer-product interactions captured in the dataset. Figure 7 displays the ABT for the models using both sequential and non-sequential features.

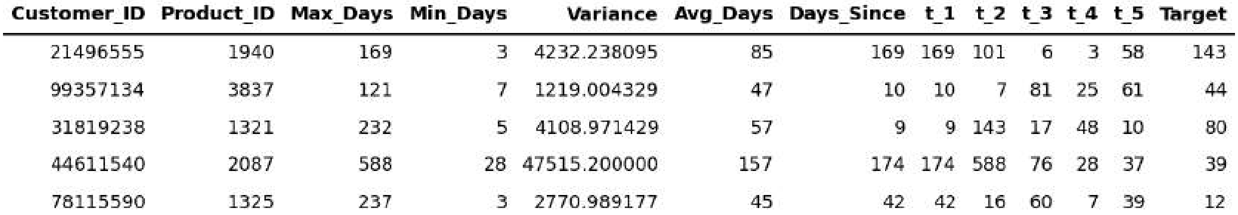
Table 3: Non-sequential feature descriptions [11]

Feature	**Description**
Customer ID	A unique identifier for each customer.
Product ID	A unique identifier for each product.
Maximum days	The maximum duration in days that a customer went without the product, based on Feature 1.
Minimum days	The minimum duration in days that a customer went without the product, based on Feature 1.
Variance	The variability within the sequence generated by Feature 1.
Average days	The mean duration in days within the sequence created by Feature 1.
Days since	The second-to-last entry in the sequence generated by Feature 2, as the last entry pertains to the target variable.
t_5, t_4, t_3, t_2, t_1	The Feature 1 sequence values corresponding to the respective windows.



Customer_ID	Product_ID	Feature_1	Feature_2	Target
10047692	1141	[120, 8, 204, 54, 15, 57, 94, 343, 38]	[4, 4, 3, 4, 2, 4, 1, 3, 4, 2]	20.0
10047692	1255	[6, 104, 28, 43, 107, 181, 132, 251, 116]	[2, 3, 2, 2, 3, 4, 4, 1, 2, 2]	4.0
10047692	1349	[35, 28, 13, 17, 34, 155, 45, 146, 6, 13, 47, ...	[6, 3, 4, 2, 4, 3, 3, 3, 4, 4, 2, 3, 4, 3, 2, ...	86.0
10047692	1922	[53, 1, 34, 146, 145, 74]	[2, 4, 1, 3, 4, 2, 2]	421.0
10047692	2368	[188, 31, 85, 43, 48, 51, 47, 19, 193, 54]	[4, 5, 3, 3, 2, 4, 1, 4, 3, 5, 5]	118.0

Figure 6: ABT containing only sequential features



Customer_ID	Product_ID	Max_Days	Min_Days	Variance	Avg_Days	Days_Since	t_1	t_2	t_3	t_4	t_5	Target
21496555	1940	169	3	4232.238095	85	169	169	101	6	3	58	143
99357134	3837	121	7	1219.004329	47	10	10	7	81	25	61	44
31819238	1321	232	5	4108.971429	57	9	9	143	17	48	10	80
44611540	2087	588	28	47515.200000	157	174	174	588	76	28	37	39
78115590	1325	237	3	2770.989177	45	42	42	16	60	7	39	12

Figure 7: ABT containing both sequential and non-sequential features

4.6 Modelling

Following the generation of the features and ABTs, the ML models outlined in Section 3.3 were developed and tested. Additionally, two baseline models were developed. To ensure sufficient prediction accuracy, ML models necessitate ample data. Consequently, the customer-product pairs were filtered to include a minimum of six entries, yielding a dataset of 45,667 pairs, encompassing 1,000 unique customers and 3,817 unique products. The filtered dataset was split into training and testing sets using an 80:20 ratio, respectively. This section discusses the implementation and parameter configuration for each model.

4.6.1 Baseline Models

The two baseline models - one focusing on customer-related trends and the other on product-related trends - compute average Feature 1 values per customer and product, respectively. The customer model captures individual customer purchasing patterns, while the product model reveals typical purchasing patterns associated with each product.

4.6.2 Advanced Models

Five advanced models - LR, XGBoost, ANN, and two RNN models - were implemented. Data scaling was conducted prior to model execution. Table 4 provides an overview of the features and packages utilised for each model.

Table 4: Advanced model descriptions

Model	Feature Type	Feature(s) Used	Packages Used
LR	Sequential	Feature 1	Scikit-learn: SGDRegressor
XGBoost	Non-sequential and sequential	All features	XGBoost
ANN	Non-sequential and sequential	All features	PyTorch
RNN1	Sequential	Feature 1	PyTorch
RNN2	Sequential	Feature 1 & 2	PyTorch

The hyperparameter ranges that were tested during model development are displayed in Table 5. While not every model includes all parameters shown, those that are available were tuned. Table 4 presents the configurations yielding the highest accuracy for each model, with default parameters utilised where not specified.

Table 5: Tested hyperparameter configurations

Hyperparameter	**Configurations Tested**
Learning rate	0.1, 0.001, 0.0001, 0.00001, and 0.000001
Number of epochs	50, 100, 200, 400, 600, and 1200
Batch size	32, 64, 128, 256, 512, and 1024
Hidden size	32, 64, 128, and 256

Table 6: Advanced model hyperparameter configurations

Model	**Selected Hyperparameter Configuration**
LR	Loss: squared_error <> Learning rate: ‘constant’ <> eta0: 0.001
XGBoost	Criterion: RMSE <> Learning rate: 0.1 <> Objective: ‘reg:linear’ Booster: ‘gbtree’
ANN	Criterion: MSE <> Optimiser: Adam <> Input size: 12 <> Num epochs: 100 Learning rate: 0.001 <> Batch size: 32
RNN1	Architecture: LSTM <> Criterion: MSE <> Optimiser: Adam <> Num epochs: 300 Activation function: ReLu <> Input size: 1 <> Hidden size: 128 <> Num layers: 2 Output size: 1 <> Dropout: 0.2 <> Learning rate: 0.001 <> Batch size: 512
RNN2	Architecture: LSTM <> Criterion: MSE <> Optimiser: Adam <> Num epochs: 200 Activation function: ReLu <> Input size: 2 <> Hidden size: 128 <> Num layers: 2 Output size: 1 <> Dropout: 0.2 <> Learning rate: 0.001 <> Batch size: 64

5 RESULTS AND EVALUATION

This section details the evaluation and prospective deployment of the DNPD Predictor.

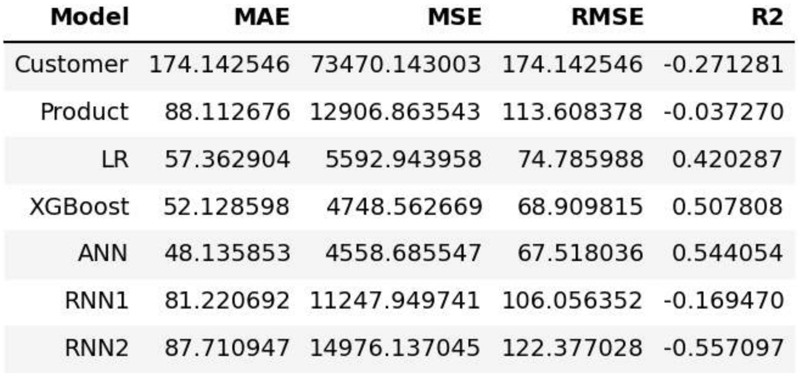
5.1 Evaluation

The evaluation of the baseline and advanced predictive models is based on key error metrics: Mean Absolute Error (MAE), Mean Squared Error (MSE), and Root Mean Squared Error (RMSE), as well as the R-squared (R2) value. Figure 8 presents the performance metrics of each model in predicting the DNPD for customer-product pairs.

The baseline models serve as a foundation for understanding the individual contributions of customer and product trends to the prediction task. Both the Customer and Product models demonstrate poor performance, characterised by high error metrics and negative R2 values, indicating significant deviations from actual values and a failure to capture meaningful variance in the target variable. Despite the Product model outperforming the Customer model with lower MAE, MSE, and RMSE values, its negative R2 score indicates a limited variance explanation. The R2 score of the Customer model indicates an even weaker fit.

Conversely, the advanced models exhibit significant improvements in predictive performance. The ANN model emerges as the most robust and accurate DNPD predictor, showcasing superior performance with the lowest error metrics. Furthermore, it has the highest R2 value (54.41%), indicating enhanced capture of variance in the target variable. XGBoost also exhibits strong performance, closely following ANN in accuracy, providing a competitive alternative.

The LR model and RNN variants (RNN1 and RNN2) demonstrate higher error values and lower R2 scores compared to ANN and XGBoost. Among these models, LR slightly outperforms the RNN variants. The RNN variants exhibit comparable performance, with RNN1 achieving a lower MAE and RMSE but a higher MSE than RNN2. Both RNN1 and RNN2 have negative R2 scores, indicating a failure to capture meaningful variance in the target variable.



Model	MAE	MSE	RMSE	R2
Customer	174.142546	73470.143003	174.142546	-0.271281
Product	88.112676	12906.863543	113.608378	-0.037270
LR	57.362904	5592.943958	74.785988	0.420287
XGBoost	52.128598	4748.562669	68.909815	0.507808
ANN	48.135853	4558.685547	67.518036	0.544054
RNN1	81.220692	11247.949741	106.056352	-0.169470
RNN2	87.710947	14976.137045	122.377028	-0.557097

Figure 8: Performance metrics of all models

Graphical representations in Figure 9 visually confirm the performance of the advanced models across various ranges of customer-product pair instances. The left graph displays the absolute error of each advanced model over the test instances. ANN consistently exhibits the lowest absolute error, followed by XGBoost, LR, and the RNN variants, with the performance gap widening as the instance count increases. The right graph zooms in on the first 500 instances, reaffirming the superior performance of the ANN and XGBoost models.

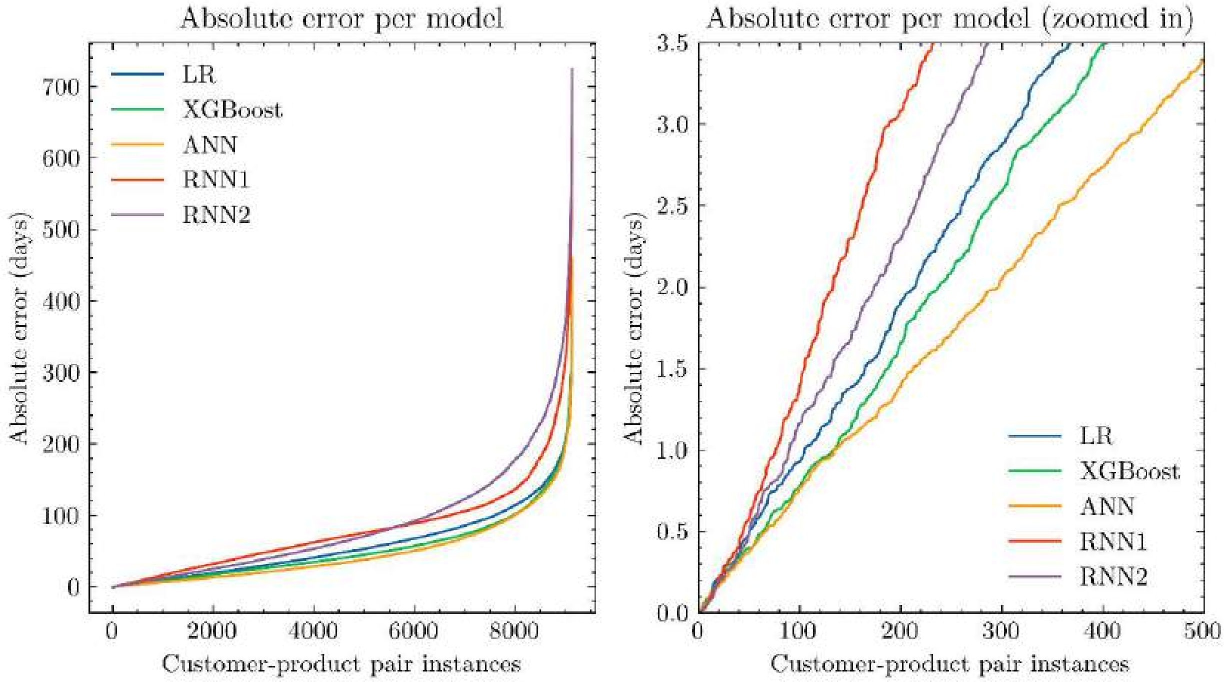


Figure 9: Absolute error visualisation

The advanced models outperformed the baseline models, showing progress in DNPD prediction. However, high error metrics indicate that the current accuracy is insufficient for reliable real-world use. Nevertheless, the improved performance suggests that further model development and refinement can enhance prediction accuracy.

The elevated errors stress the need for enhancements in the simulation process to improve the quality of the generated data. By incorporating additional measures that more accurately capture customer behaviour, the simulation will better reflect real-world customer purchase patterns. Moreover, simulating a wider variety of retail scenarios will support the development of models that are both robust and scalable across different contexts.

While the current results fall short of the desired prediction accuracy, they demonstrate the feasibility of this approach and provide a good foundation for further enhancements. By focusing on simulation improvements and continued model optimisation, the level of accuracy required for practical implementation can be achieved. The progress made thus far serves as an encouraging indication of the potential for this methodology to ultimately deliver reliable DNPD predictions.

5.2 Deployment

The DNPD predictor implementation is iterative, involving ongoing monitoring and refinement of predictive models based on feedback and new data. This continuous improvement ensures accuracy and adaptability to changing market dynamics, positioning retailers for long-term success and customer-centric differentiation.

6 CONCLUSION

This study has illuminated the development of the DNPD predictor tailored for individual customers within the FMCG retail sector. It was demonstrated that leveraging information systems and DES for data generation, combined with ML techniques, facilitated individual customer-product purchase behaviour predictions.

Two baseline models were established, and five advanced models were generated. The ANN model emerged as the top-performing technique across all metrics, highlighting its efficacy in predicting dynamic consumer trends. Following closely behind was the XGBoost model as the runner-up. The LR model exhibited moderate performance, whereas the baseline models and RNNs showed significant deviations from actual values, with limited variance capture. Based on the performance evaluation of the models, the ANN was selected as the DNDP predictor.

As retailers attempt to gain a competitive edge in the evolving market landscape, integrating predictive tools becomes pivotal for informed decision-making and personalised marketing initiatives. This study not only advances the understanding of predictive modelling in retail but also offers actionable insights for organisations aiming to enhance customer engagement and drive sustainable growth.

This study identifies opportunities for further work, including:
- Enhancing the simulation to more accurately represent customer behaviour by refining repurchase occurrences, incorporating scenarios where users drop out or join at a later stage, and introducing seasonality into the model.
- Implementing further refinement and hyperparameter optimisation of the ML models.
- Expanding the DNPD predictor to forecast product purchase quantities.
- Addressing the challenge of cold starts, attributed to the need for ample instances of customer-product pairs for precise DNPD predictions.

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THE ROLE OF DIGITAL TECHNOLOGIES IN PROCUREMENT

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ABSTRACT

Selecting a digital technology for procurement digitalisation has proven to be challenging. This paper aims to critically consolidate and examine published journals to provide an in-depth overview of the current literature regarding the role of different digital technologies in the procurement process related to performance effects and functions. By doing so, it seeks to illuminate the path for researchers and industry experts in selecting the most suitable technology for their specific needs to reap the maximum benefits.

It was found that artificial intelligence, blockchain technology, and big data are among the most used digital technologies compared to the Internet of Things, augmented supply chain, and machine learning. Furthermore, the application of digital technology in the procurement process depends on the business's strategic objective. Lastly, the adoption and implementation of digital technologies in procurement digitalisation are affected by many barriers. Intra-organisational barriers were the most prevalent.

Keywords: procurement, digital technologies, digitalisation, digital procurement

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1 INTRODUCTION

The digitalisation of procurement is using innovative technologies to enhance the process's integrity and agility, improving customer service and sustainable business performance [1]. In today's ever-changing and complex business environment, the convergence and tracking of information from various sources have become challenging, driving organisations to invest in intelligent digital technologies to facilitate communication integration between people and other technologies [2].

As an independent concept, digitalisation involves systematically using data to enhance production and operation efficiency, transform procurement and supply chain processes, and propel quality development [3]. The shift from traditional paper-based processes to digital ones, using technologies like Artificial Intelligence (AI), Cloud Computing (CC), and Big Data (BD), has significantly affected procurement and supply chain processes [4]. These technologies enable businesses to adopt data-driven approaches for predicting market demand and optimising production and logistics [5]. Furthermore, they allow businesses to identify and forecast risk situations, maintain situational awareness, reduce the likelihood of supply chain disruption, and improve resilience capabilities [6].

On the other hand, procurement, as a concept, is a process that organisations utilise to source and acquire all necessary goods and services for their operations. This process includes the identification of the operational needs, finding suppliers who offer the best value, establishing and maintaining supplier relationships, negotiating prices, and ensuring timely and insured delivery of the ordered items to align purchases with the business strategy [7]. This step is part of a broader process known as supply chain management. Supply chain management involves coordinating people, activities, information, and resources to move a product or service from the supplier to the customer[8]. It covers the entire production process, from the procurement of raw materials to the final product delivery.

Integrating digitalisation into procurement and supply chain management processes helps dismantle traditional discrete, siloed steps into an integrated system that operates flawlessly [9]. The benefits of such an integration are realised when embedded digital technologies collect data from suppliers and customers to guide companies in conducting data-driven products and service development to meet customers' diversified and customised needs [10]. Further, advanced digital technologies can help businesses identify underlying business value from large volumes of data to bring new products and business models [11].

Therefore, businesses must adopt digital technologies in their procurement and supply chain practices to proactively evolve ahead of their competitors and build toward sustainability. However, the literature regarding the role of different digital technologies in procurement to build a sustainable supply chain is highly dispersed and fragmented in different research areas. This systematic literature review aims to critically consolidate and examine published journals to provide an in-depth overview of the current literature and offer a comprehensive and state-of-the-art guide that captures the applications, roles, and challenges in implementing digital technologies in the procurement phase of the supply chain. This study is conducted to help industry professionals gain insights and learn from the experiences of academics and researchers on how to construct a procurement system that is both resilient and sustainable, thus yielding a competitive advantage. Previous review studies have focused on factors influencing the digitisation of procurement and supply chains [12]and how digital procurement can strategically contribute to the company's digital direction and competitive advantage [13]. This systematic literature review seeks to bridge a knowledge gap by strictly focusing on the role of advanced digital technologies in the procurement phase. This will be achieved by systematically reviewing literature from credible online libraries such as Scopus and Web of Science and further applying the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology, which provides a strict guideline for reporting different types and aspects of systematic reviews[14]. Furthermore, this review will offer a guide to help industry practitioners better understand and strategically approach the challenges of selecting and implementing advanced digital technologies in the procurement stage of the supply chain, therefore reducing the risk of failure and maximising the benefits. This will yield better decision-making by providing a complete set of considerations to improve outcomes and mitigate risks. This literature review presents answers to the following research questions (RQ):

RQ1: What are the technology-based intelligent products used in digitising procurement processes?

RQ2: How has each technology been applied in the procurement process?

RQ3: What are some limitations or challenges towards implementing these technologies?

2 REVIEW METHOD

This section guides the systematic literature review process, outlining the methods used to identify, gather and synthesise relevant journals to answer the research questions.

Relevant journals on digital procurement were found by searching titles, abstracts, and author keywords using these specific keywords (TITLE-ABS-KEY (“Procurement digitalization” OR “Digital procurement”)) on Scopus and Web of Science. These platforms were chosen for their multidisciplinary and international literature selection. Web of Science was used for its peer-reviewed journal database and Scopus for its comprehensive abstract search[15].

Figure 1 depicts the method used for literature screening, exclusion and inclusion to select relevant journals for the systematic literature review. This was achieved by following the PRISMA 2020 guidelines [11].

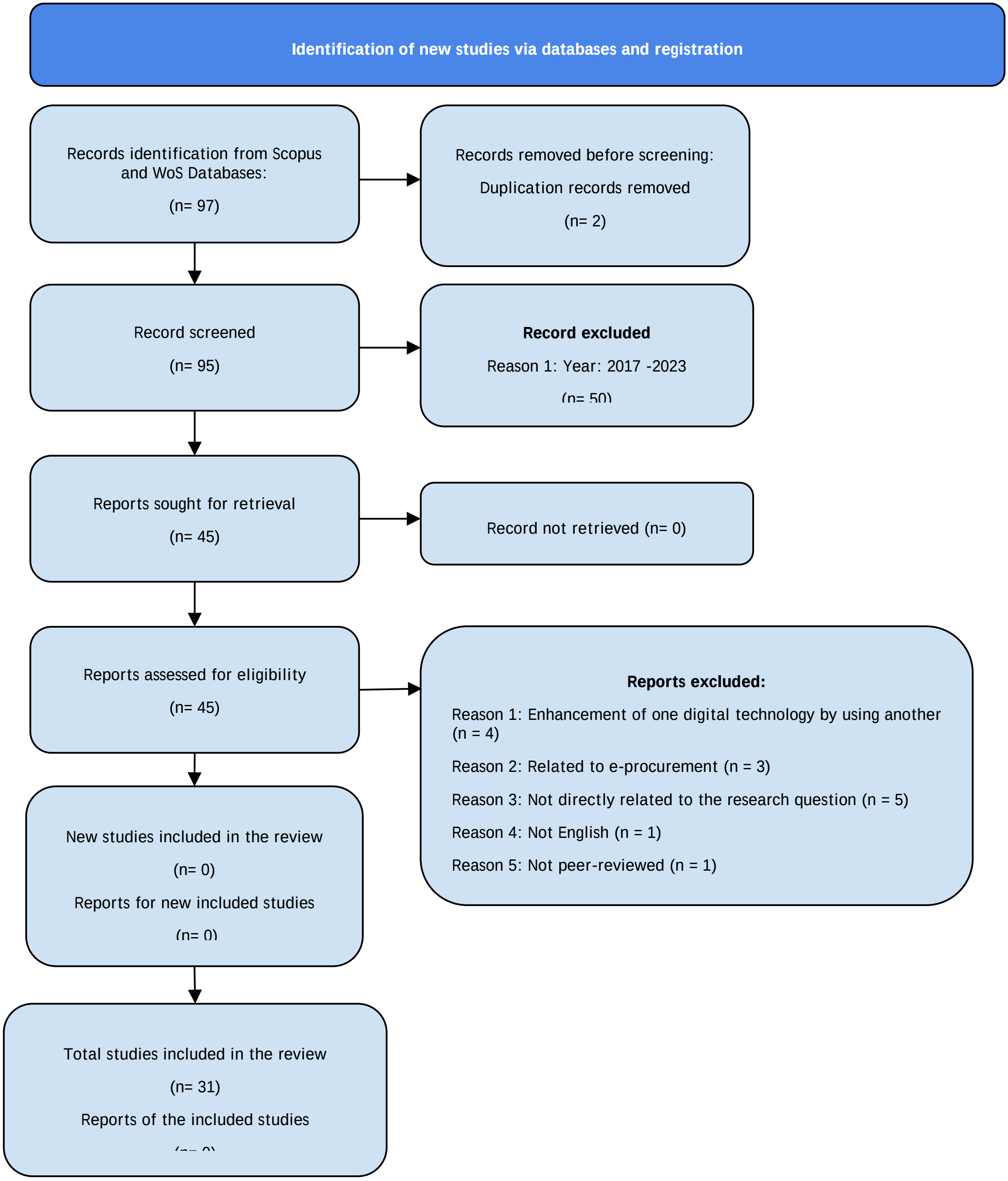

Figure 1: Literature screening and selection process (own compilation)

After removing duplicates, the following exclusion and inclusion criteria were set to select suitable journals.

Exclusion criteria included:

- Journals published before 2017 to focus on recent developments.
- Journals focusing on enhancing one digital technology with another, thereby capturing the effect of a single technology on procurement.
- Journals that include e-procurement are considered basic digital technology, while the focus is on advanced technologies like IoT, BD, and AI [12].
- Journals unrelated to the research questions.
- Non-English journals.

- Non-peer-reviewed journals.

The inclusion criteria were:

- Journals that concentrate on digital technologies and digital procurement.
- Journals that address the impact of advanced digital technology in the procurement stage.

Qualifying journals were then consolidated into a single table. Microsoft Excel was used as a tool to gather and sort information from the journals to evaluate and verify their credibility and accuracy about the literature review topic and questions. Table 1 presents a concept matrix visually representing a link between respective digital technologies, the reviewed journal articles, and the research question to which the journal articles will contribute.

Table 1: Reviewed journals and conceptual matrix

Digital technology	References	RQ1	RQ2	RQ3
AI	[3], [8], [10], [17], [18]	x	x	x
Augmented Supply chain	[19]	x	x	x
Big Data	[4], [6], [11], [20], [21], [22]	x	x	x
Blockchain technology	[23], [24], [25], [26], [27]	x	x	x
IoT	[28], [29], [30], [31]	x	x	x
Machine learning	[5], [32]	x	x	x
Challenges in adoption and implementation	[1], [2], [16], [33], [34], [35]			x

A histogram illustrating the number of journals published yearly from 2017 to 2023 is represented in Figure 3 below. The reviewed journals reveal that digital procurement research predominantly focuses on digital technologies like BD, Blockchain, AI, and IoT. However, there is a noticeable downward trend in the annual publication volume, with 2018 and 2019 marking the peak of the most publications, as shown in Figure 2.

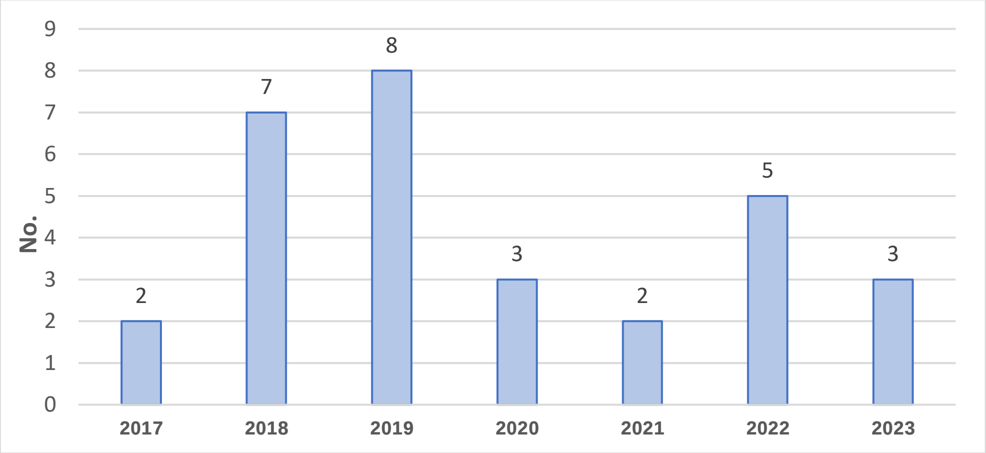

Figure 2: Number of papers published yearly

3 FINDINGS AND DISCUSSION

This section presents the findings obtained from the literature review to provide a critical and detailed elaboration of the information from different journals.

Table 3 summarises the different applications in procurement where specific digital technologies are applied. Table 4 (included in Annexure A) gives a detailed overview of the applications (general and specific) and the limitations of digital technologies. Based on the information gathered, it is clear that choosing a digital technology for procurement digitalisation to produce valuable outputs and enhance the procurement process efficiency and effectiveness is both complex and challenging. Tables 3 and 4 demonstrate that different digital technologies can achieve similar objectives, making the process even more challenging.

Table 3: Procurement applications making use of digital technologies

Applications	AI*	ASC*	BD*	BC*	IoT*	ML*	RPA*
Create new revenue streams.			x				
Creating a virtual reality procurement process		x					
Credit risk analysis	x						
Data security				x			
Decision making	x		x		x		
Demand forecasting			x				
Distribution planning			x				
Drive pricing decisions	x		x		x		
Facility planning		x	x		x		
Improve operational speed		x					x
Improve procurement visibility and transparency (Transactions)			x	x			
Improve trust between buyer and supplier.			x	x			
Inventory control			x				
Performance monitoring	x			x			
Predictive planning for purchasing	x					x	
Product quality improvement			x				
Promote data sharing			x	x			
Facilitate product quality improvement.			x				
Reduces transactional costs				x			x
Reduces data manipulation				x			
Resource management	x						
Risk management	x		x	x	x	x	
Scenario building	x						
Strategic Sourcing	x		x				
Supplier evaluation and selection	x		x				
Tracking goods (Remote management of goods)				x	x		

*- AI - Artificial Intelligence; ASC - Augmented supply chain; BD - Big Data; BC - Blockchain; IoT - Internet of Things; ML - Machine Learning; RPA - Robotic Process Automation

It is explicit that AI, BD, IoT, BC, and ML are predominantly used for risk management within the procurement process as they have proven effective in mitigating various risks associated with procurement. However, the approaches for managing risk vary across different technologies. For instance, it was found that blockchain technology can mitigate opportunistic behaviours between buyers and suppliers, as this can increase mistrust and inefficiency in the procurement process [27]. Equally, AI can facilitate optimal data-driven decisions, mitigating the risk of selecting an inappropriate supplier during the supplier scouting stage. This is an essential step in the procurement process because making a poor choice can lead to significant losses. Therefore, applying digital technologies in the procurement process depends on the business's strategic objective [3]. Blockchain technology can be suitable if the objective is to mitigate opportunistic behaviours and data manipulation. However, AI, BD, and IoT may be the preferred technological choices if the objective is to make data-driven decisions.

According to the data presented in Table 4, and considering the limitations of this literature review, BD, AI, and BC technologies are amongst the most commonly adopted digital technologies, given their broad application domains. Conversely, ASC, ML, RPA, and IoT are among the least adopted technologies in the procurement process. This could be linked to the observed limitations regarding resources and capabilities, such as the lack of technological readiness, knowledge and skills, scalability challenges, and the absence of an implementation framework.

Table 5 presents the grouped implementation barriers of digital technologies to identify commonalities, offering a comprehensive insight into the reviewed digital technologies. Implementing or adopting digital technologies may encounter various barriers. These can be categorised as Intra-organisational (within the organisation), Inter-organisational (between two or more organisations), System-related (inherent to the digital technology with regards to functioning or purpose), and External (factors, elements or conditions that are beyond the scope of the technology and remain outside its control) [11]. From the results presented in Table 5, AI, BC, and BD encounter more barriers that could hinder their implementation and value generation compared to IoT, ASC, and ML. This can be attributable to the diverse applications of the digital technologies. Moreover, these barriers depend on the application area of the digital technology, as depicted in Table 4 (Annexure A).

For instance, the use of BD analytics was evaluated in supply chain management to make the procurement phase more efficient, and the following barriers were identified [20]: (i) the knowledge gap on how to implement BD analytics in the process and the challenges of selecting suitable data to extract value that will transcend the business, (ii) a cultural change barrier resulting in low acceptance, (iii) the need to create capabilities to ensure data sharing among all stakeholders involved in the procurement process and data security within the value chain. Another author evaluated the role of BD in explaining disaster resilience in supply chain management and specifically the procurement process for sustainability and found the following barriers [22]: (i) limited funding to develop the digital technology fully, (ii) a lack of knowledge and expertise, (iii) lack of external stakeholder involvement, and (iv) data security challenges.

These barriers highlight the complexities of implementing a single digital technology, BD analytics, in the procurement process. While some challenges are similar, it is essential to note that the implementation barriers of advanced digital technologies largely depend on the purpose of their application, the stakeholders involved, and the available capabilities and resources to ensure maximum value is realised. Therefore, businesses and supply chain practitioners need to carefully consider these factors when planning to implement digital technologies in their procurement process and not simply generalise these barriers as they differ based on application. Hence, preparations and measures can be implemented to ensure that the business and all its stakeholders are technologically ready. This will have a positive impact as the technology will be readily accepted by the users, countering one of the intra-organisational barriers.

Table 5: Grouped implementation barriers

Implementation barriers	AI	ASC	BD	BC	IoT	RPA
Inter-organisational						
Challenges to collaborate with stakeholders				x		
Lack of trust between stakeholders to share sensitive data			x			
Intra-organisational						
Culture change	x		x	x	x	
Difficulties in converting from the old to the new system	x		x	x		x
Lack of collaboration between functions			x			
Lack of knowledge and skills	x		x	x		

Lack of technological readiness	x		x	x	x	x
Limited investment in technology development	x	x	x			
Limited computer capabilities to support digital technology	x		x			
Low level of acceptance			x	x		
Misalignment of digital technology implementation and business strategy			x		x	
System-related barriers						
Access to technology			x	x		
Cyber security	x		x		x	
High cost of implementation				x	x	
Scalability challenges			x	x		x
Technology immaturity	x		x	x		
Time-consuming to implement			x			
Low level of customisation	x					
External barriers						
Absence of implementation framework	x			x	x	
Lack of government policies				x		
Uncertainty of value generation/Return on investment	x		x	x		
Insufficient data generation infrastructure			x			

Intra-organisational barriers are more prevalent in implementing advanced digital technologies, as presented in Table 5, indicating that successful deployment of digital technologies depends on internal business activities (i.e. misalignment of digital technology implementation and business strategy) and conditions (i.e. culture change) that are under the control of the organisation. However, other barriers impacting technology utilisation, integration, and value generation should not be overlooked. These include inter-organisational barriers, system-related barriers inherent to advanced digital technologies, and external factors.

The selection and implementation of digital technologies for procurement digitalisation is a complicated process that requires a holistic approach and careful consideration of various factors. These considerations include the specific technological advancement which the organisation wants to achieve in their procurement process, all the barriers related to that technological advancement, the alignment of the business strategic objectives and digital technology strategy, technological and human resource capabilities and technological capabilities of all the stakeholders in the procurement process and supply chain. Secondly, the specific needs of the procurement process are to address how and which digital technology needs to be selected and implemented By considering these factors, businesses can make informed decisions and successfully implement digital technologies to generate value and enhance their procurement process's operational efficiency and effectiveness.

3.1.1 Strengths and limitations of the review

This literature review was written using peer-reviewed journals relevant to the research questions and offers a comprehensive, holistic view of the existing knowledge. The review method ensures transparency and evidence-based data extraction and synthesis, ensuring credibility and reproducibility while reducing biases. Despite the systematic approach, the review has several limitations:

- Journals were sourced from relevant databases using specific keywords. These keyword sensitivities may have excluded literature with slightly different keyword inputs.

- The literature review covers a period from 2017 to 2023 (7 years), excluding journals published before 2017 and after 2023.
- The scope of the study was limited to a systematic review of literature, excluding interviews with industry experts who could have provided real-world examples of the role of digital technologies in procurement. This limitation prevented the creation of evidence-based guidelines based on what has proven successful or unsuccessful in practice.

3.1.2 Generalisability and managerial implications

The systematic literature review reveals a wide application and comprehensive understanding of the application of digital technologies in procurement and supply chain management, delineating their uses and limitations. This review serves as a valuable resource for professionals in the procurement space regarding digitalisation adoption challenges, such as implementation (which include both technical and organisational challenges), value creation, and resistance to change and innovate the traditional procurement process. Furthermore, the review emphasises the importance of making data-driven decisions for predictive analysis, supplier scouting, and competitive advantage.

The review also emphasises the need for procurement and supply chain stakeholder collaboration. Therefore, by making stakeholders and managers aware that by fostering a collaborative partnership, organisations can create synergies of the digitally enhanced ecosystem that leverages the strengths of each stakeholder. This collaborative approach can yield more effective decision-making processes, improved risk management efforts, and increased operational efficiency within the procurement process.

Lastly, this review serves as a guideline for procurement professionals by providing valuable insights and illuminating guidance for the successful selection and adoption of digital technologies in procurement and supply chain management.

3.1.3 Future Research Recommendations

Digital technologies, with their diverse applications and complexities, require future research to focus on their implementation in specific procurement domains. Such an approach can help practitioners reduce ambiguity and clarify digital technology's value to that specific domain.

To address the leading implementation barrier, intra-organisational barriers are another important area for future research. These barriers often emerge from the resistance to change, lack of knowledge about the technology, and inadequate digital infrastructure to support the technological transformation. To overcome these barriers, research should develop a comprehensive framework to prepare top management and employees for digital technology adoption. This framework should include strategies for upskilling human resources, fostering a culture of innovation and willingness to change, and building digital infrastructure that is robust and scalable. Therefore, focusing on these areas, research can positively facilitate the digital transformation of the procurement processes in businesses, ultimately leading to increased operational efficiency, effectiveness, and competitive advantage.

4 CONCLUSION

This systematic literature review focused on procurement activities, which digital technologies can transform. The review evaluated the role of digital technologies in procurement over the past seven years, using published journals from relevant databases to answer the outlined research questions. The journals were further filtered based on the set inclusion and exclusion criteria. Lastly, the PRISMA 2020 guideline was used to evaluate the quality and relevance of the research question and topic.

To answer the first research question of the literature review. Given their wide application domains, BD, AI, and BC are the most commonly adopted digital technologies. This has also been supported by the number of published papers in the seven-year period under investigation. Conversely, ASC, ML, RPA, and IoT are amongst the least adopted technologies in the procurement process

To answer the second research question, it was found that digital technologies can provide a wide range of applications, some of which can be similar. However, the selection and application of digital technology in the procurement process depend on the business's strategic objective, the technological capabilities of the business and the parties in the supply chain, the human resource skills, and available technological infrastructure.

Lastly, the adoption and implementation of digital technologies in procurement are influenced by various barriers, with intra-organisational barriers being the most prevalent. This suggests that successful implementation and value generation from digital technologies is mostly determined by internal business activities. This denotes the importance of addressing these internal barriers to fully harness the value of digital technologies. Therefore, businesses must focus on their internal processes and culture to adopt and implement digital technologies in procurement. However, other barriers which could potentially impact technology utilisation, integration, and value generation should not be overlooked. These include inter-organisational barriers, system-related barriers inherent to digital technologies, and external factors.

As the digital landscape continues to evolve and improve, businesses must remain adaptable and open to new digital technologies to stay competitive amongst other businesses. This review serves as a valuable guideline for professionals in the procurement space regarding technology selection, application, and adoption challenges, reducing the risk of failure and maximising value from digital technology implementation in the procurement process. This is achieved through providing relevant information and illuminating insight to enhance the understanding, benefits, and challenges associated with digital technologies in procurement.

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Annexure A

Table 4: Detailed findings on the different digitalisation technologies

Technology	General application	Detailed applications	Limitations during Implementation	Reference
AI	Building supply chain resilience through uncertain situations that can disrupt the flow of supplies and information	1) Support a self-adapted and highly reliable decision-making process to alleviate uncertainty 2) Advanced predictive technologies that can model future scenarios	1) Absent of frameworks to implement the technology	[17]
	AI as a tool to improve the performance of the purchasing department	1) Shifts purchasing from operational to strategic based on data analysis capabilities 2) Predictive purchasing to anticipate and mitigate supplier failures 3) Manages all facets of supplier risk in real time. 4) Aid strategic decision-making, intelligence gathering, supplier integration, and prediction 5) Monitors performance and manages resources and risk	1) Data is not analytically processed thoroughly due to a lack of specific skills or appropriate tools 2) Resistance to digital transformation and the adoption of AI in the purchasing department	[10]
	To build supply chain resilience	1) A tool that uncovers new insights for experts to make optimal decisions in supply chain risk management	1)Insufficient or invalid data due to safety, security, and transparency issues 2) Stakeholders may resist sharing detailed data with partners	[8]
	Purchasing supplier selection and supply risk management	1) AI-based solutions replace tedious procurement tasks, enhancing decision-making 2) Map suppliers to manage global supply chain complexity 3) Aids in credit risk processes in procurement via simulation-based optimisation 4) Supports financial service providers in assessing supplier creditworthiness and operational performance 5) Automates repetitive tasks like paperwork for supplier evaluation and onboarding 6) Handles multi-criteria and multi-stakeholder supplier selection in the sourcing stage 7) Scans complex supplier networks in a structured manner 8) Supplier scouting 9) Captures necessary information for negotiation and supplier understanding	1) AI-based solutions for supplier selection are emerging due to activity complexity and data requirements 2) There's a need for capabilities to process information and utilise technology. 3) Business cultural barriers due to a lack of internal analytical skills and digital maturity 4) Uncertainty about AI's real applications hinders maximum value extraction caused by low technology awareness 6) Data consistency is compromised when old systems overlap with new ones 7) Lack of human skills 8) Limited customisation 9) Poor investment limits the full exploitation of AI capabilities	[3]

Augmented supply chain	The Augmented Supply Chain	1) Virtual reality can simulate the procurement process using wearable devices 2) Order packing Optimisation 3) Facility Planning 4) Eliminate paper-based loading instructions	1) Insufficient investment, which hinders full exploitation of the technology 2) Heavy equipment and their battery capabilities are not fully developed	[19]
Big data	Procurement and supply chain process risk management and new product creation	1) Used in storage assignment and inventory control 2) To facilitate supplier selection and reduce sourcing costs 3) To facilitate sourcing risk management 4) Enhances demand forecasting by analysing demand behaviours 5) Shaping demand to be aligned with production and logistics capacity 6) Create new revenue streams from entirely new (data) products	1) Lack of knowledge on how it can be implemented 2) Culture change barrier resulting in low acceptance 3) Creating capabilities to ensure data sharing and security within the supply chain	[20]
	To improve the value of an existing procurement and supply chain	1) Improve firm performance through new data products and services 2) Improves customer service through data analytics 3) Facilitates strategic sourcing 4) Assists in selecting distribution centre locations 5) Aids in product design and development by understanding customer requirements from purchase records and online behaviours 6) To detect supply chain risk using internal and external big data 7) To aid in logistic planning and scheduling 8) Optimise inventory ordering decisions 9) Improve end-to-end visibility, creating an agile supply chain	1) Restrictions related to environment, culture, politics, and the management team within the organisation 2) Insufficient resources with analytics capabilities 3) Misalignment between data experts and business functions 4) Lack of cross-functional collaboration	[11]
	Procurement risk forecasting	1) Supports decision-making through analytics 2) Improve demand forecasting accuracy, reducing safety stocks and uncertainty 3) Increase network visibility and transparency 4) Facilitates real-time decision-making and fast responses to disruptions	1) Misalignment of the digital technology adoption plan with the overall business strategy 2) Limited understanding of the capabilities required 3) High concerns about data security	[21]
	Managing disasters in the procurement and supply chain	1) Promoting data sharing can increase trust between suppliers and buyers 2) Decision-making regarding pricing, optimisation, risk reduction, and improved delivery through analytics 3) Develop and implement policies and strategies for disaster management and understanding people's responses to disasters	1) Limited funding to fully develop the digital technology 2) The lack of knowledge and expertise 3) Lack of external stakeholders' involvement 4) Data security challenges	[22]
	Drive sustainability in the procurement process	1) Reveals financial and operational risks towards sustainability	1) Lack of suitable frameworks related to capability development 2) Lack of skills in using generated data	[6]

Big data	Procurement and Supply chain management	1) Influences data-driven decisions and predictive planning	1) Uncertainty about potential benefits 2) Insufficient data generation infrastructures and data sources 3) Lack of data governance 4) Insufficient data security measures 5) Cultural and political barriers 6) Lack of People Skill 7) Techniques and procedures to implement digital technology are lacking 8) Challenging data scalability requirements 9) Difficult to calculate the return on investment 10) Testing and developing is time-consuming	[4]
Blockchain	Used in transactional cost reduction	1) Enables efficient and transparent transactions 2) Eliminate the need for a trusted intermediary between buyer and supplier 3) Reduced transaction costs 4) Tracking goods from production to delivery 5) Enables immutable transactions and security of the records 6) Foster data sharing to increase trust between supplier and buyer	1) Uncertainty about the value created by the technology 2) Difficult to scale 3) High development cost 4) Not a well-established technology	[23]
	Creating a secured procurement process	1) Serves as a distributed digital ledger, ensuring transparency, traceability, and security 2) Decentralised, therefore, a single point failure does not affect the whole information system 3) Facilitates reliable and transparent flow of material and information	1) Still in the emerging stages	[24]
	Security: increasing transparency and traceability	1) Increase transparency and accountability.	1) Collaborating with supply chain parties to build necessary capabilities for realising technology value is challenging 2) Deploying decentralised blockchain solutions is complicated due to existing laws 3) High computerisation is required	[25]
	Cost reduction	1) Ensuring transparency and immutability of data for troubleshooting high-cost and quality issues	1) Lack of skilled people to develop the blocks necessary to form the digital ledger 2) The need for multiple platforms to develop blocks directly impacts operational costs 3) Multiple transactions can lead to scaling issues during block development	[26]
	Creating tracking capabilities	1) Enhancing transparency and accuracy in tracking capabilities 2) Boosting trust between buyer and supplier through improved supply chain visibility and product compliance	1) Implementing blockchain technology necessitates uniform technological capabilities	[27]

		3) Reduces paperwork and administrative costs 4) Reducing opportunistic behaviours	across all supply chain parties, which may not always be feasible 2) Lack of access to the technology	
IoT	Securing the supply chain	1) Sensor-based technology and information-sharing capabilities are offered to efficiently address supply chain challenges 2) Tracking finished goods along the supply chain 3) Enables stakeholders to make data-driven decisions based on real-time information 4) Connects the entire business digitally 5) Efficient remote management of goods	1) Uncertainty if IoT would influence the procurement process since it is still at the initial stage	[28]
	In the development of business capabilities	1) IoT can be used to stimulate innovation in the procurement value chain	1) Need for extensive human and capital resources	[29]
	Mitigating opportunistic behaviours and increasing traceability	1) Limit opportunistic behaviour 2) Drive pricing decisions daily to (limited discounts) normalise in-store inventory levels	1) Uncertainty exists about IoT's impact on procurement due to its infancy	[31]
Machine learning	Risk prediction and mitigation	1) Purchasing risk prediction		[5]
Robotic process automation	Cost and time reduction in the procurement process	1) Utilised for cost savings and enhanced operational efficiency in transactional and operative tasks within the procure-to-pay process	1) The technology is still new to purchasing and unexplored 2) Organisational readiness and maturity in digital procurement are critical 3) Lack of technological readiness 4) Organisational readiness to transform from an existing technology is critical	[32]

ILLUMINATING FRAMEWORKS FOR MANAGING TECHNOLOGICAL INNOVATION: RECOGNISING CONSTRAINTS AND LIMITATIONS

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ABSTRACT

An evaluation of the historical progression of technology innovation shows that the management of the process had to adapt to specific societal changes. Over time, organisations experienced increased uncertainty and complexity in their operating environment, necessitating revisions to their innovation management practices. Understanding the context that triggered a change in managerial approaches to innovation enables an appreciation for the challenges organisations face to survive throughout the years.

Frameworks that enable the measurement of innovation management in an organisation are appraised through a narrative literature review. This study identifies and illuminates limitations associated with the published frameworks, thereby aiming to contextualize the contribution this study intends to make to technology innovation management.

Several relevant frameworks were identified to help organisations to implement, maintain, and improve innovation management systems. Appraisal of the published frameworks revealed a need to evaluate interrelationships between success factors for each innovation process stage.

Keywords: innovation management, innovation management frameworks, technology innovation

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1 INTRODUCTION

Innovation process models have progressed through several generations, from simple linear models to progressively interactive and complex models. Managing innovation effectively has become increasingly important, especially in rapidly changing and uncertain environments [1]. The survival of organisations depends on effective innovation [2].

Innovation processes describe the activities performed at each stage of innovation development [3], while innovation management involves the governance and handling all the activities [4]. The various generations of innovation management have emerged at different times in history and in different contexts, requiring distinct types of innovation processes [5]. The main reason for the emergence of a new generation is to indicate when a specific innovation management approach was considered the dominant best practice. [6] and [3] use notable historical events in the societal context to establish when a specific generation arose. Generally, new generations of innovation management surfaced due to two forces: innovation management adapts to a changing context and remedies the disadvantages of earlier generations [3].

The historical overview of the evolution of innovation showed that the complexity of managing technology innovation has increased as the process models have evolved. The innovation process models have become highly integrated, which introduced more uncertainty through external influences, thus requiring an increased focus on effective management of the process [7]. Considering the importance of innovation for organisational survival, any inefficiencies in managing the process must be addressed rapidly. According to Drucker [8], the actual status of the innovation management activities must be determined before innovation can be managed effectively.

A popular quote by Peter Drucker reads: “You cannot manage what you cannot measure”, which is also true when evaluating innovation management [8]. Drucker [9] argues that, unless you measure something, you do not know if it is getting better or worse; you cannot see positive progress unless you measure to see what is improving and what is not.

This paper reviews the literature on frameworks for assessing innovation management within organisations, identifying constraints and limitations to illuminate and enhance the understanding of technology innovation management.

2 RESEARCH METHODOLOGY

The literature review followed a narrative approach to provide a comprehensive and objective research approach of innovation management frameworks. A narrative review’s scope is to provide an overview of the research topic, identifying key themes and trends, as well as gaps in the literature. Two primary articles [3], [6] were used as the basis for the study. Keywords and references from these two articles, as well as more recent articles that referenced these scholars, were used to search for further suitable articles, which were screened for relevance and, where appropriate, included in the review. This non-structured, snowballing approach was continued for the remainder of the study.

The review specifically focused on frameworks for assessing innovation management within organisations. The research questions guiding this review are:

- What frameworks exist for assessing innovation management within organisations?
- What are the key components and characteristics of these frameworks?
- What constraints and limitations regarding these frameworks are identified in the literature?

This methodology ensures a broad understanding of innovation management frameworks by highlighting important research developments, identify gaps in the literature and areas for future investigation.

3 RESULTS

There is some disagreement amongst innovation publications regarding the number of generations and their names. [10], [11], [12] argue the evolution of only four generations of innovation process models, stating that they believe the subsequent generations described by other scholars are merely an implementation of the fourth generation. Considering that the work by [10], [11], [12] was respectively published almost twenty and ten years before the advent of the Fourth Industrial Revolution (4IR), one might understand the reasoning for supporting only four generations of innovation process models. Yet, the technological advancements made over recent years [13], [14], [15], supported by the emergence of the 4IR, suggest that innovation has evolved to subsequent generations when compared to the dates of publications that describe only four generations [10], [11], [12]. Furthermore, support exists in innovation literature for the evolution of five generations of process models [6], [16], as well as a sixth generation through the European Standardization of Innovation Management (CEN/TS 16555) [17]. This research agrees with the latter publications and discusses the evolution of innovation management over six generations. The context for the changes in innovation management and the relevant innovation process models are described in the following sections.

3.1 First generation: technology push

The historical overview of innovation management starts after World War II because, after the war, the advanced market economies enjoyed unparalleled economic growth rates, largely through rapid industrial expansion [6]. During this time, innovation was generally considered to be essential to the economic recovery of nations and organisations [18]. New industries emerged, based largely on technological opportunities, such as automobiles, pharmaceuticals, and electronic computing [10]. These developments resulted in rapid employment creation, rising prosperity, and an associated consumer boom, ultimately leading to demand exceeding production capacity [11].

During this timeframe, innovation was generally perceived as a linear progression from scientific discovery, through technological development in organisations, to the marketplace [19]. The first-generation innovation process model emerged, and it featured between the 1950s to mid-1960s [6] The linear model was based on the premise that innovation is performed in discrete stages, starting with basic science, then technology development and manufacturing, and ending with marketing and sales [6], as shown in Figure 1.

Figure 1: First generation innovation model - technology push (adapted from [6]).

The stages followed a basic linear structure that mapped innovation as a sequential flow of knowledge within the organisation, without incorporating any strategic goals [10]. This first generation, or technology push concept of innovation, assumed that “more R&D in” resulted in “more successful new products out” [6]. Little attention was paid to the role of the marketplace as part of the process [11].

3.2 Second generation: market pull

Towards the second half of the 1960s, manufacturing output continued growing due to increased global productivity [6]. In many countries, manufacturing employment was more or less static or grew at a considerably reduced rate than during the 1950s [19]. Organisations emphasised growth and diversification [20]. While new products were still being developed, these were mainly based on existing technologies, and in many areas, supply and demand were more or less in balance [18]. Competition between organisations intensified, which resulted in growing emphasis on marketing as organisations fought for market share [6]. Viewpoints of the innovation process began to change towards emphasising demands from the marketplace [10]. Whereas the first-generation innovation management focused on technology push, the second-generation innovation management focused on market pull [11], as shown in Figure 2.

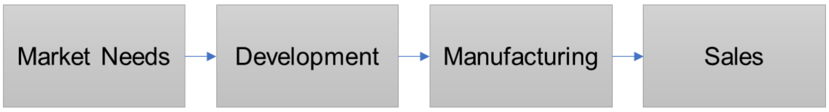

Figure 2: Second generation innovation model - market pull (adapted from [6]).

The first studies on innovation management were published, such as an evaluation of individual, organisational and environmental impacts on innovation by [21], factors influencing innovation by [22], and an analysis of organisational structures by [23]. These studies represented the first step towards developing operational tools for improved innovation management, resulting in the incorporation of formal project management principles, lacking from the first-generation process models [11].

One of the most well-known second-generation, linear innovation process models is the Stage-Gate® model, developed by [24], and shown conceptually in Figure 3. The purpose of the Stage-Gate model is to manage the movement of innovation activities from one stage to the next. The model divides the innovation process into stages with defined gates that act as decision milestones between stages [24]. Innovation activities progress to a respective gate, where a review is conducted to evaluate whether the activities performed in the stage were successful. If the result from the review is positive, work may proceed to the next stage. If unsuccessful, rework or iterations are required within the stage until the gate review decides when work may proceed to the subsequent stage of the process.

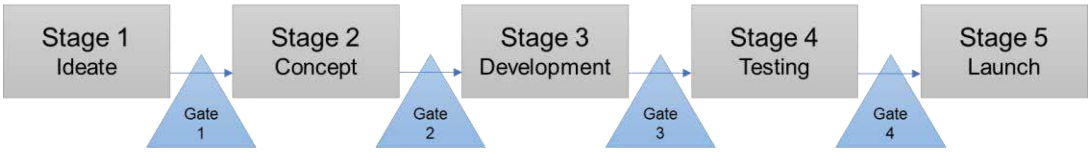

Figure 3: Concept of Stage-Gate® as an example of a second-generation innovation model (adapted from [24]).

The staged approach of second-generation innovation models aimed to control the process through disciplined steps, involving key stakeholders in gate reviews to decide on the project's continuation, revision, or termination, thereby limiting waste and ensuring transparency [24], [25], [26]. Despite its structured management, this approach has been criticized for rigidity and slow progression [27]. The Stage-Gate process's lack of flexibility for iterative feedback is a significant weakness [26], [27].

Like first-generation models, the second-generation models were linear but drew ideas from the market, leading to a reactive approach focused on incremental innovations while neglecting radical ones. This focus on customer needs may stifle technological innovation and harm long-term business success [28]. This was a primary disadvantage of second-generation innovation management [3].

3.3 Third generation: coupling

The early to late 1970s, with two major oil crises, was a period of high inflation rates and demand saturation, in which supply capacity generally exceeded demand [6]). Unemployment increased and organisations were forced to adopt strategies of consolidation and rationalisation, with focus on cost control and -reduction [10]).

During this time of severe resource constraints, it became increasingly important to understand the basis of successful innovation to reduce the occurrence of wasteful failures [6]. Several detailed, empirical studies were conducted, such as the identification of success factors for industrial innovation by [28], the development of a model of process and product innovation by Utterback and Abernathy (1975), and the identification of success factors for new product development by [29]. These empirical studies indicated that the technology push and market pull models of innovation were extreme examples of a more general process that couples the two, leading to the rise of the third-generation innovation process model [30], shown in Figure 4. During this timeframe, innovation management focused on cost reductions in economic conditions of reduced demand and more competition [30]. Studies published in these societal and organisational contexts evaluated strategic matters, such as how the competitive position of organisations could be improved with technology and technology-based innovation strategies [31].

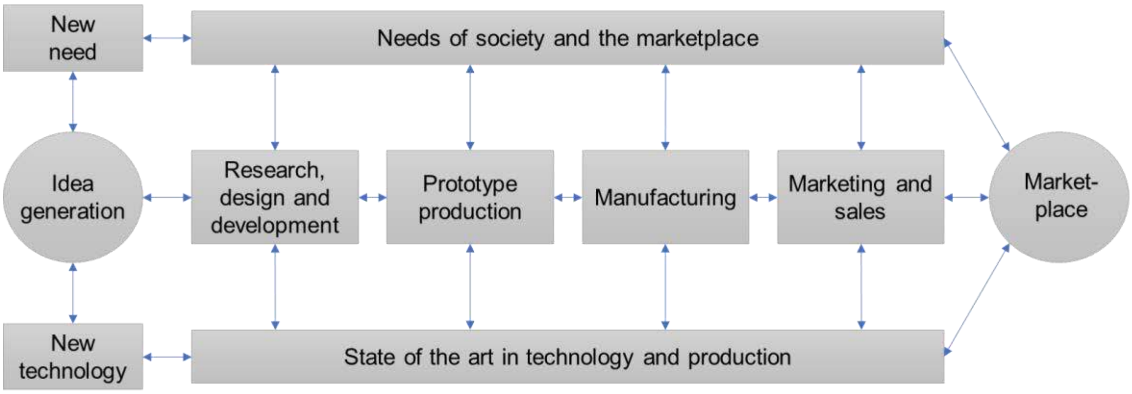

Figure 4: Third-generation innovation model - coupling (adapted from [6]).

The third-generation innovation models introduced multi-directional information flows within organisations, overcoming the linear shortcomings of earlier models by incorporating interaction and feedback loops between innovation stages, organisational functions, and the marketplace [10], [11]. This coupling model featured sequential processes with feedback loops, enhancing integration and requiring effective communication and coordination [6]. Success depended on coordinating multiple tasks, reflecting a multifaceted approach to innovation management [18]. Despite integrating internal activities, these models focused primarily on internal knowledge development, with limited collaboration with external parties [32]. The third generation highlighted the highly integrated nature of innovation activities and functions [20].

3.4 Fourth-generation: integration management

The early 1980s marked a period of economic recovery, with organisations focusing on core businesses and technologies [6]. This era saw the emergence of innovation strategy [33] and a growing emphasis on shortening product innovation timeframes to enhance competitiveness [6]). Japanese companies excelled in global markets through their “just-in-time” (JIT) philosophy, which aimed to produce quality products at the right time with minimal inventory [34]. Key features of Japanese innovation systems included integration and parallel development [35], forming the basis of fourth-generation innovation management.

Fourth-generation innovation models are built on the third-generation with a stronger focus on technology strategy, global strategy, strategic alliances, and information technology [36]. Innovation management now involves integrated activities across departments, with simultaneous rather than sequential innovation processes, emphasizing functional overlap and effective communication [6], [10], as shown in Figure 5.

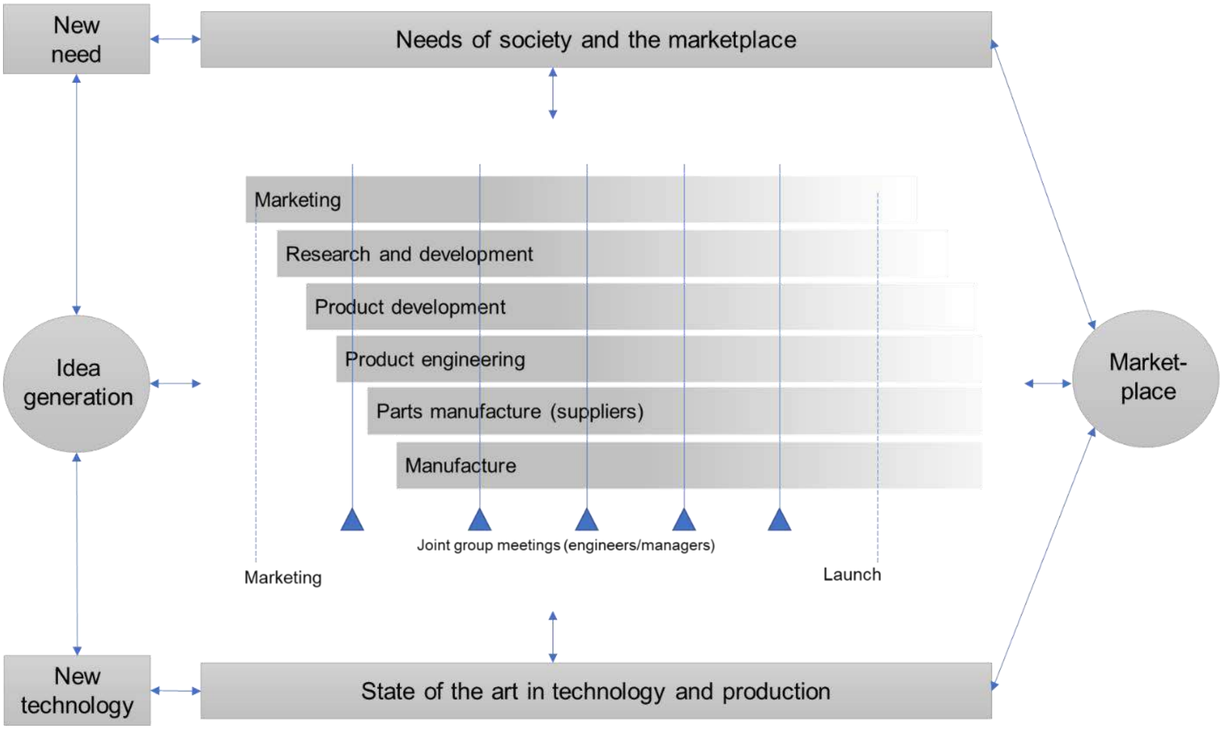

Figure 5: Fourth-generation innovation model - integration management (adapted from [6]).

The shift from third to fourth-generation innovation models marked a transition from an internal to an external knowledge focus. Fourth-generation models emphasised non-linear, inter-organisational information flows through partnerships [11]. The key philosophy was knowledge creation within organisations, with external input from suppliers and partners [10]. Innovation became collaborative, involving multiple partners, making execution more complex [11]. Unlike third-generation models, fourth-generation models were fully integrated and non-linear [16].

A practical example of fourth-generation innovation management is the concept of concurrent engineering, shown in Figure 6.

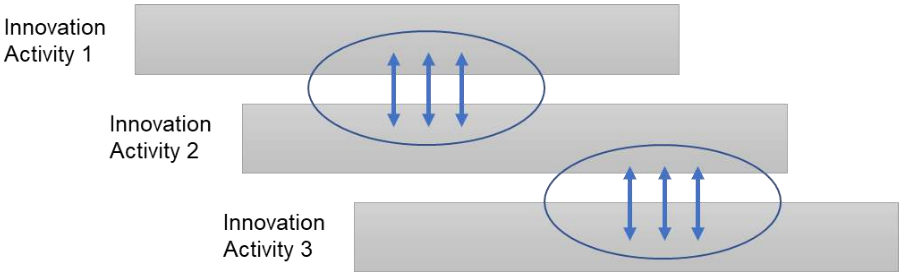

Figure 6: The concept of concurrent engineering as example of fourth-generation innovation management (adapted from [37].

Concurrent engineering is based on the principle that multiple cross-functional teams work in parallel on separate aspects of the innovation initiative [37]. By performing several development activities concurrently, the time involved in getting a new product to the market is decreased considerably [37]. A challenge for innovation management is the often complex technical coupling between the teams required to integrate activities effectively [38]. In a concurrent engineering environment, not all tasks can be executed simultaneously; however, innovation managers must aspire to achieve maximum overlap between otherwise sequential activities [38]. The principles of concurrent engineering were also incorporated into established models for innovation, such as the Stage-Gate process to overcome its rigidity [39].

3.5 Fifth generation: systems integration

In the early 1990s, the National Centre for Supercomputing Applications introduced the World Wide Web, marking the rise of the global mainstream internet. Berners-Lee [40] invented the web as a "linked information system" and a prominent part of the internet, facilitating human interaction through technological networks. Since its inception, the web has evolved significantly. Web 1.0, the first generation, emerged as a read-only platform where organisations broadcast information. This early version of the web provided limited user interactions, focusing primarily on searching and reading information [41].

Proposed timeframes for the fifth-generation innovation process models [5], [16], [42], [43] parallel Web 1.0's era [41], circa 1990s to mid-2000s. Key to this era was system integration, strategic collaboration with external partners, and customer engagement [6]. Though scholars agree on the onset of the fifth generation and its emphasis on systems integration none directly tie it to Web 1.0's rise [5], [16], [42], [43], [44].

During this period, organisations gained unprecedented access to data, facilitating information gathering from suppliers and customers, and market trend analysis [45]. Web 1.0, emphasizing read access, spurred intense marketing efforts [46]. Websites mainly served to showcase products and services, offering catalogues and contact options [45], aiming for constant availability and establishing an online presence [47].

Fifth-generation innovation management overcame geographical constraints, similar to the fourth, but with web-enabled system integration (Figure 5). Like the technology-push focus of the first generation, Web 1.0 lacked interaction, a flaw rectified by Web 2.0, coinciding with the sixth generation of innovation management [42], [48], [49].

3.6 Sixth generation: network integration

In the mid-2000s, Web 2.0 emerged, allowing user interaction and content modification, fostering collaboration and collective intelligence [47]. It facilitated global network integration [50]. Concurrently, Chesbrough [51] introduced open innovation, marking the sixth generation of innovation management [42]. Open innovation contrasts with closed innovation, where internal processes lead to internally developed products [52]. Open innovation involves purposeful knowledge exchange to accelerate internal innovation and expand external markets [53]. Figure 7 illustrates the differences between closed and open innovation models. Open innovation assumes that organisations can and should use external and internal ideas, and internal and external paths to the market, aiming to advance their innovations [54].

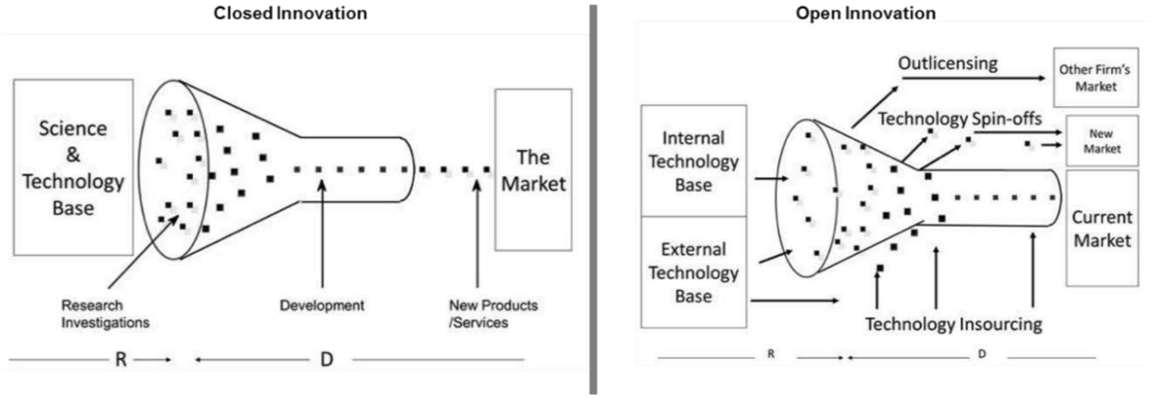

Figure 7: Comparing closed and open innovation processes (adapted from [52]).

The Cyclic Innovation Model (CIM) by [12], illustrated in Figure 8, embodies sixth-generation innovation management principles through open innovation. It depicts innovation as a holistic process, interlinking changes in science, industry, technology, and markets [12]. Although [12] classify it as a "fourth-generation innovation process model," their timeline differs from this study's. They combine the timelines for the third and fourth generations and the fifth and sixth generations into a single fourth generation. However, this study argues for distinct generations based on contextual shifts leading to innovation management evolution. The CIM aligns with the principles of sixth-generation innovation management within this context.

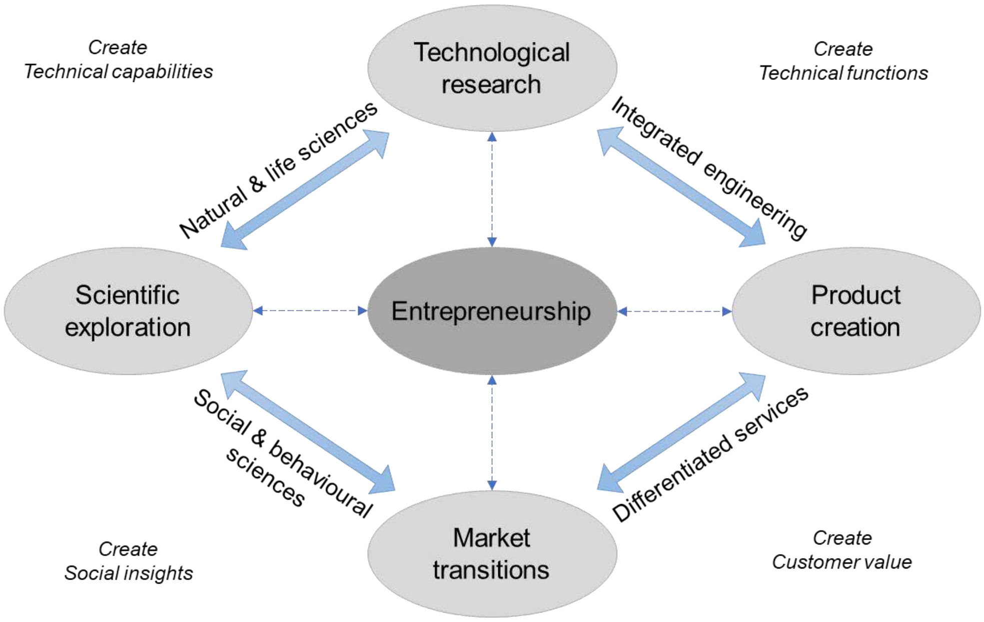

Figure 8: Cyclic innovation model as example of sixth-generation innovation management (adapted from [55]).

The CIM, designed for iterative idea progression in any direction, reflects the fluidity of innovation processes [12]. [56] also emphasises smooth transitions between stages. Figure 8 illustrates a perpetual, interconnected innovation process [57], aiding organisations in gathering, utilizing, and leveraging information and knowledge for competitive advantage [58]. Open innovation, with entrepreneurship as a pivotal driver [55], organizes interconnected cycles, linking social sciences with engineering and life sciences with market goals [12]. Recent research positions open innovation as the pinnacle of innovation management [5], [59], [60], orchestrating global innovation networks [61]. Managing innovation communities becomes crucial [62]. With advancements like the 4IR since Web 2.0's advent, a new generation of innovation management may be emerging [63].

3.7 Towards a next generation?

Innovation management has progressed through generations, evolving from technology push to open innovation. Each era introduced new best practices, adapting to changing social, economic, and technological landscapes [3]. The web's evolution significantly influenced innovation management. Web 1.0 facilitated the fifth generation through systems integration, emphasizing information sharing [50]. Web 2.0 ushered in the sixth generation, emphasizing network integration and interactive connectivity [50]. Web 3.0, emerging alongside the Fourth Industrial Revolution (4IR) in the mid-2010s [47], [63] focuses on immersive knowledge connections [50]. As innovation management adapts to changing contexts, Web 3.0 and the 4IR features can reshape societal, economic, and technological landscapes, shaping present-day innovation [3].

[59] proposed a potential seventh generation of innovation management, emphasizing innovation ecosystems, global partnerships, and human-centric organisations, but no formal adoption has occurred. Innovation process management, evolving through generations, has become increasingly complex [3]. Contextual innovation management has been suggested to address this complexity, advocating adaptation to specific organisational and societal contexts [3], [64]. Instead of introducing a new mainstream generation, contextual innovation offers a portfolio approach, allowing organisations to tailor their innovation processes to their unique contexts [3]. Scholars like [64], [65] stress the importance of aligning innovation management with organisational strategy and adapting to changing circumstances. Even during the prevalence of sixth-generation open innovation, older linear and non-linear models may remain relevant in different contexts [65].

As [64] proposed, contextual innovation requires adapting innovation practices to specific contexts. Understanding different innovation management approaches and their pros and cons is essential for selecting the best approach [3]. Innovation is crucial for survival in today's competitive landscape [1]. However, poorly managed innovation can lead to organisational downfall [65] and must be quantified.

4 FRAMEWORKS TO ASSESS INNOVATION MANAGEMENT

4.1 Progression towards innovation measurement frameworks

During the fourth-generation era of innovation management, starting in the 1980s, organisations prioritized enhancing innovation for growth and diversification [6]. [66] stressed cultivating entrepreneurship for successful innovation, expanded by [67] into a framework for measuring innovation capabilities. Innovation strategy management began incorporating measurement for improvement [33]. Benchmarking gained attention through the Malcolm Baldrige Award and the Deming Prize, applying sophisticated frameworks [68]. Initially, innovation performance assessment focused on process inputs and outputs [69] yielding compliance insights but lacking actionable performance improvement plans [70]. [71] introduced innovation auditing, comparing practices with targets or best practices. Audits, crucial for renewing innovation strategy [72], identify strengths, weaknesses, and areas needing focus for innovation management improvement [73], [74]. Since measuring innovation in and outputs indicates performance rather than explaining it, innovation auditing addresses this limitation and enables the development of strategic interventions for improvement [74].

[71] pioneered the comprehensive innovation audit, expanding evaluation beyond inputs and outputs to assess various process stages. Their framework, depicted in Figure 9, focuses on the innovation process and performance, integrating enablers like resource deployment and management leadership. This model aligns with fifth-generation process models, consisting of four interconnected stages.

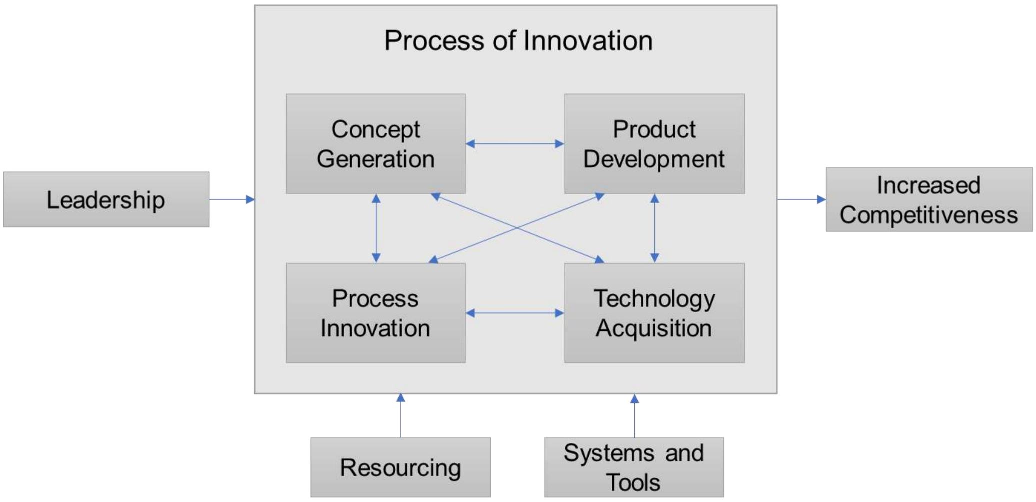

Figure 9: An assessment framework for innovation auditing (adapted from [71]).

Before [71] technology innovation audit, innovation assessment primarily focused on process inputs and outputs. A competence audit evaluates inputs like human and organisational skills, such as resources, leadership, and management, while a performance audit assesses process outputs [71]. These audits provide insight into an organisation's innovation capabilities, addressing innovation's qualitative and nuanced nature [75]. While absolute audit scores are elusive, developing measures can aid in evaluating an organisation's innovation management capability [75].

The competence audit enables the measurement of inputs to the innovation process, which indicate if the organisation is doing enough of the right activities to reach its goals and whether appropriate resources are allocated [76]. Examples of input measures include research and development spending as a percentage of sales, the number of innovation projects started in the past year, and the number of new ideas in the pipeline per year [77]. Interestingly, [78] indicated that measurement techniques tend to concentrate on financial indicators as inputs, while the softer inputs of skills and knowledge are poorly represented in publications. Input measures play a valuable role in innovation measurement because they are responsive, and enable an organisation to react to changes sooner [79].

The performance audit, spearheaded by [71], scrutinizes the measurable outcomes of technology innovation, aiming to enhance competitiveness (Figure 9). It demands metric identification for output measures, facilitating quantitative comparison of current and targeted performance in innovation management [80]. Output measures gauge if organisational activities and resources yield desired innovation outcomes, like new technology launches or profits [77]. However, top-down implementation and lack of employee involvement can hinder performance audit effectiveness [79], [81].

Despite its merits, the performance audit alone isn't sufficient for learning and improvement, lacking insights into causality [71]. Outputs, while crucial, might not offer actionable insights or illuminate the innovation process's inner workings [79], [80].

Addressing this, the process audit introduced by [71] focuses on innovation initiative actions and adherence to best practices, fostering employee participation [82]. Process audits delve into holistic innovation attributes, revealing gaps between organisational practices and best standards [72], [83]. Yet, some throughput measures may isolate targets like patent filings, neglecting comprehensive evaluation across all innovation stages [79]. Integrating these audits throughout the innovation life cycle provides nuanced insights compared to input and output measures alone, offering a more comprehensive view of innovation management [79].

4.2 The purpose of innovation assessment frameworks

The innovation audit developed by [71] ignited interest in the topic, and a number of frameworks to assess innovation were published thereafter. [84] extended the applicability of the audit by [71] to service organisations. [85] developed a framework to determine the potential for capability development within organisations. [86] developed a framework to evaluate the management of ideas for innovation in an organisation. [87] developed a framework that measures ten types of innovation which, they argue, occur simultaneously in an organisation. [88] propose a framework that synthesises the measurement of inputs, indicators of the innovation process, outputs, innovation strategy, culture and structure, and idea and knowledge management. Each framework construct by [88] is evaluated against pre-determined performance indicators.

Although each framework mentioned undoubtedly contributes to innovation theory regarding evaluating innovation management in organisations, elaborating on each would be futile for this research study. Assessment frameworks represent how innovation is managed in a particular organisation [89]. Considering that the framework by [71], as an example, was developed during the advent of fifth-generation innovation management, adaptations to their framework (Figure 9) might be needed to account for the features of the sixth generation of innovation management and the 4IR. Using the cyclic innovation model (Figure 8) as foundation, [89] advises that frameworks must reflect the reality that an organisation faces, especially in the context of increasing uncertainty and complexity. Additionally, [75] emphasise that the format of the particular framework should not be prescriptive. The central requirement for any measurement framework is that it enables an integrated review of the factors influencing innovation success, and how the process management might be improved [75].

Innovation literature that provides guidance to organisations regarding measurement frameworks for innovation management [71], [75], [89] was recently augmented through the publication of the first international management standard for innovation by the International Organisation for Standardisation (ISO). The ISO 56000 family of standards provides a framework for organisations to implement, maintain and improve innovation management systems [90].

Considerable research has been devoted to the questions of what and how to measure innovation [88], [91]. However, the risk exists that focus is primarily placed on the questions, while managers lose sight of the practical objective of the innovation assessment, which is to reflect and improve the management of the process [75]. Determining what to measure is context-specific and depends on how the organisation manages innovation [75]. Through measuring indicators of successful innovation practices, managers must remember that the aim of the assessment is not to score absolute points, but to enable the operation of an effective learning cycle by adding the dimension of structured reflection [92]. Such assessments do not necessarily have to involve comparison with another organisation, but can usefully be done against ideal-type or normative indicators of good practice [75]. The purpose of innovation management assessments is not simply to collect data but to use the information to drive improvement in the innovation process and how it is managed [90]. A necessary precursor of improvement is the transparency of the current innovation management performance in the organisation [92]. Regular and effective measurement of innovation management in the organisation is essential [93].

4.3 Limitations Identified to Innovation Measurement Frameworks

4.3.1 Limited assessment of the innovation process stages

The previous sections described different aspects of innovation that can be assessed, such as input, throughput, and output measures.

The evaluation approach is derived from operations management [94] and is based on organisational-level innovation outputs. Output measures do not assess the distinct innovation process stages. This assessment method reveals organisational processes and tools that are "more or less effective" at contributing to innovation outcomes [92]. Even though organisations are more likely to measure innovation outputs than other indicators [91], results from such assessments do not provide a basis for improvement, rendering it an inadequate approach to evaluate innovation management for this study.

The approach for assessing inputs [29], as well as throughputs [71], is rooted in product development and based on the identification of success factors for innovation-related themes, such as industrial innovation [20], product innovation [95], or process innovation [96]. This approach yields innovation attributes associated with success [92]. Focusing only on inputs to innovation does not provide any insight into what happens during the management of the different process stages, and no judgment can be made regarding the effectiveness of innovation in an organisation [79]. Therefore, an evaluation of each process stage is needed to gain relevant insights from measuring how innovation is managed in an organization.

[71] were the first to apply such an approach to innovation auditing (Figure 9), and several others followed in adopting a process audit approach. However, assessing factors contributing to innovation success throughout the different process stages tends to feature less than the measurement of inputs and outputs [79].

4.3.2 Limited evaluation of holistic attributes of innovation

The success factors to measure during an innovation management assessment depend on how the organisation manages innovation [75], [97]. Although such measures are context-specific, literature does guide what factors to consider for measurement [81].

The previous section highlighted the predominance of inputs and outputs as measures for innovation assessments. Exacerbating this disjointed approach to measuring innovation, assessments tend to concentrate on financial measures, such as funding for innovation projects, spending on advertising, and revenue from new products [78]. In other instances, innovation assessments focus on isolated metrics, such as the number of patents produced in a given period [78], the number of ideas generated [86], and the average time from idea submission to feedback [88]. However, other factors related to innovation management, such as innovation strategy and organisational culture receive limited attention in the literature [78]. Identifying measures for an innovation management assessment requires a holistic perspective and fundamental understanding of all the relevant factors that enhance the organisation's innovation ability [72].

4.3.3 A lack of assessing interrelationships between success factors

The ISO 56000 family of standards promotes an integrated approach to identifying success factors for innovation management assessments, and suggests factors such as innovation strategy, innovation organisation and culture, innovation life cycle processes, and innovation results [90]. "Such aspects of innovation management are interrelated and jointly managed to maximise value" [92]. However, innovation management assessments do not yet evaluate the interconnection between factors.

Publications tend to evaluate a single factor in isolation, without considering the relationships between various factors [98]. Literature does identify the importance of determining the influence that factors have on others, referring to the need for measuring interrelationships [89], interactions [99], interlinkages [92], and interconnections [75] that exist between factors. Nevertheless, such assessments have not yet been featured in publications.

5 CONCLUSION

The management of innovation has evolved over several decades and across different generations. The historical overview of innovation management began around the 1950s when innovation followed a linear, technology-push approach. In subsequent years, societal changes triggered revisions of managerial approaches for innovation, which resulted in the progression of innovation management across several generations. Innovation management is characterised by a highly integrated process, with organisations operating in a complex innovation ecosystem within a global marketplace.

The appraisal of the literature revealed several relevant frameworks for the assessment of innovation management, such as the works of [71], [78], [85], [86], [88], to name a few. Furthermore, the recently-published ISO 56000 family of standards provides valuable guidance to managers regarding the management [92] and assessment [92] of innovation in organisations. However, several limitations were identified which are associated with published innovation measurement frameworks. The primary limitations include the limited assessment of the different innovation process stages, the limited evaluation of holistic attributes of innovation, and a lack of determining interrelationships between success factors as part of innovation management assessments [100].

This study identified the absence of an integrated framework for managing technology innovation in an organisation. The appraisal of literature has illuminated the problem and described the disjointed perspective prevalent in publications that do not address the overall impact of the interactions of different factors on each other. The limitations have revealed the need to evaluate interrelationships between success factors within each innovation process stage.

Innovation theory was explored for guidance regarding published frameworks that enable the evaluation of how innovation is managed in an organisation. Several relevant frameworks were identified, including the recently published ISO 56000 family of standards, designed to provide a framework for organisations to implement, maintain and improve innovation management systems. Appraisal of the published frameworks illuminated a need to evaluate interrelationships between success factors for each innovation process stage. Such an integrated evaluation of technology innovation management is not featured in innovation literature and intends to create a comprehensive basis for identifying areas for improvement.

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ASSESSING INFRASTRUCTURE CONDITION IN SOUTH AFRICATHROUGH TOPIC MODELLING OF ONLINE NEWS ARTICLES

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ABSTRACT

The lack of comprehensive data on the condition of infrastructure across South Africa makes it difficult to compile holistic infrastructure report cards. Without transparency, decision-makers cannot allocate resources optimally. Online news articles can provide insights into the condition of infrastructure, but the analysis of thousands of articles is time-consuming and costly when done manually. This study proposes the use of topic modelling to semi-automatically evaluate the condition of infrastructure in South Africa from online news articles. More than 26,000 online news articles were collected, grouped into topics using topic modelling, and analysed. The proposed methodology enables the discovery of emerging issues and illuminates infrastructure sectors previously underreported in infrastructure report cards. The findings demonstrate the potential of using online news articles and topic modelling to enhance infrastructure report cards.

Keywords: Infrastructure Condition Monitoring, Infrastructure Report Cards, Natural Language Processing, Topic Modelling

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1 INTRODUCTION

Investment in public infrastructure leads to economic growth, which in turn alleviates poverty and reduces income inequality [1], [2], [3], [4], [5]. Given the critical role of infrastructure, it is imperative to allocate resources optimally to develop and maintain infrastructure. Infrastructure report cards (IRCs) support infrastructure investment decisions by providing a consolidated and consistent assessment of a country's infrastructure, enabling the identification of gaps, informing strategic planning, and promoting stakeholder engagement [6]. IRCs are used in various countries, including Australia, the Democratic Republic of the Congo, Canada, Kenya, Ghana, Nigeria, Rwanda, Spain, South Africa, the United Kingdom, the United States of America and Zambia [6], [7], [8].

The South African Institution of Civil Engineering (SAICE) compiles IRCs for South Africa. The first South African IRC was published in 2006, followed by subsequent editions in 2011, 2017 and 2022 [7]. Over time, these reports have become more comprehensive. The 2006 SAICE IRC covered eight infrastructure sectors, which have since been expanded to thirteen sectors in the 2022 IRC [7], [9]. Infrastructure sectors are further divided into subsectors, to provide a more granular view of their condition, similar to the approach used in the IRCs of other countries like Australia, Canada, and Zambia [6]. For instance, healthcare infrastructure is divided into hospitals and clinics in the 2022 SAICE IRC [7].

To allow subsectors to be compared over time and against one another, a common grading scale is employed [7], [8]. This scale ranges from A, indicating infrastructure in excellent condition, to E, representing infrastructure that has failed or is near failure and poses safety risks [7], [9]. The intermediate grades include B for good condition, C for acceptable but stressed infrastructure, and D for infrastructure struggling with demand and poorly maintained [7], [9]. Along with grades for subsectors, the report cards also include a text summary which provides additional context with regards to the grade [7].

To ensure infrastructure assessments are meaningful and support evidence-based decision-making, infrastructure conditions must be evaluated objectively using accurate data. Schmitz and Eksteen [10] illustrated the significant impact of using inaccurate data in infrastructure planning in South Africa. By comparing the investment required to provide education infrastructure in Gauteng using data from the Department of Basic Education versus verified data, their analysis revealed that relying on inaccurate data could result in an additional cost of 40 million South African Rand [10].

While efforts are made to perform data-based objective assessments, the SAICE IRC was independently criticised as being subjective [6]. This critique is not surprising, given that one of the main themes echoed throughout the latest SAICE IRC is a lack of reliable data [7]. In extreme cases, essential public infrastructure, such as municipal electricity distribution networks, was not rated [7].

Obtaining accurate infrastructure data is not without its challenges. In the 2011/22 administration year, only 38 out of 257 South African municipalities achieved a clean audit [11]. These failures point to systemic issues, including poor record-keeping, lack of accountability, and financial mismanagement, which complicate the task of gathering accurate infrastructure data. Moreover, the SAICE has a limited budget and resources available, preventing the institution from gathering data themselves [12].

In the meantime, investment decisions are still being made, but without reliable data, these decisions are likely to be sub-optimal, potentially impeding economic growth. Consequently, the need arises to find alternative data sources to assist the SAICE with the compilation of IRCs, taking into account the limited resources available.

This study proposes using online news articles as an additional source of information to assess the infrastructure condition of South Africa. South Africa has several reputable online news agencies that are generally trusted and considered independent [13]. According to the Reuters Institute for the Study of Journalism, trust in news in South Africa remains high, with 57% of the sample population expressing confidence in news sources [13]. Furthermore, Reporters Without Borders ranked South Africa 25th in their World Press Freedom Index, reflecting the relative freedom of the media landscape in the country [14].

Online news articles often contain valuable information about infrastructure issues, such as reports on service disruptions, maintenance backlogs, and public dissatisfaction with infrastructure quality. For instance, the excerpt from the online news article illustrated in Figure 1 highlights the poor state of water and electricity in Soshanguve, a township in South Africa. To establish the overall condition of infrastructure in Soshanguve, multiple online news articles can be collected and analysed. The manual and regular collection and analysis of thousands of online news articles would however require significant and ongoing human effort, which is both time-consuming and costly.

Sosh residents protest power, water outages

They haven’t had electricity in over 24 hours amid water shortages in the last few days.

January 31, 2023 Nhlawulo Chauke 1 minute read

Figure 1: Excerpt of an online news article published on the Pretoria Rekord Central news website (adapted from [15]).

This study aims to establish whether online news articles about infrastructure can be efficiently collected and analysed to assist in assessing the condition of infrastructure in South Africa. Towards this extent, a methodology is developed to automatically retrieve online news articles, which are then analysed using topic modelling - a natural language processing technique that identifies topics from a large corpus of text [16]. By categorising the articles into topics, the study enables the efficient evaluation of a large number of news articles by focusing on a much smaller subset of categorised articles.

The paper is structured as follows: An overview of topic modelling is provided in Section 2. The methodology developed to collect online news articles and to group the collected articles into topics is discussed in Section 3. The effectiveness of the proposed methodology is evaluated by collecting and categorising more than 26,000 news articles. The results of this evaluation are discussed in Section 4. Section 5 concludes the paper with a discussion on the appropriateness of using online news articles to evaluate infrastructure conditions.

2 TOPIC MODELLING

Topic modelling is a natural language processing technique that categorises large volumes of text data by grouping similar text documents and representing a group of documents as a topic [16]. Topic modelling algorithms use inherent patterns in text data to group similar documents together which eliminates the need for a list of predefined topics or annotated documents [16]. The capability to discover new topics is particularly valuable in the context of infrastructure evaluation, where new topics can emerge. For instance, if there is a sudden increase in reports about water shortages in a particular region, topic modelling can identify and group these reports. To illustrate how topic modelling works consider the set of text documents in Table 1. Initially, the topic of each text document is unknown. After applying a topic modelling algorithm, these documents may be categorised into two topics: road and water.

Table 1: Text documents without topics.

Document text	Topic	Assigned topic
There was a water shortage	?	Water
There are many potholes in the road	?	Road
The lack of water is upsetting residents	?	Water
Nothing is being done about the road condition	?	Road
The road is in terrible condition	?	Road
There is no water in the taps	?	Water

Topic modelling has been used in multiple disciplines to aid in the analysis of large data sets of documents [17]. Within the scope of infrastructure, Sun & Yin [18] used topic modelling to discover themes and trends in transportation research. Their analysis demonstrated that topics in transportation can be detected in academic journals over time, which aids in the identification of emerging topics. Zhou *et al.* [19] used topic modelling to understand public opinion concerning the construction of the Hong Kong-Zhuhai-Macao Bridge (HZMB). Their study showed that topics related to the condition of the HZMB, although not their primary aim, can be extracted with topic modelling. For instance, the projected lifespan of the HZMB and the daily usage were apparent from the topics found.

In the context of South Africa, Moodley and Martivate [20] applied topic modelling to understand the political topics covered in news during elections. Mutanga and Abayomi [21] and Kekere *et al.* [22] separately analysed Twitter, now known as X, data using topic modelling to discover the issues being discussed in South Africa concerning the coronavirus disease 2019.

Although topic modelling has shown promising results within the scope of infrastructure and the content of South African news, no prior work was found that specifically aimed to assess the condition of infrastructure from online news articles using topic modelling.

To perform topic modelling, various algorithms can be used. Traditional approaches, such as Latent Dirichlet Allocation (LDA) and Non-Negative Matrix Factorisation (NMF), require the number of topics to be known before application and are inferior in performance to new topic modelling techniques such as BERTopic [23], [24]. Unlike, LDA and NMF, BERTopic can automatically determine the number of topics to extract and has shown promising results in recent topic modelling studies [25], [26], [27], [28].

The BERTopic algorithm employs five sequential sub-models to assign topics to documents [29]. Documents are first represented numerically. Next, the size of these numerical representations is reduced to facilitate the grouping of documents during the third step. After clustering the documents into groups or topics, each topic is explained using keywords over the final two steps. The process used to assign topics to documents is illustrated in Figure 2 and is subsequently discussed in more detail.

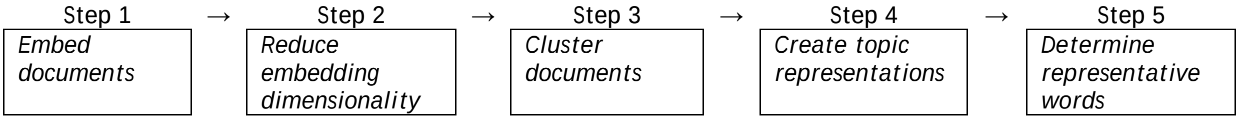

Figure 2: BertTopic steps

*Sub-module 1***:** The first sub-module of BERTopic transforms each document from text to a numerical representation to allow for subsequent processing. To perform this transformation, an embedding model is used. While custom embedding models can be developed, it is common practice to use models previously trained on millions of documents, as they provide robust and efficient representations without the need for extensive computational resources.

Sub-module 2: Since the grouping of documents into topics is computationally expensive, the dimensionality of the embeddings must first be reduced. Uniform Manifold Approximation and Projection (UMAP) preserves the local and global characteristics of the embedding in a lower dimension [29], [30].

Sub-module 3: The reduced-dimensional embeddings are then grouped using a clustering sub-module. Hierarchical Density-Based Spatial Clustering of Applications with Noise (HDBSCAN) can automatically determine the number of clusters to extract and can identify outlier documents [29], [31]. Clustering algorithms group documents but it does not inherently explain what each group represents. The fourth and fifth sub-modules of BERTopic aim to explain what each group represent.

Sub-module 4: After clustering the document embeddings, the original text of all the documents assigned to a specific cluster is concatenated to form a single document. The frequency of each word within a cluster is then calculated, creating a bag-of-words representation for each cluster [29].

Sub-module 5: To determine which words in a cluster are the most representative of the cluster, the class-based term frequency-inverse document frequency (c-TF-IDF) method is used. This approach uses the bag-of-words representation to calculate an importance score $W_{x,c}$ for each word x in cluster c. $W_{x,c}$ is calculated as

$$W_{x,c} = ||f_{x,c}|| * log(1 + \frac{A}{f_x}) \tag{1}$$

where $||f_{x,c}||$ is the L1-normalised frequency of word x in cluster c and accounts for the variation in the number of words per cluster, A is the average number of words per cluster, and f_x is the frequency of word x across all clusters. A larger score is assigned to words that are frequently used in a cluster and are distinctive when compared to the overall usage in the articles. To infer a topic of a cluster, the N words with the highest importance scores can be analysed, referred to as the top-N words of a topic.

Based on the specific sub-modules used and the selected hyperparameter values of each sub-module, different topics are identified. Manual evaluation and comparison of topics between approaches are time-consuming. Therefore, evaluation metrics are used as a proxy to infer the quality of topics obtained. The most prevalent topic modelling performance measures used in the literature are topic diversity and topic coherence [32], [33], [34]. Both topic diversity and topic coherence are determined using the top-N words. Topic diversity can be measured using the Proportion of Unique Words (PUW), which is defined as

$$PUW = \frac{t_{unique}}{t_n}. \tag{2}$$

Here t_{unique} is the total number of unique top-N words, and t_n is the total number of words across topics [32]. PUW ranges from zero to one, where a PUW value close to one indicates that topics are described by different words and are therefore considered diverse.

Topic coherence measures how related the top-N words are in each topic and is commonly measured using Normalised Pointwise Mutual Information (NPMI). NPMI measures the extent to which words in a topic co-occur more often than would be expected by chance. The NPMI between the words w_i and w_j is defined as

$$NPMI(w_i, w_j) = \frac{1}{-\log P(w_i, w_j)} \log\left(\frac{P(w_i, w_j)}{P(w_i)P(w_j)}\right). \quad (3)$$

Here, $P(w_i, w_j)$ is the probability that the words w_i and w_j co-occur, and $P(w_i)$ and $P(w_j)$ are the individual probabilities of the words. NMPU ranges from negative one to positive one, with higher values indicating coherent topics.

When applied to online news articles, BERTopic produces a list of topics and representative words for each topic. By studying the topics and associated keywords: (i) non-infrastructure topics can be identified and removed, (ii) emerging infrastructure topics can be identified, and (iii) infrastructure evaluation can be performed efficiently by focusing on a smaller number of topics and associated articles.

3 METHODOLOGY

To extract topics from online web articles, a four-step methodology was developed. The methodology starts with the collection of news articles. Once collected, the articles are preprocessed to address data quality issues such as duplicate articles. Topic modelling is then applied to the cleaned data set, followed by an analysis of the identified topics. The methodology developed is illustrated in Figure 3, and subsequently discussed.

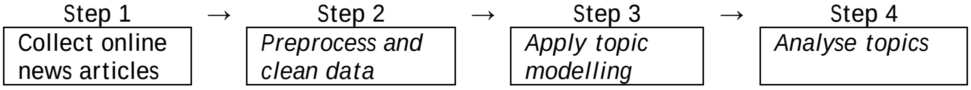

Figure 3: Proposed methodology to identify infrastructure topics from online news articles

3.1 Step 1: Collect online news articles

To create a data set of news articles, online news websites must first be identified. Since news websites cover a variety of news, not all related to infrastructure, a process is required to identify and download relevant articles from the identified news websites. To identify relevant news articles, the search strategy suggested by Georgieva-Trifonova and Dechev [35] was adopted and used. Keywords related to infrastructure sectors are first defined and refined through a trial-and-error manner. Once defined, these keywords are used to search for relevant articles which are stored in a database. Each entry in the database includes the article title, subtitle, text, author, publication date, extraction date, uniform resource locator, and the name of the news website. The steps followed to download news articles are outlined in Algorithm 1.

Algorithm 1: Online article retrieval

```
Input: websites W; keywords K; maximum pages max_results_pages;
Output: database D;

For each website w in W
    For each keyword k in K
        Set p equal to 1
        While $p \leq$ max_result_pages
            Search the website w using keyword k and page number p;
            store the webpage as R
            If R contains no articles, break the loop
            For each article a in R
                Extract article data and add it to database D
```

```
9    Increment $p$ by 1
```

3.2 Step 2: Preprocess and clean data

Since different keywords can return the same article, the database created in Step 1 can include duplicate news articles. To avoid skewing the results, duplicate articles must be identified and removed. A single text field is created by concatenating the topic title, subtitle, and main text. Thereafter, instances with an empty concatenated text field are removed.

Since embedding models are not always trained using non-standard text characters, these characters must be removed. To remove non-standard text characters the Python library *unicodedata* [36] was used. Lastly, since the choice of embedding model should be informed by the language(s) used in the articles, the language of each article was determined using the Python library *langdetect* [37].

3.3 Step 3: Apply topic modelling

Topic modelling can be applied to the overall data set. However, when applied to the entire data set, topics might be formed based on frequently mentioned locations and the topics can be biased toward news websites with more articles. Therefore, BERTopic was applied to the data extracted from each news website individually. Developing a model per news website not only mitigates these biases but also improves the credibility of the results since the application of topic modelling is accessed on multiple data sets.

Two pre-trained embedding models were considered: *all-MiniLM-L6-v2* an English embedding model, and *paraphrase-multilingual-MiniLM-L12-v2* a multi-language embedding model that supports over 50 languages [38]. To reduce the size of embeddings UMAP [30] was used. Clustering was then implemented using HDBSCAN [31]. Since the output of HDBSCAN is sensitive to the minimum number of documents required to form a cluster, minimum cluster sizes of 10, 15 and 20 were considered. A bag-of-word representation was then obtained for each cluster and the c-TF-IDF was subsequently calculated. To refine the top 10 topic words, KeyBERTInspired was used [39].

The different topic models considered were named using the following convention: BERTopic models that used the English embedding *all-MiniLM-L6-v2* starts with the letter *E*, whereas the name of BERTopic models that used the multilingual embedding *paraphrase-multilingual-MiniLM-L12-v2* starts with the letter *M*. The second part of the BERTopic model name was a 10, 15 or 20 which corresponds to the minimum cluster size used in the HDBSCAN sub-model of the respective BERTopic model. For example, *E10* referred to the BERTopic model which used the *all-MiniLM-L6-v2* embedding with a minimum cluster size of 10.

To assist in labelling topics, a topic labelling guide was developed. This guide was used to roughly match infrastructure sectors to topics by considering the top 10 words and the three most representative articles of each topic. To aid in model selection the number of topics, the number of infrastructure topics, the infrastructure coverage, the number of outliers, the PUW, and the NPMI were calculated for each model. These performance measures were then used to select a single model.

3.4 Step 4: Analyse topics

Each topic obtained from the selected model was then meticulously assigned to an infrastructure sector and an infrastructure subsector. While the SAICE IRC infrastructure sectors were utilised for this classification, the subsector classifications were not strictly followed, allowing for the discovery of more granular or novel topics. Similarity matching was used to assign topics to the news website articles not covered by the selected model. For each of the news websites not covered, a topic model with the same configuration as the selected model was selected. To match topics, the cosine similarity was calculated between the topic embeddings of each of the selected topic models and the topic embeddings of the baseline model. Whilst topic matching is not strictly needed, it can speed up the assignment of topics. Once topics are assigned to each newspaper, an IRC can be compiled per subsector by manually analysing the much smaller subset of relevant articles.

4 RESULTS

4.1 Data collection

Online news articles were collected from a single major news website per province (Table 2). The choice of newspaper can bias the result. For example, the Bloemfontein Courant is likely to be more focused on Bloemfontein rather than representing the entire province. However, the number of newspapers selected was deemed sufficient for determining whether infrastructure conditions can be identified and assessed from online news articles.

Table 1: News websites used for data collection.

Province	Name of news website	Homepage uniform resource locator
Eastern Cape	My Gqeberha	https://mygqeberha.com/
Free State	Bloemfontein Courant	https://www.bloemfonteincourant.co.za/
Gauteng	Pretoria Rekord Central	https://rekord.co.za/
Kwazulu Natal	South Coast Sun	https://southcoastsun.co.za/
Limpopo	Bosveld Review	https://reviewonline.co.za/
Mpumalanga	Ridge Times	https://ridgetimes.co.za/
North West	Kormorant	https://kormorant.co.za/
Northern Cape	Diamond Fields Advertiser	https://www.dfa.co.za/
Western Cape	Cape Town Etc	https://www.capetownetc.com/

Keywords were defined for each of the eight infrastructure sectors consistently covered in past SAICE IRCs as well as general infrastructure-related keywords. The keywords selected are provided in Table 3.

Table 2: List of keywords used to search for relevant news articles

Keyword group	Keywords
General	infrastructure, municipality, protest, service delivery, shutdown, strike
Education	learner placement, learner protest, principal, school, school bus, school infrastructure, school overcrowding, school protest, school theft, school vandalism, schools, student protest, teacher
Electricity	blackout, cable, electricity, eskom, load shedding, power, power cut, power outage, power problem, power station, prepaid meter, substation
Healthcare	ambulance, clinic, clinic protest, clinic shortage, health service, healthcare, hospital, hospital capacity, nurses, patients
Rail	derailment, locomotive, metrorail, prasa, rail, rail corridor, rail line, railway, railway line, train, train crash, train service, transnet, train station
Road	bridge, collision, manhole, pothole, road, road closed, road closure, sanral, street light, streetlight, toll, traffic, traffic light
Sanitation	river pollution, sanitation, sewage, sewerage, smell, spillage, stench, stink, water pollution, water treatment
Solid waste	dumping, filth, garbage, landfill, litter, refuse, trash, waste, waste collection
Water	dam level, drinking water, drought, leak, pipeline, reservoir, river, tap, water, water dam, water level, water problem, water quality, water restrictions, water shortage

The *max_results_pages* parameter used in Algorithm 1 was set per newspaper, as opposed to globally, since the websites considered returned a different standard number of articles per page. In total 28,018 news articles were retrieved.

4.2 Data cleaning

Missing values were present in the subtitle (40.78%), author (19.13%), article text (1.84%), title (0.06%), and publication date (0.06%) fields. Four of the nine news websites did not use subtitles and as a result, 40.78% of the total articles did not contain subtitles. The author field was missing for 19.13% of the articles. Automated extraction of the article author commonly failed for articles from *Bloemfontein Courant* and *My Gqeberha* which represented author(s) inconsistently between articles. Only 14 of the 28,018 articles had to be removed since these articles contained missing values for the title, subtitle, and text data fields.

Apart from retrieving the same article using different keywords, duplicate articles were also retrieved when a news website published the same article on multiple dates. A total of 1,868 duplicate articles were removed. The limited number of duplicate articles suggests that the search keywords defined in Table 3 were diverse rather than repetitive. After removing the 14 articles with missing data and the 1,868 duplicate articles, the data set contained 26,136 articles. Of the 26,136 articles, 25,696 were English articles, 428 were Afrikaans articles, and the remaining 12 articles were written in other languages.

The number of news articles collected per news website and year of publication is summarised in Table 4. On average, 2,904 articles were retrieved per news website, with the number of articles per website ranging from 1,543 to 4,131. About 30.62% of the articles were published in 2022. Articles from 2023 represent a smaller proportion of the total number of articles since data collection was performed in the first quarter of 2023. The number of articles retrieved reduced from 2022 to 2016, because a maximum page limit was used in Algorithm 1.

Table 3: Number of news articles per news website and per year

	Year of publication									
News website	**≤2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**Total**
Pretoria Rekord Central	305	197	181	302	513	535	672	1132	294	4131
Bosveld Review	502	296	310	481	468	440	423	493	103	3516
Diamond Fields Advertiser	0	0	0	0	72	501	722	1433	727	3455
Cape Town Etc	31	31	79	206	249	455	680	1264	384	3379
Ridge Times	312	163	248	324	342	412	391	579	130	2901
South Coast Sun	368	160	203	232	279	239	352	727	156	2716
Bloemfontein Courant	371	234	236	196	243	251	384	559	159	2633
My Gqeberha	0	0	0	0	0	0	590	1079	193	1862
Kormorant	0	0	0	0	17	272	470	736	48	1543
Total	1889	1081	1257	1741	2183	3105	4684	8002	2194	26136

To evaluate whether news articles cover the range of infrastructure sectors considered, the number of articles retrieved per infrastructure category was calculated. The search terms defined returned articles for each infrastructure sector across years and news websites, as illustrated in Figure 5. There was an abundance of news articles that covered infrastructure across South Africa over time. However, the manual analysis of the 26,136 articles is unfeasible, necessitating the use of topic modelling to efficiently categorise and analyse the content.

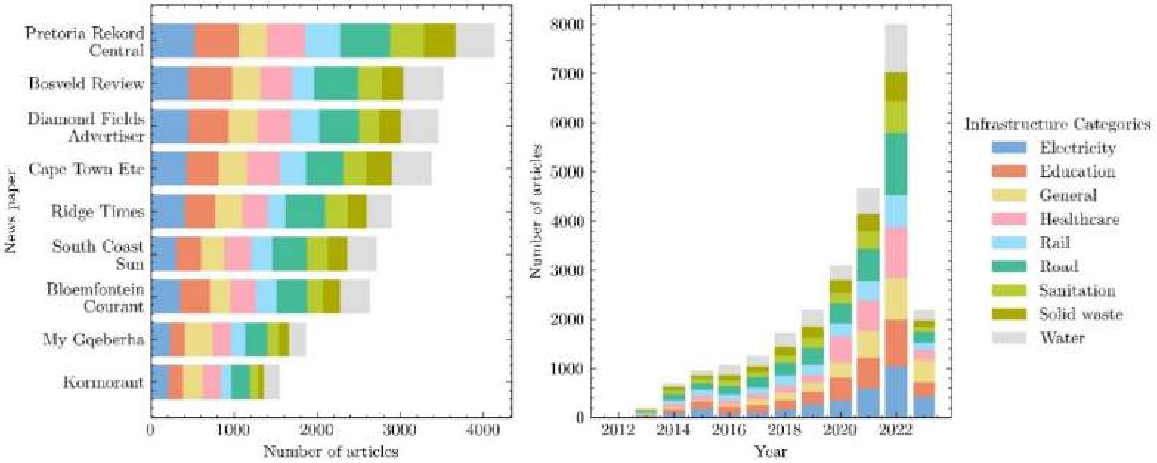

Figure 5: Number of news articles retrieved per search category

4.3 Model selection

The mean performance along with the standard deviation of the six topic model configurations considered is summarised in Table 5. Using topic modelling significantly reduces the number of articles to be analysed. This is evident from the average number of outlier documents across models, which was 25.6%. In addition to the outlier documents, documents assigned to non-infrastructure topics also do not need to be analysed. On average 55.6% of the topics were unrelated to the condition of infrastructure, covering topics such as international news, vehicle reviews, sports events, art, and crime not related to infrastructure, among others.

When the minimum cluster size was increased in increments of five, the average number of topics returned decreased. The decrease in the number of topics was paired with a decrease in infrastructure coverage. However, the reduced set of topics was more unique and less repetitive, according to the PUW and NPMI values obtained.

The large standard deviation among the performance measures can be partially attributed to the large variation in the number of news articles retrieved per news website. The Pearson correlation coefficient between the number of news articles and topics identified was 0.63, indicating that the number of topics increases as the data set size increases. These results suggest that the minimum cluster size should be selected based on the data set size, which supports the recommendation of Grootendorst [40].

Table 4: Mean model performance across newspapers

	Performance measure					
Model	**Topics, #**	**Infrastructure topics, #**	**Infrastructure coverage, %**	**Outlier documents, %**	**PUW, %**	**NPMI**
E10	59 ±19	42 ±9	94 ±9	26 ±4	68 ±9	0.06 ±0.01
M10	55 ±15	39 ±10	93 ±17	28 ±5	66 ±7	0.06 ±0.01
E15	36 ±15	50 ±21	85 ±28	24 ±9	73 ±10	0.08 ±0.01
M15	37 ±11	44 ±10	90 ±12	28 ±7	70 ±8	0.07 ±0.01
E20	25 ±14	49 ±24	71 ±34	21 ±13	75 ±11	0.08 ±0.03
M20	26 ±7	43 ±10	85 ±14	26 ±4	75 ±7	0.08 ±0.01

To further analyse the relationship between the minimum cluster size and the infrastructure coverage, an infrastructure coverage heatmap was constructed for each newspaper and model (Figure 6). *Rail*, *sanitation,* and *solid waste* were the least covered infrastructure topics across models. *Rail* is expected to have variable coverage across news websites, as rail infrastructure varies across the provinces in South Africa. In contrast, *education*, *healthcare,* and *road* had the highest coverage across models. These infrastructure sectors had poor oversight in the latest SAICE IRCs, which can potentially be improved by evaluating the news articles assigned to these topics.

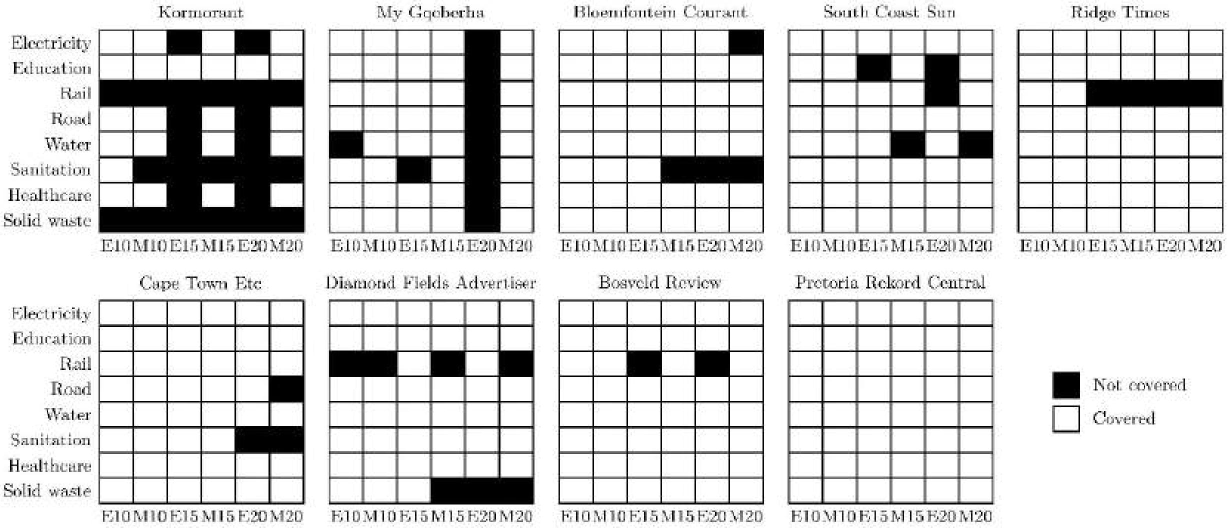

Figure 6: Topic coverage per news website and model

When the minimum cluster size was set to higher values for news websites with fewer than 2000 articles like the *Kormorant* and *My Gqeberha*, the number of topics retrieved was limited. Furthermore, these topics were typically not coherent but rather covered multiple infrastructure sectors and/or themes.

The embedding model used also influenced the number of topics obtained and the infrastructure coverage, as illustrated in Figure 7. In general, more topics were retrieved when the multi-language embedding model was used. When the English embedding model was used, articles written in languages other than English formed distinct topics. For instance, consider the two-dimensional approximation of the embedded *Kormorant* articles using the English embedding model (*all-MiniLM-L6-v2*) and the multilingual embedding model (*paraphrase-multilingual-MiniLM-L12-v2*) illustrated in Figure 7. When the *all-MiniLM-L6-v* embedding model was used, the articles written in Afrikaans formed a distinctive cluster. In contrast, when the multi-lingual embedding model was used, the Afrikaans articles were integrated with English articles. The *paraphrase-multilingual-MiniLM-L12-v2* model was however not specially trained in Afrikaans, and as a result the embeddings obtained may be wrong.

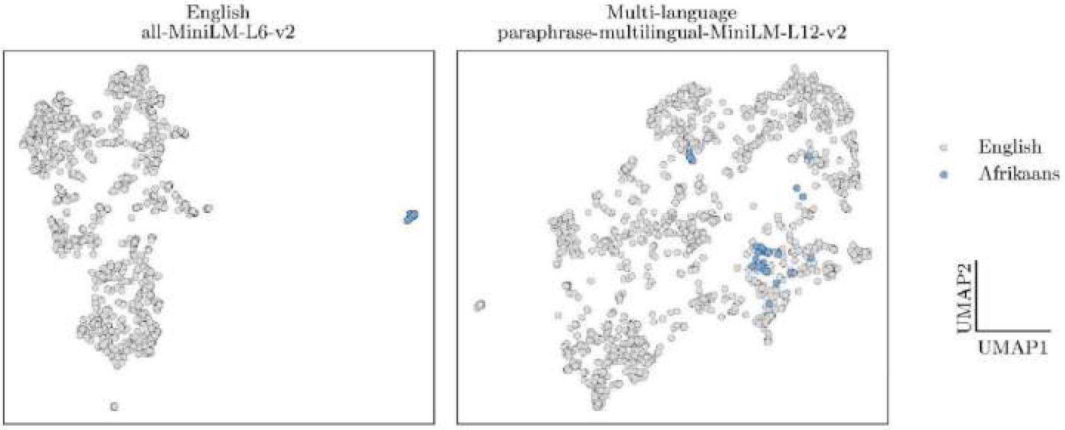

Figure 7: Two-dimensional representation of the different embeddings applied to the Kormorant news articles

Based on the various performance measures considered, it was decided to select the E10 models for all the newspapers. The E10 model extracted the most topics (59 ±19) and covered the most infrastructure sectors (94 ±9%) on average. Less emphasis was placed on the diversity and coherence of topics since subsectors will naturally be related. Since only around 1,69% of all the articles were written in languages other than English, it was decided to use the English embedding model to avoid introducing errors into the analysis due to incorrect embeddings. The Pretoria Rekord Central E10 model was used as the baseline model since this model extracted the most topics of all the E10 models.

4.4 Topic analysis

To analyse the baseline model topics, an infrastructure sector and infrastructure subsector were assigned to each topic of the baseline model. The topics and the relationship between the topics are visualised in Figure 8, which shows a two-dimensional representation of the news article embeddings annotated with infrastructure sector and subsector labels.

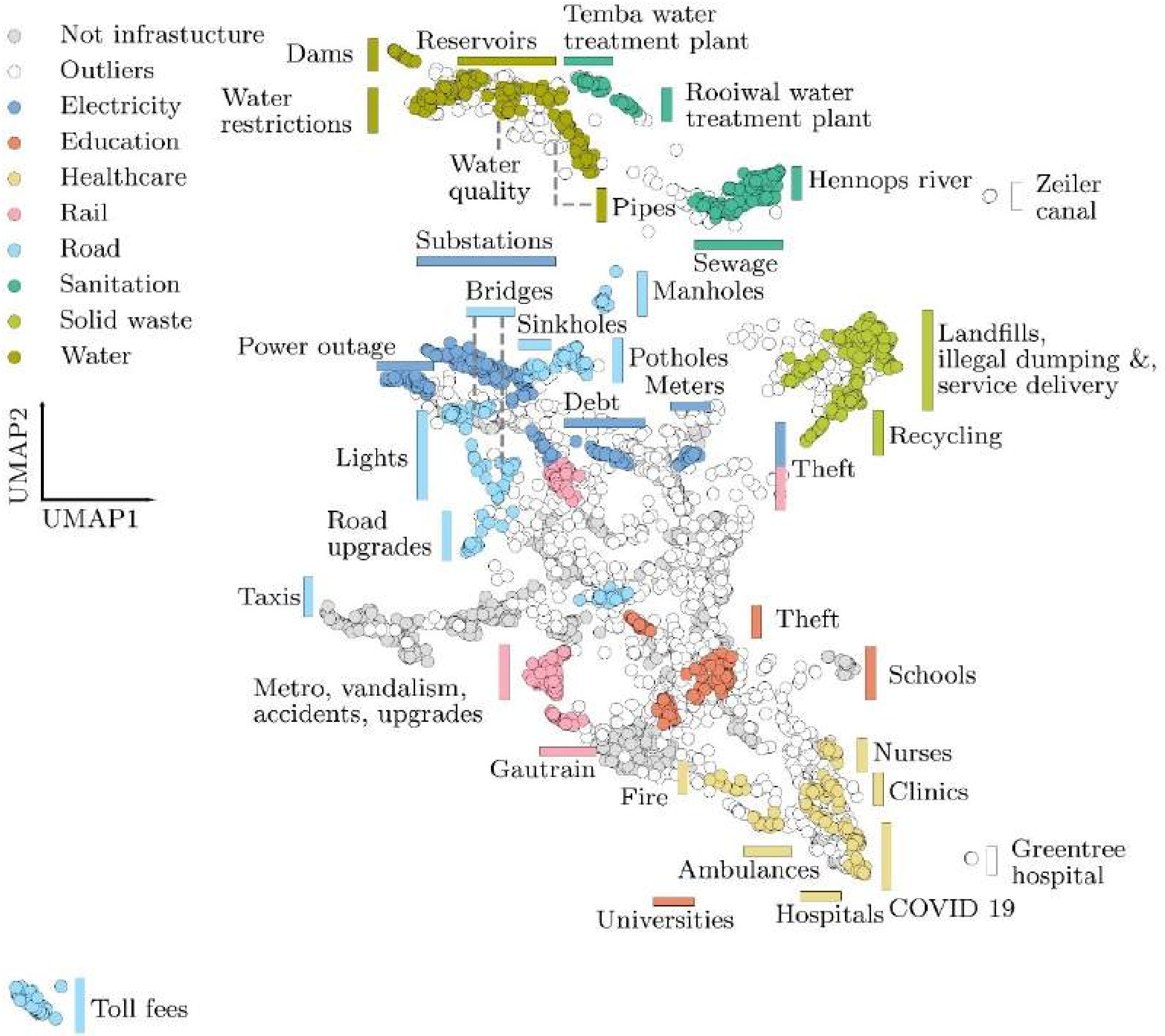

Figure 8: Two-dimensional representation of the topics identified from Pretoria Rekord Central newspapers

Distinct clusters were obtained for the different infrastructure topics. Not using the exact subcategories as the 2022 SAICE IRC proved to be beneficial since more granular subtopics were highlighted. For instance, road infrastructure was divided into *bridges*, *lights*, *manholes*, *potholes*, *sinkholes*, *taxis* and *road infrastructure upgrades*. This level of granularity allows for a more detailed understanding of the various issues within each infrastructure sector, providing insights into specific problem areas that may require attention. Topics that can support areas underreported in the 2022 SAICE IRC were also identified. For instance, the *substations*, *meters* and *power outage* topics provide insights into the performance of local distribution. The multiple healthcare topics extracted were also promising since this infrastructure sector is inadequately covered in the 2022 SAICE IRC [7].

Some infrastructure subsystems consistently performed poorly. These subsystems were reported on multiple times and as a result formed individual topics. For instance, the Temba water treatment plant and the Rooiwal water treatment plant each formed individual topics. While this helps to highlight focus areas, it can prevent the successful matching of topics.

The articles illustrated in Figure 8 appear to converge in the centre. This convergence most likely reflects the interconnections and overlap between different subsectors and overarching themes. Topics in the centre of the visualisation were often difficult to categorise. For instance, one of the topics at the centre of the visualisation was related to protests due to a lack of service delivery across multiple infrastructure sectors. Theft was also a recurring converging theme linked to rail, electricity and education infrastructure sectors.

To assign topics to the remaining eight news models, the cosine similarity was calculated between each topic embedding and every baseline model topic embedding. The label of the baseline topic with the highest cosine similarity was then assigned to each topic. Figure 9 shows the infrastructure category assigned to each topic per newspaper. This proposed approach for automatically labelling new topics achieved an accuracy of 75%.

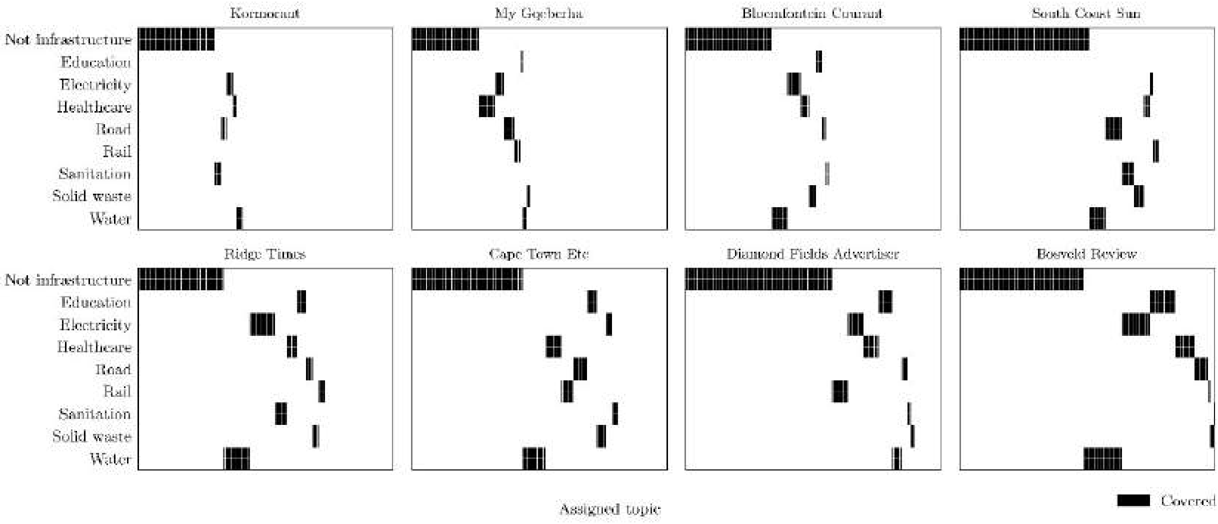

Figure 9: Assigned topic per news website data set

5 CONCLUSION

This study demonstrated the feasibility of using online news articles as an alternative source to monitor the condition of infrastructure in South Africa. News articles were automatically collected from nine newspapers using a keyword search strategy. After removing duplicate articles and articles with missing text, topic modelling was used to analyse the 26,136 articles identified.

Different configurations of BertTopic were implemented and evaluated. In the context of this study, an English embedding model with a minimum cluster size of 10 yielded the best results. The use of topic modelling proved to be useful in analysing the large number of online articles. The suggested approach allowed irrelevant articles to be effectively identified and topics underreported in the 2022 SAICE IRC to be discovered. This included detailed insights into local electricity distribution, road conditions, and healthcare facilities.

Since the methodology does not require specific infrastructure subsectors to be specified, new and emerging topics can be discovered which might otherwise be overlooked. Furthermore, the proposed methodology can be implemented in an online setting, enabling real-time monitoring and continuous updates of infrastructure conditions. This is a significant improvement over traditional SAICE IRCs, which are released every five years, allowing for more frequent and up-to-date data-driven decision-making.

Although promising, the suggested methodology still has several limitations. News websites do not necessarily cover all areas in South Africa comprehensively. Even when coverage is available, the focus is often on failing infrastructure, which may not provide a complete picture, particularly in terms of planning and proactive maintenance efforts. Therefore, it is recommended to use our proposed approach as an additional source of insights; complementing and not replacing methods currently used to compile IRCs.

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LIGHTING THE WAY TO PROFITABLE RECHARGING: A TECHNO-ECONOMIC ANALYSIS OF WORKPLACE SOLAR-POWERED ELECTRIC VEHICLE CHARGERS IN POTCHEFSTROOM, SOUTH AFRICA

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ABSTRACT

The increased number of electric vehicles (EVs) in South Africa necessitates increased charging infrastructure and reliable electricity supply. Efficient electricity generation and EV charging strategies are required to avoid increasing electrical grid strain. Deploying solar-photovoltaic EV charging stations can reduce electrical grid strain whilst increasing the number of available chargers. By analysing the energy requirement for recharging EVs, as well as the cost associated with a solar-powered charging system, a system configuration that allows for profitable operation can be determined. This approach utilises HOMER GRID software to minimise cost while ensuring system effectiveness. The results of this study can provide valuable information to policymakers, industry stakeholders and investors, enabling them to make informed decisions on the feasibility, development and implementation of workplace charging infrastructure. This research contributes to the integration of EVs and sustainable renewable energy generation by offering a practical solution for workplace EV charging infrastructure.

Keywords: Electric Vehicle, Techno-Economic, Solar, Renewable Energy, Recharging

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1 INTRODUCTION

The global automotive industry is undergoing a paradigm shift towards the electrification of vehicles. The International Energy Agency (IEA) [1] reported that Electric Vehicle (EV) sales accounted for 8.6% of total vehicle sales worldwide. However, the global increase in EV sales is contrasted by low EV sales in South Africa (SA) [2]. In 2023, EV sales accounted for a meagre 0.3% of new vehicle sales in the country [2]. When comparing original BRICS-group members, SA has at least an order of magnitude lower EV sales share [2]. The stark disparity indicates that significant constraints are impeding the adoption of EVs - in developing countries more so.

1.1 Finding the way in the darkness

One of the primary challenges to EV adoption in SA is the sparse network of more than 400 public EV charging stations [3]. Although the density relative to the number of EVs is world-leading, the low number of EVs and the extensive geographical area of SA make these chargers inaccessible to many potential EV owners [4]. Haidar & Rojas [5] found that increasing the number of publicly available EV charging stations will help promote the adoption of EVs. Powering these chargers remains a challenge in the current South African energy system.

A critical issue in SA is ensuring sufficient electricity generation capacity to support an increase in the number of EVs [6]. Effective EV charging, especially fast charging, requires an electrical power supply that far exceeds the daily electrical power demand of the average citizen in SA [7]. According to Pillay [8], if SA reached its Paris Climate Agreement goal of 2,389,950 EVs in 2040, the electricity demand would increase to 2,764 GWh per annum. Research by Calitz [9] found that if SA followed current electrification trends, the additional electrical load could exasperate the current energy crisis - potentially leading to increased rolling blackouts (Loadshedding).

The intermittent nature of the enormous electricity load of EV charging presents significant challenges for Eskom, SA's national electricity utility. Additional studies by Calitz and Bansal [10], and Pillay [11] emphasised that the potential future power demand of EVs requires increased investments in power generation to avoid the risk of overstraining the national electricity grid.

Naidoo [12] states that EVs' environmental impact heavily depends on the source of electricity that is used to charge the EV. The lower emissions of an EV compared to an internal combustion engine vehicle (ICEV) remains one of the key drivers in EV adoption [4]. When considering this, powering an EV from high-carbon emission electricity from a polluting coal-fired power station is much less acceptable than powering an EV from a low-emission Renewable Energy (RE) source. The need to reduce reliance on coal-fired power stations to reduce CO_2 emissions from EVs is supported by the findings of both Buresh et al. [13] and Pillay et al. [11].

One of the core benefits of an EV is that electric power stations of various types and sizes can supply the electricity to power it; this includes small-scale renewable energy plants.

1.2 Shining a light on the opportunity

The adoption of EVs can serve as a helpful buffer that can absorb the excess power production from intermittent renewable energy sources [14], [15]. When using optimised charging strategies, low-cost Solar Photo-Voltaic (SPV) and wind energy can be adopted to reduce the overall cost of electricity by using the low-cost but intermittent nature of RE [9].

Not all RE sources are equal in cost, effectiveness and reliability in certain conditions. On-shore wind and SPV have already reached the point where the Levelized Cost of Energy (LCOE) is less expensive than coal-fired electricity [16], [17]. However, the intermittency of wind energy in most parts of South Africa's high-solar power potential interior region increases the

LCOE of these systems. In a study by Olatayo et al. [18], it was found that the payback period on a small 1kW wind turbine system can reach 255 years, compared to an average of 7 to 10 years for small-scale SPV power production. The more significant intermittency and higher wind power installation costs compared to SPV, make SPV power a more financially feasible option with a lower LCOE [19].

The combination of sunshine-dependent, low-cost SPV energy during the day and the stationary nature of EVs during working hours creates various opportunities for using a solar-powered EV charging system (SPEVCS). A study by Buresh et al. [13] has demonstrated that implementing SPEVCS at large businesses and carparks can significantly reduce the impact of additional EVs on the electricity grid. Adding local energy storage can further reduce the reliance on the grid to maintain energy availability for EV charging [20]. This strategy alleviates strain on the national grid by consuming more electricity immediately where it is generated.

Solar energy production peaks on most days during the late morning and early afternoon, coinciding with the period when most vehicle owners are at work. During this period, the national grid's electricity demand is at a local minimum between the morning and evening peaks [21]. This scenario can enable the efficient use of renewably generated electricity to charge EVs and to store the surplus in batteries for use during evening peaks.

A slower, low-power EV charger can be used when an EV is stationary for extended periods, at home or at a workplace. The Small Scale Embedded Generation (SSEG) systems that are available to households and businesses can be enlarged to provide sufficient electricity to recharge EVs. Implementing this charging scenario reduces reliance on the national grid and presents a potential business opportunity.

In an investigation into the feasibility of solar-powered EV carports, Buresh et al. [13] found that charging EV owners a tariff higher than the rate for feeding electricity into the grid but lower than the grid electricity cost creates a mutually beneficial scenario. This situation can be preferred over selling electricity back to the grid at a significantly lower rate and administrative cost [22]. Therefore, businesses benefit from the increased profitability of selling surplus electricity while consumers benefit from the lower cost of operating their EVs. This financial model can incentivise businesses to invest in SPEVCSs and employees to purchase an EV.

Some challenges related to EV adoption can be partially addressed by increasing the number of publicly available EV chargers. However, this will inevitably increase electricity demand in a country with an already overstrained grid. Charging an EV on the current coal-dominated South African grid undermines their CO_2 emission reduction potential. When EVs emit more CO_2 than their ICEV equivalents, one of the primary motivations for adopting EVs is negated. Fortunately, utilising newly installed SPV for EV charging mitigates the environmental and grid impacts of using EVs. Deploying these chargers at workplaces where vehicles are stationary during the effective period of solar power production, a mutually beneficial financial opportunity can arise for the EV owner and employer. EV owners pay a lower electricity tariff than their utility rate, whilst the employers sell electricity at a rate higher than the grid feed-in tariff. This scenario can reduce the financial burden of operating an EV and installing solar power capacity for the EV owner and employer. This study explores the techno-economic implications of increasing the number of EV chargers - thereby addressing one of the critical constraints on increased EV adoption in South Africa [23].

2 LITERATURE REVIEW

Various studies have been conducted on the implementation of SPEVCSs. For this study, the literature review focused on the design and modelling of an SPEVCS. Researchers at Stellenbosch University, under the leadership of MJ Booysen, have confirmed the preliminary technical and financial viability of using SPEVCSs in South Africa [13], [20], [24], [25], [26]. With the technical and financial viability established, further investigation into the conditions of profitable operation can be done. This will be accomplished by conducting a Techno-Economic Analysis (TEA) of SPEVCS.

2.1 Designing the SPEVCS

Before the economics of the system can be considered, the technical configuration of the SPEVCS should first be determined. A study by Mouli et al. [27] investigated the design of a hybrid SPV and local battery storage system to power a DC-DC EV charger. A local battery storage system was determined to help reduce grid dependency and meet charging requirements. The findings of a study by Vermaak and Kusakana [28] further emphasise the importance of using a hybrid energy source system. The authors found that additional energy generation or storage is required to mitigate the intermediary nature of RE.

A hybrid-energy system that provides less intermittent power was developed by Mouli et al. [27]. Based on their research, a system could be designed for this study. Some alterations to the design by Mouli et al. [27] are made due to the study's different requirements. The first change is the replacement of the DC charger with a much less expensive AC charger. This can be done as Vehicle-to-Grid (V2G) charging and discharging are not investigated in this study. A low-power AC charging system will recharge an EV sufficiently over the 6 to 8 hours the vehicle will be stationary during the day.

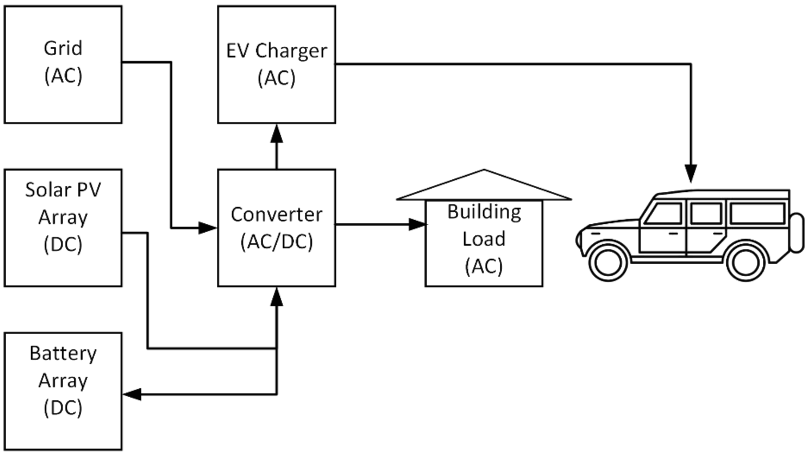

Figure 1: SPEVCS Diagram [27], [29]

The basic system architecture for a SPEVCS, as tested in this study, is shown in Figure 1. Power is generated by the SPV array and then transmitted to the hybrid converter system (converter). This system converts the DC power input into an AC power output that the building can use to power the building load, export to the grid, or, most importantly, recharge the EV. If necessary, the converter combines the power output from the DC SPV and battery systems with AC power from the grid to meet the building and EV electric loads. Additionally, it can redirect DC power to recharge the batteries directly. The SPEVCS's components are discussed in the following sections.

2.2 Modelling the SPEVCS

Each component in the system has a unique functionality that must be combined to supply power to the EV and building successfully. To recharge an EV and power the existing load of the business, energy is required from either the battery, the SPV array or the grid connection. The energy required can be represented by Equations 1 and 2 [30]:

$$E_{Demand_t} = P_t * t \tag{1}$$

Where E_{Demand_t} is the energy demand of the system, P_t is the power requirement and t is the time step over which the power demand persists. The total energy demand over all time steps can be determined per Equation 2.

$$E_{Demand_{Total}} = \sum_{i=1} n_t * E_{Demand_t} \tag{2}$$

However, DC power from the SPV array must be converted into AC power to charge the EV through the selected charger. Therefore, a converter is required. This converter also converts the AC power from the electricity grid into DC power to charge the system's battery. This converter does not have perfect efficiency when converting the various current types. The efficiency of the system can be described by Equation 3 [30]:

$$\eta_{coverter} = \frac{P_{output}}{P_{input}} \tag{3}$$

The efficiency ratio of the converter is noted with $\eta_{\text{converter}}$. The input power from the AC or DC source that needs to be converted is indicated with $\mathrm{P}_{\text{input}}$, whilst the output power is noted with $\mathrm{P}_{\text{output}}$.

The primary power source of the system is the SPV array. The SPV modules generate power from the sun's radiation using semiconductors. The power production of these modules is described by Equation 4 [31].

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}}\right) \left[1 + \alpha_P \left(T_c - T_{c,STC}\right)\right] \tag{4}$$

The power produced from the SPV array is represented by P_{PV}. The rated capacity and derating factor of the array are noted by Y_{PV} and f_{PV} respectively. The ratio of $\bar{G}_T$ and $\bar{G}_{T,STC}$ represents the effective solar radiation incident on the SPV modules compared to standard test conditions. α_P represents the temperature coefficient of the power. The PV cell temperature in the current time step is noted by T_c whilst the PV cell temperature under standard lab conditions is noted by $T_{c,STC}$.

If the SPV array's power production exceeds the building and EV charger's power requirements, excess production can be diverted to the battery storage. The battery storage unit utilises chemical reactions to store the excess electricity for later use. Suppose the battery SPV system does not produce enough power to meet the demand of the building and EV charger. In that case, the system controller releases energy from the battery to supplement the deficit. The battery power, P_B, can be described by Equation 5.

$$P_B = P - P_{PV}, P \leq P_{PV} \tag{5}$$

When P_B is smaller than 0, the battery is being recharged with excess SPV power. Suppose the power demand of the building and EV charger exceeds the available power from the battery and SPV array. In that case, power is imported from the electricity grid to meet the demand. Electricity is exported to the grid when the battery is fully charged, and the load power requirement is less than PV power production. The power import and export to and from the grid can be represented by equation 6 [30].

$$P_G = \begin{cases} P - P_{PV},\ P \leq P_{PV} + P_B \\ P - P_{PV} - P_{B_{max}},\ P \geq P_{PV} + P_{B_{max}} \end{cases} \tag{6}$$

The maximum power that the system's battery can deliver at the current time step is represented by $P_{B_{max}}$. When P_G is smaller than 0, electricity is being exported into the electricity grid.

3 METHODOLOGY

The TEA of this study was conducted using HOMER Grid 1.10 [32]. The analysis of this study included the development of a case study model focusing on a building at the North-West

University in South Africa. Whilst conducting this analysis, various economic values were calculated and analysed to determine the financial feasibility of using SPEVCSs.

3.1 Energy simulation tool

The chosen software, HOMER Grid that was utilised to conduct the TEA of this system was developed by the US National Renewable Energy Laboratory (NREL) [33]. The software is suited to model and analyse hybrid energy systems to determine the economic and technical feasibility of implementing a system. [28], [30], [34], [35], [36], [37], [38], [39]. One of the critical features of this software is the ability to conduct sensitivity analysis and optimise microgrid systems. Additionally, HOMER Grid adds the ability to add EV recharging to the microgrid that is being simulated [30].

3.2 Model development

Various inputs are required to develop a HOMER Grid model. The first is where the system is planned to be located, known in this study as the study area and the electric load scheduled for the system. After this, data on this location's solar radiation and other atmospheric conditions must be imported into the model. The input resource data input is followed by local tariff information and the selection of appropriate incentives - if applicable.

The technical information can be entered once the location information has been entered into the model. The technical information relates to the equipment specification, including additional loads such as EV recharging and project information. Finally, the financial information that will influence the system's implementation, such as discount rates and system cost, must be entered.

After the model inputs have been finalised, the variables that have been selected to be optimised can be optimised, and HOMER Grid can choose an ideal configuration. Optimisation mainly takes place by varying the size and type of RE sources and the battery and converter size. The various combinations of these systems must meet the minimum energy requirements specified for the model. The variations that meet the minimum energy requirements of the system are then evaluated based on specific economic indicators.

3.3 Optimal system evaluation criterion

To determine the optimal solution that meets the requirements of the system, the different SPEVCS configurations were objectively compared. The economic indicators that HOMER used to compare the various configurations are the Net Present Cost (NPC) and Cost of Energy (COE) [30], [34], [35], [38], [39]. The calculation of the NPC of the system is shown by Equation 7:

$$NPC = \frac{C_{total,annual}}{CRF} \tag{7}$$

The total annualised cost of the system to supply electricity is represented by $C_{total,annual}$. The Capital Recovery Factor (CRF) calculation is described by Equation 8:

$$CRF(i,N) = \frac{i(1+i)^{N}}{(1+i)^{N-1}} \tag{8}$$

The real discount rate is represented by i whilst N represents the number of years over which the project is implemented. The COE calculation of the system is indicated by Equation 9:

$$COE = \frac{C_{total,annual}}{E_{total,used}} \tag{9}$$

The $E_{total,used}$ represents the total amount of electricity consumed over a year. This is calculated by adding the total amount of electricity generated and used by the system, E_{iu}, and the amount of electricity that was imported from the electricity grid, E_g, as shown by Equation 10:

$$E_{total,used} = E_{iu} + E_g \tag{10}$$

4 CASE STUDY

The study area of this case study is a building of the Faculty of Engineering of the North-West University's Potchefstroom campus. The North-West University's Potchefstroom Campus is located in the North-West province of South Africa. The building is located at 26°40 "S 27°05'41.0" E [32]. Olatayo et al. [18] found that the solar radiation potential in this region is significantly higher than the wind potential. The main reason for selecting this specific location is the ease of accessing load data and the potential for higher EV adoption rates under higher-educated individuals [40].

4.1 Local electrical load profile

The function of the building determines the load profile of the case study and when it is used. For this case study, a complex of academic buildings that serve as offices, practical laboratories and workshops was chosen. These buildings are typically used between 07:00 and 16:00 from Monday to Friday. After hours, some building functions, such as computer server operations, remain active and require electrical power. The hourly average load profile, computed from measured data, of the chosen engineering buildings is depicted in Figure 2.

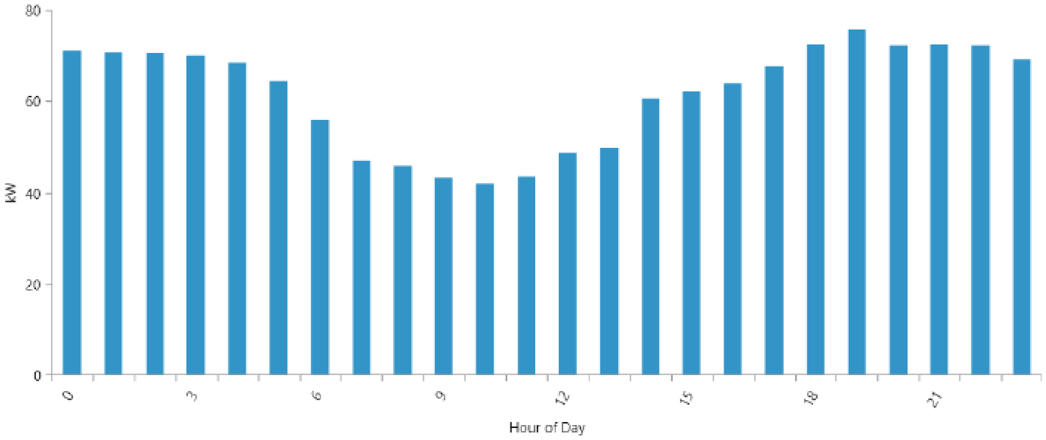

Figure 2: Daily Load Profile of the Engineering buildings

Subsequently, the load profile for each month is shown in Figure 3. The maximum power requirement of these buildings is 251.34 kW, whilst the daily average energy consumption is 1 932.9 kWh. An important note for this study is that the impact of intermittent electricity blackouts will not be considered.

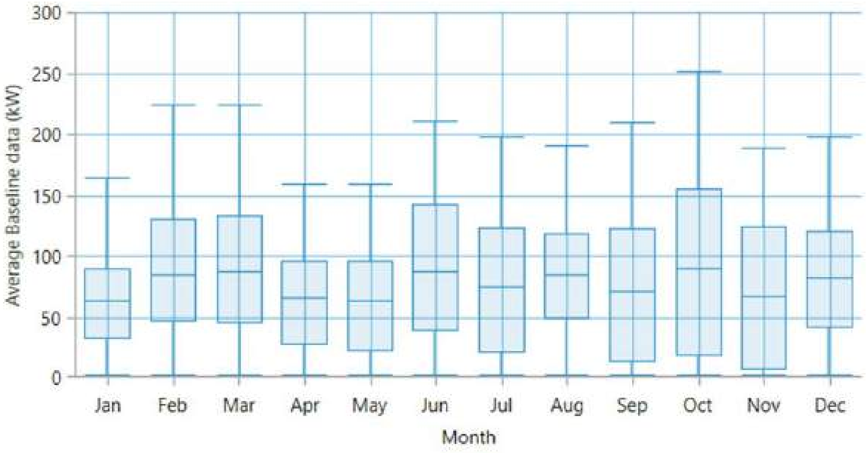

Figure 3: Seasonal Load Variation of Engineering Buildings

4.2 Environmental data

The solar radiation data required to develop the HOMER Grid model was obtained from the NREL's National Solar Radiation Database (NSRDB) [41]. HOMER Grid uses Global Horizontal Irradiation data to calculate the daily energy potential and clearness rating. This data is fed into the SPV model to determine the power output per time step. The daily average energy potential and the clearness over the same period has been summarised and is shown in Figure 4.

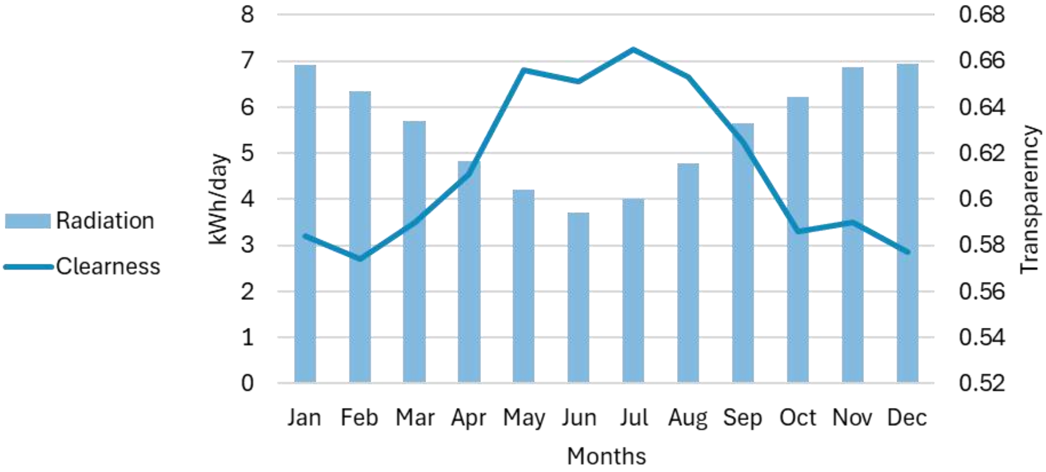

Figure 4: Average daily solar radiation and clearness

The ambient temperature around SPV modules has an impact on the power production capacity of these modules [27]. HOMER Grid utilises the ambient temperature in calculations to determine the power output of these modules as they heat up and cool down during their daily cycles. The temperature data obtained for this model is obtained from the NSRDB [41]. A summary of the temperature variations per month is included in Figure 5.

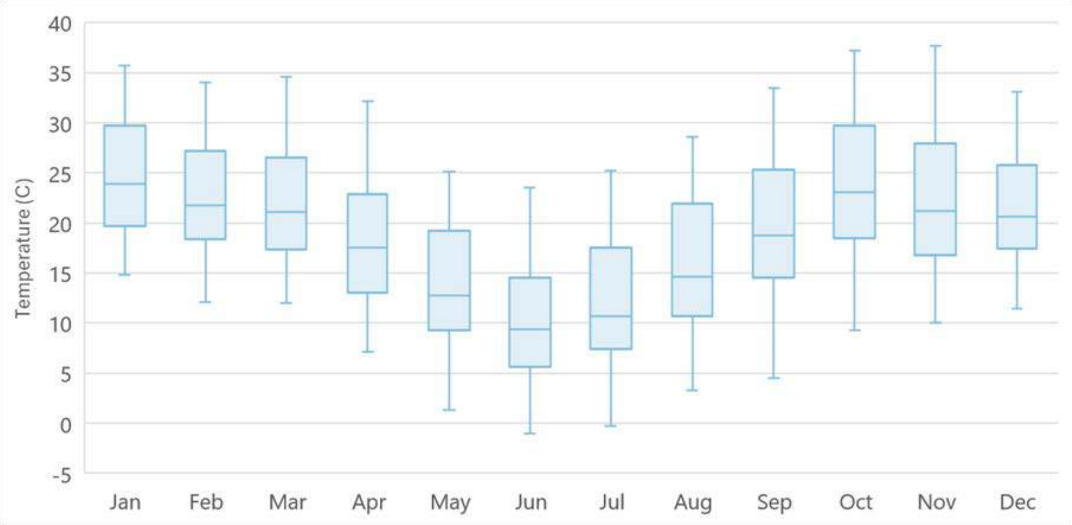

Figure 5: Monthly Temperature Ranges

4.3 System Configuration

The grid-connected hybrid SPV/battery EV charging system consists of an SPV array, converter(s), a battery array, a grid connection, the local electrical load and the EV charging load. Each of the model inputs have distinct characteristics that influence the model's operation. HOMER Grid has built-in models of various off-the-shelf components that can be implemented in the HOMER Grid model. The main characteristics of the SPV array modules, battery modules, converters and the grid connection itself are indicated in this sub-section. An overview of the HOMER Grid model is shown in Figure 6.

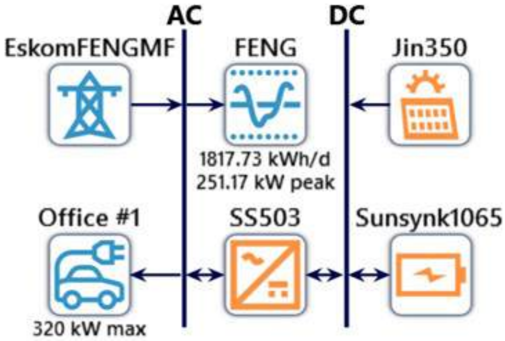

Figure 6: Block diagram of PV/Battery/Grid Hybrid system

The chosen SPV module is Jinko Solar Co., Ltd.350JKM350PP-72-V. The main characteristics of this SPV module are indicated in Table 1. HOMER Grid automatically calculates the ideal slope of the PV modules. The excess energy generated by the SPV array can be stored in a battery system.

Table 1: Solar Photo-voltaic System Configuration

Parameter	**Value**	**Unit**
Capacity	0.350	$kW/module$
Maximum system capacity	500	kW
PV Slope	26.8	°
Derating Factor	85	%
Temperature effects on power	-0.440	$\%/°C$
Nominal Operating Temperature	45.3	$°C$
Efficiency of PV arrays	13	%
Capital Cost	4,117	R/kW
Replacement Cost	2,058	R/kW
Operation and Maintenance Cost	205	$R/year/kW$

The specific battery unit used is the SunSynk Battery Lithium-Iron Phosphate 10.65kWh. The characteristics of the battery system are indicated in Table 2.

Table 2: Battery System Configuration

Parameter	**Value**	**Unit**
Nominal Voltage	51.2	V
Nominal Capacity	9.22	kWh
Round trip efficiency	98	%
Lifetime throughput	80,000	kWh
Minimum State of Charge	20	%
String Size	4	$units$
Capital Cost	55,000	$R/unit$
Replacement Cost	35,000	$R/unit$
Operation and Maintenance Cost	550	$R/year/unit$

The converter system functions to convert DC power into AC and vice versa. The converter system used in this model is SunSynk-50K-SG01HP3-EU-BM4. It must be noted that the South African renewable energy marketplace places emphasis on lower costs and higher value products. The details of the converter system are shown in Table 3:

Table 3: Converter System Configuration

Parameter	Value	Unit
Capacity	50	kW
Efficiency	97	%
Capital Cost	115,000	$R/unit$
Replacement Cost	75,000	$R/unit$
Operation and Maintenance Cost	1,500	$R/year/unit$

HOMER Grid allows a significant amount of variability in EV charging. The variability of EV charging is shown in Figure 7

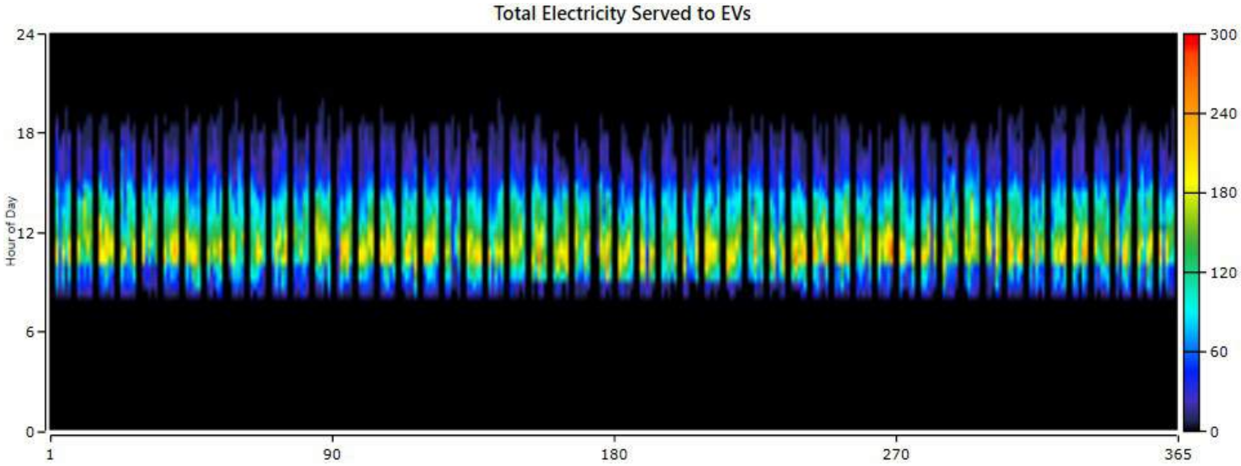

Figure 7: Variation in power requirement for EV charging.

The standard configuration of chargers used for this study is indicated in Table 4. The Capital Costn and Operation and Maintenance Cost represents the per charger costs of the System Fixed Capital Cost System Fixed Operation and Maintenance Cost respectively in Table 5.

Table 4: Electric Vehicle Charger Configuration

Parameter	Value	Unit
Number of chargers	40	$chargers$
Maximum charging rate	8	kW
Electricity cost	2.50	R/kWh
Number of charging sessions	40	$sessions$
Capital Cost	10,000	$R/unit$
Replacement Cost	10,000	$R/unit$
Operation and Maintenance Cost	500	$R/unit/year$

4.4 Economic project parameters

The economic analysis in this study requires certain inputs to be performed. Eskom's MegaFlex Local Authority tariff was used for this study [42]. HOMER Grid automatically utilises the parameters indicated in Table 5 in conjunction with Eskom's tariffs to perform the economic analysis.

Table 5: Economic Project Parameters

Parameter	Value	Unit
Nominal discount rate	8.25	%
Expected inflation rate	6	%
Electricity cost inflation rate	13	%
Project Lifetime	15	$years$
System Fixed Capital Cost	400000	R
System Fixed Operation and Maintenance Cost	20000	R

5 RESULTS

The Techno-Economic Analysis (TEA) is carried out with HOMER Grid. The technical analysis was conducted by inputting the load demand and resource data into HOMER Grid's electricity generation and consumption models. The model considered the power generated by the SPV system, the battery charging and discharging, the load of EV charging, and the base load of the buildings. A small example of the energy production, import and power of solar power production and electrical load on the state of charge can be seen in Figure 8. The red line represents the power production from the SPV array, the yellow line represents the electrical load of the system, and the blue line indicates the battery's state of charge (SoC).

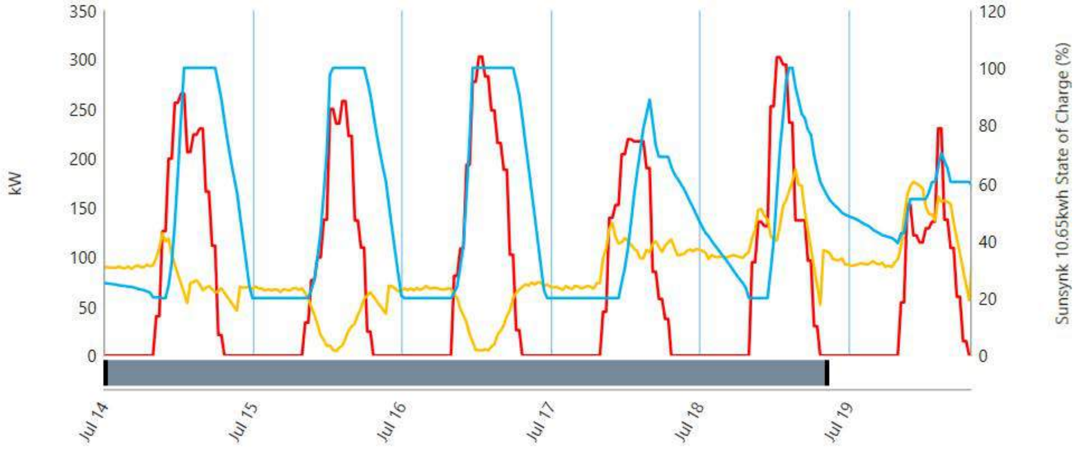

Figure 8: Solar Power, AC Load and Battery State of Charge

5.1 Optimal configuration

HOMER Grid groups the analysis findings into four distinct categories, with the most optimal configuration for each category. One of the four configurations will be the most optimal configuration out of all four configurations. The four categories of configurations are determined by their energy sources. The first category only obtains electricity from the electricity grid. The second category uses SPV and the electricity grid as a hybrid energy supply. The third category is a hybrid system combining the electricity grid and the battery system. Finally, the fourth category uses the SPV array, batteries and the grid to supply energy to the system. The results for each category is shown in Table 6.

HOMER Grid conducts the optimisation over a given search space. The search space for the converter and SPV system is between 0 kW and 500 kW. The converter system was incremented in 50 kW steps to represent the addition of a converter unit with each step. The SPV array always tended towards the upper limit of the optimisation range. The 500 kW array size limit was imposed due to limited space availability for the system. The search space for the battery system was 10 to 100 string units in 10-unit increments.

Table 6: Best configurations per category

Architecture	SPV (kW)	Battery (kWh)	Converter (kW)	NPC (R)	LCOE (R/kWh)	Operating cost (MR/yr)	CAPEX (MR)
Grid	0	0	0	59.9	5.38	4.68	0.4
Battery/Grid	0	922	250	52.0	4.66	3.57	6.48
PV/Grid	500	0	300	22.4	1.35	1.51	3.15
PV/Battery/Grid	500	1106	300	6.95	0.52	-0.22	9.75

The optimal configuration was determined by comparing it to a grid-only electricity supply to meet the system's load. The most optimal configuration is a hybrid system that combines SPV and grid connection with a battery system to absorb excess electricity production for later use. The system consists of 500 kW of SPV, 1106 kWh of battery and 300 kW of converter capacity.

The most optimal system requires a large Capital Expense (CAPEX) of R9.75 million compared to the R400,000 CAPEX required for the base system. However, from the first day of operation, the system generates revenue from electricity sales. Consequently, as the operational expense of the SPV and battery system is significantly lower than the base case, the NPC of the system is considerably lower. This is illustrated by comparing the discounted cumulative cash flow of the base and the proposed system in Figure 9. The total NPC of the best case is R6.95 million, the LCOE is R0.515 per kWh of electricity, and the operating cost of the system is -R219,868 per year. The discounted payback of the proposed system is 4.2 years, whilst the Internal Rate of Return (IRR) is 31%.

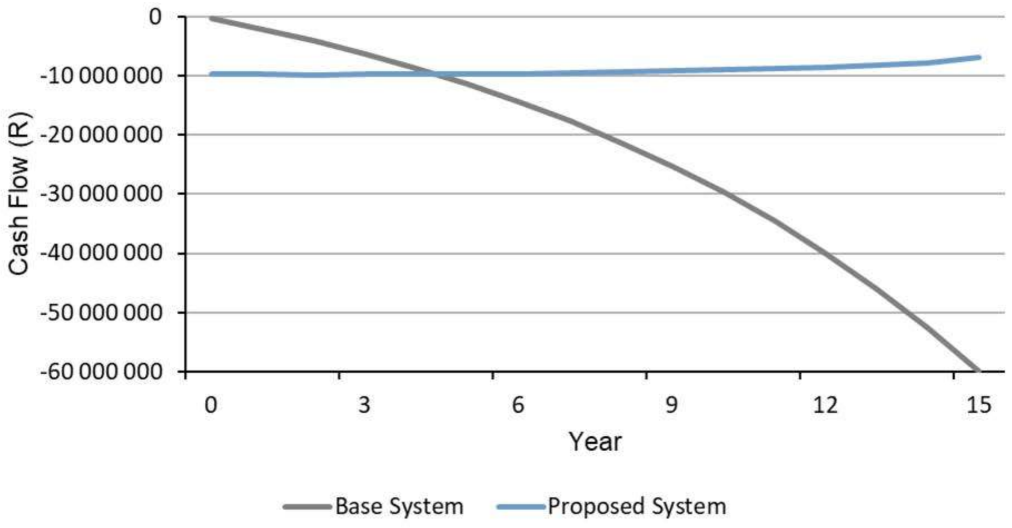

Figure 9: Base Case and Proposed Case Discounted Cumulative Cash Flow

5.2 Sensitivity Analysis

A sensitivity analysis was conducted to test the impact of changes to the SPEVCS. The sensitivity analysis was performed by varying the cost of the SPEVCS and the number of recharging sessions per day. The aim of varying these variables is to test the potential profitability of the system under different future use cases.

5.2.1 Reducing system costs

Three different SPV, battery and converter system costs were considered. These costs were created to equal 50%, 75%, and 100% of the SPEVCS' cost. These three cost points provide a broad range of potential future system costs. The result of the sensitivity analysis of the various energy system costs is shown in Table 7.

Table 7: Reduced System Cost Sensitivity Analysis

Ratio of SPEVCS cost (%)	Battery (kWh)	NPC (MR)	LCOE (R/kWh)	Operating cost (MR/year)	CAPEX (MR)
100%	1106	6.95	0.515	-0.22	9.75
75%	1106	4.12	0.305	-0.26	7.41
50%	1475	1.1	0.083	-0.40	6.17

Additionally, a reduction of 30% in battery cost was tested. The significant reduction in battery price scenario was tested as current expectations are that new battery chemistries, such as Sodium-Ion, will significantly reduce the cost of energy storage within the next five to ten years [43], [44]. The results of this sensitivity analysis, as optimised by HOMER Grid, are a CAPEX of R7.77 million, an LCOE of R0.350 per kWh, an Operating Cost of R239,668 per year, and an NPC of 4.72 million.

5.2.2 Changing the number of charging sessions

Another important system variation is the average number of charging sessions per day. This change represents changes in the number of EVs that employees own. For this study, a variation of 20, 30, 40, and 60 charging sessions were tested. For the 20 and 30 charging sessions, 20 charging stations were used. For the 40 and 60 charging sessions, 40 charging stations were used. The result of the sensitivity analysis is shown in Table 8.

Table 8: Charging Session Sensitivity Analysis

Charging Stations (chargers)	Charging sessions (sessions per day)	Battery (kWh)	NPC (R)	LCOE (R/kWh)	Operating cost (MR/yr)	CAPEX (MR)
20	**20**	1475	12.3	1.01	0.05	11.6
20	**30**	1475	11.5	0.94	-0.01	11.6
40	**40**	1106	6.95	0.515	-0.22	9.75
40	**60**	1106	6.40	0.47	-0.26	9.75

The results of this sensitivity analysis confirm that increased EV adoption and charging requirements can yield improved revenue from the SPEVCS. Additionally, selling electricity to the EV owner reduces the need to store electricity to generate value from its work.

6 CONCLUSION AND RECOMMENDATIONS

During this case study, HOMER Grid was utilised to conduct a Techno-Economic Analysis (TEA) of a Solar-Powered Electric Vehicle Charging System (SPEVCS) at the North-West University, Potchefstroom Campus in South Africa. The SPEVCS consists of a Solar Photo-Voltaic (SPV) array, battery system and the national electrical grid.

The results demonstrate that an SPV-dominated SPEVCS offers the most cost-effective solution to recharging Electric Vehicles and providing power for the building's electricity demand, compared to a national electricity grid-dominated SPEVCS. Unfortunately, under current SPEVCS cost and electricity tariff conditions, the profitable operation of an SPEVCS appears challenging. Beyond the long-term cost reductions achieved by technological development, policy adjustments can be made to reduce the cost of implementing SPEVCSs at workplaces in South Africa.

Despite the economic constraints, the long-term energy cost savings from implementing a SPEVCS warrant serious consideration for implementing such a system in businesses. Increasing the prevalence of SPEVCS at South African businesses can help to increase the number of publicly available charging points for EV owners. Additionally, using SPV for electricity can help reduce emissions and the reliance of businesses and EVs on the national electricity grid.

Implementing more SPEVCSs will help increase the number of publicly available EV chargers that won't destabilise the grid or increase emissions. Thus, one of the main limitations to the adoption of EVs can be addressed in a more holistic, financially sustainable way.

In summary, although current conditions are challenging, adopting SPEVCSs presents a promising solution to the need for more, sustainably power EV charging points in South Africa.

6.1 Limitations

One of the study's main limitations was the unavailability of EV recharging data. Additionally, the high cost of using HOMER Grid makes further application of these findings on others less accessible.

6.2 Future Recommendations

For future studies, this can be applied to various regions in South Africa and internationally to compare the financial viability of using SPEVCS at different locations and under different use cases. Additionally, although this study focuses on deploying EV charging stations, further investigations can be made by applying this methodology to different electricity use cases, such as electrified mining operations.

One of the main limitations of HOMER Grid is its high cost and unnecessary functions for certain types of investigations. Developing a lower-cost simulation method that focuses explicitly on modelling SPEVCSs without unnecessary functionalities might enable more individuals or organisations to investigate the potential deployment of SPEVCSs.

Batteries are crucial to enable the technical independence of the SPEVCS from the grid, yet their contribution to system cost is significant. Therefore, innovations in battery technology can meaningfully reduce the system's total cost. Subsequently, when the cost of energy storage has decreased significantly from the date of writing (July 2024), a future re-evaluation of the financial viability of SPEVCS could yield promising results.

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OPTIMISING STARTUP MANUFACTURER'S SUPPLY CHAIN: ANALYSIS AND INVENTORY SYSTEM DESIGN

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ABSTRACT

The study addresses the challenges a startup manufacturing company encounters amid expansion, primarily due to inconsistent production levels and inadequate inventory management practices. It investigates carefully identified scenarios to enhance supply chain efficiency and evaluates the feasibility through financial analysis. Additionally, a basic raw material inventory management system is designed to ensure an adequate supply of raw materials for continuous production. A ten-step scenario analysis methodology is used to complete the scenario analysis, complemented by the DMADV methodology to design the inventory management system. The scenario analysis yielded that investing in new machinery is the optimal expansion strategy. The inventory management system effectively tracks raw material and finished goods inventory levels with additional useful features. This study provides insights into overcoming challenges in the startup manufacturers' supply chain and lays a foundation for further refinement of the supply chain.

Keywords: startup manufacturing, supply chain optimisation, scenario analysis, inventory system design

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1. INTRODUCTION

1.1 Background

Startup businesses are focused on a single product or service that founders want to bring to the market [1]. These businesses often lack a completely formed business concept and the capital to advance to the next stage of development [1]. Startups usually have limited resources, a small team, and high uncertainty and risk. Common challenges startup manufacturing businesses face include a lack of skilled workers, inventory, project management, consumer trends, scaling, and globalisation. Additionally, inventory management and production scheduling-related problems are some of the leading causes of startup failures [2]. Over- and under-stocking inventory leads to cash flow problems, a primary concern for startups. Inventory investment is a significant portion of a small business's total budget; however, inventory control is one of their most ignored management areas [3]. Many small companies have an excessive amount of cash tied up in inventory due to poor inventory management or an inability to handle inventory efficiently [3].

Company XYZ is a small start-up manufacturer specialising in genuine leather and sheepskin slippers. It was established in June 2021 and officially began manufacturing in November 2021. The highest recorded production rate is 75 pairs per week, averaging 30 pairs per week. The slippers are available in three styles: mule, classic, and cosy, each in 5 to 6 colour options. Several factors influence company XYZ's demand variability, including seasonal demand fluctuations, supply chain disruptions, and market competition. Seasonal factors impact slipper sales, with higher demand during colder months. Supply chain issues, such as delays from long lead times, port congestions and supplier shutdowns, have disrupted production. Additionally, the company's strategy to scale production from 75 pairs per week in 2022 to 1100 pairs per week by the end of 2025 introduces variability, requiring accurate inventory management.

1.2 Problem Investigation

The company is experiencing inconsistent production levels and shutdowns due to a periodic shortage of raw materials. The shortage resulted in the production facility being unable to manufacture products for five out of the past fifteen months. They can enter the retail market but require higher and more consistent production levels. The root cause of the material shortage is determined using the 5 WHYS analysis tool introduced by Toyota in the 1930s [4].

Table 1: 5 WHYS analysis tool to determine the root cause

Question	Answer	Countermeasure Used
Why did production stop?	Shortage of raw materials.	Ordered more materials.
Why was there a shortage of raw materials?	Ordered materials from China with unpredictable and long lead times.	Ordered material in larger quantities.
Why are the lead times long and unpredictable?	The products must be shipped, and South African harbours face significant issues.	Unsuccessfully sourced for raw materials in South Africa.
Why are raw materials not sourced locally?	Processed sheep skins are rare and of lower quality than imported sheepskins.	Ordered from China again.

The shortage of sheepskin availability in South Africa is the primary root cause of production issues, as illustrated in Table 1. Bezuidenhoudt [5] notes that very few merino skins are processed in South Africa; most are salted, exported, and processed overseas. Ludolph [6] further supports this, stating that over 98% of unprocessed skins are exported, with China being the largest market.

Figure 1 visually represents that sheepskin shortage is the leading cause of production shutdowns, emphasising the critical nature of this issue.

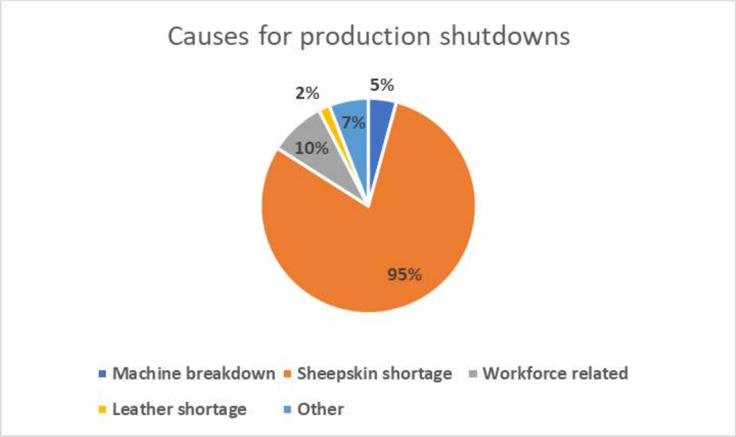


Figure 1: Causes for production shutdowns

Importing materials from China to South Africa has long and highly variable lead times (around four months). This unpredictability makes it challenging for the company to place large orders in advance. Company XYZ faces additional constraints as a startup regarding limited capital and insufficient storage space. These factors prevent the company from making large enough orders to serve as safety stock. Consequently, production is frequently halted due to raw sheepskin shortages, highlighting the need for improved inventory control measures. This lack of inventory control procedures is the second root cause of interrupted production.

1.3 Problem Statement

The company's inability to enter the retail sector is attributed to inconsistent production rates stemming from poor inventory management practices.

1.4 Aim and Objectives

The project aims to address the factors causing inconsistent production levels by investigating different scenarios to improve the efficiency of the supply chain. A financial analysis will be conducted to assess the feasibility of each scenario. Furthermore, a basic inventory management system was designed to ensure an adequate supply of raw materials. Both solutions aim to work in conjunction to ensure improved continuous production.

The objectives are to:

1. Investigate the inconsistent production levels and identify the root cause.
2. Conduct a scenario analysis to determine future business expansion options for the organisation.
3. Design a fit-for-purpose basic inventory management system for the organisation.

2. LITERATURE STUDY

2.1 Inventory Management

Inventory is usually the most significant asset on a company's balance sheet [7]. The primary goal of inventory management is to determine when items should be ordered and how much should be ordered [7]. Inventories allow different entities of a supply chain to operate independently. The famous trade-off exists between quicker customer demand response and more expensive inventory investment expenses.

2.1.1 Types of Inventories

Inventory exists in the upper and lower echelons of the supply chain. The upper echelons are the inventories closer to the customer, such as the retail store and warehouse inventory. The inventories in the lower echelon are for the raw materials and the manufacturing plant. The lower echelon inventories are used to ensure efficient production processes. [7]

The identified root cause falls within the lower echelon inventory and will be the focus point.

2.1.2 Inventory Management Software

Inventory management software is a digital tool designed to automate and improve tracking and managing inventory efficiency. It allows businesses to monitor stock levels, manage customer orders, and oversee incoming shipments to reduce costs and increase operational efficiency. In manufacturing, it helps to manage the flow of raw materials and parts through the supply chain and keep track of essential production documents, such as bills of materials and work orders. [8]

Inventory software features encompass various functionalities vital for efficient inventory management. These include real-time inventory tracking, purchase order and supplier management, multiple warehouse support, accounting and commerce integrations, production management and optimisation, and reporting and analytics.

2.2 Scenario Analysis

Scenario analysis is a valuable method to assess different possible outcomes and potential risks associated with various business expansion strategies. In this study, scenario analysis is exclusively used to identify the optimal business expansion strategy required by the company. Scenario analysis assesses expansion strategies, guiding the company's growth decisions. The following scenario analysis model was adapted from Kosow and Gabner [9]:

1. **Define scenarios:** Identify different expansion scenarios, such as facility expansion, supplier changes, outsourcing, and equipment acquisition.
2. **Identify key variables:** Determine the critical factors that will significantly influence each scenario, such as market demand, costs, supplier performance, and equipment efficiency.
3. **Determine possible values:** Assign a range of values to each key variable to represent various potential scenarios.
4. **Create data tables:** Set up data tables or spreadsheets to calculate outcomes based on the input values for each scenario.
5. **Calculate scenario outcomes:** Use the data tables to calculate each expansion strategy's financial performance, risks, and opportunities.
6. **Visualise results:** Present the scenario outcomes visually using charts or graphs to compare the scenarios.
7. **Sensitivity analysis:** Conduct sensitivity analysis to understand how changes in specific variables impact overall results.
8. **Interpret results:** Analyse the scenario model outcomes to gain insights into potential benefits and risks.
9. **Make informed decisions:** Use the insights from scenario models to make well-informed decisions about the best expansion strategy.
10. **Monitor and update:** Continuously monitor business performance and adjust scenario models as new data becomes available to stay responsive to changing market conditions.

2.3 DMADV Methodology

The Define-Measure-Analyse-Design-Validate (DMADV) methodology is widely used in various industries. It is beneficial in sectors where process quality, efficiency, and customer happiness are essential success factors. Manufacturing, healthcare, financial services, and telecommunications are among the industries that have successfully applied the DMADV technique. [10]

DMADV is focused on the process of designing a new product, service or process, incorporating the following phases [10]:

1. **Define:** Define the process and design goals.
2. **Measure:** Measure and identify critical-to-quality characteristics of the product, service or process. This includes risk and production capabilities.
3. **Analyse:** Analyse the data to find the best design.
4. **Design:** Design and test the product, service or process.
5. **Verify:** Ensure that the design output meets the design input requirements (verification) and that the designed product performs satisfactorily under actual or simulated conditions of intended use (validation).

Nieves-Castro [11] used the DMADV methodology to implement and improve inventory management. DMADV was used to define the project scope, measure cycle times and holding costs, analyse their impact on inventory management and identify opportunities for reduction. The inventory management system was then redesigned to address these findings. Finally, the redesign was validated with a prototype, and it was found that along with a 20% decrease in holding costs, the cycle times were also significantly reduced. [11]

Furthermore, a financial services company revamped its performance management system using the DMADV methodology. Initially, they defined goals for a comprehensive system and measured the current system's limitations through stakeholder interviews. The analysis identified key problems and requirements, leading to a design phase that chose average performance as a dynamic target baseline. Lastly, automated data validation and verification were employed to test functional and IT perspectives. The five-step DMADV methodology was successfully used to design a new management system within 12 months. [12]

2.4 Verification and Validation Methodology

Verification and validation are crucial for designing an effective and accurate product or service. Verification ensures the model is built correctly, whereas validation ensures the suitable model is built according to the customer's requirements [13].

2.4.1 Sensitivity Analysis

Sensitivity analysis was performed to verify the unit cost and break-even point calculations for the different scenarios. This approach is commonly employed in business and economics. The most significant advantage of a sensitivity analysis is that it can uncover errors in the original benchmarks and reduce uncertainty and unpredictability [14].

Utilising surveys with Likert scale questions served as a robust validation tool. Using this scale to design questions that capture the opinions and insights of relevant stakeholders, the Likert scale responses offer a quantifiable way to gauge the alignment of real-world perceptions with the scenario analysis outcomes. [15]

2.4.2 Inventory Management System

The inventory management system was custom-designed to fit the company's needs and expectations. White box and black box testing verify and validate new software developments. Table 2 explains the test differences [16].

Table 2: Software verification techniques

	Black Box Testing	**White Box Testing**
Definition	A software testing method that evaluates a software system's functionality without prior knowledge of how it operates internally.	A software testing method that tests a software system's internal operations.
Performed	The test is performed from the user's perspective.	The test is performed from the developer's perspective.
Goal	Evaluating if the system fulfils the user's needs and performs as predicted.	Testing the system's internal logic, performance, and efficiency.
Types of Testing	System testing and acceptance testing.	Unit testing and integration testing.

Table 3 defines the different types of tests used for black-and-white box testing [16]. This table is a valuable reference point, delineating the distinct methodologies and their respective roles in the testing process.

Table 3: Test definitions

Type of Test	**Explanation**
System Testing	Verifies the entire inventory management system, ensuring all components and functions work together to meet the system's requirements and objectives.
Acceptance Testing	Evaluates whether the inventory management system satisfies user requirements. It often involves user acceptance testing to validate that the system meets user expectations and business needs.
Unit Testing	Focuses on testing individual system components to ensure they perform as expected. It helps to identify and rectify errors at the smallest functional level.
Integration Testing	Checks the interaction and integration between different system components to validate that they work together correctly.

A combined approach of white box and black box testing methods represents a robust strategy for verifying and validating the inventory management system.

3. CONCEPTUAL DESIGN

3.1 Scenario Analysis

Scenario analysis was performed to determine the best business decision regarding the manufacturing cost of slippers. The unit cost of the slippers was calculated for different scenarios based on varying quantities sold. Considering different quantities sold, the break-even point for each scenario was calculated and compared.

3.1.1 Methodology

The ten-step scenario analysis methodology discussed in the literature review was followed to complete the scenario analysis, and Microsoft Excel was used for all the calculations. Figure 2 displays the methodology that was followed throughout the section.

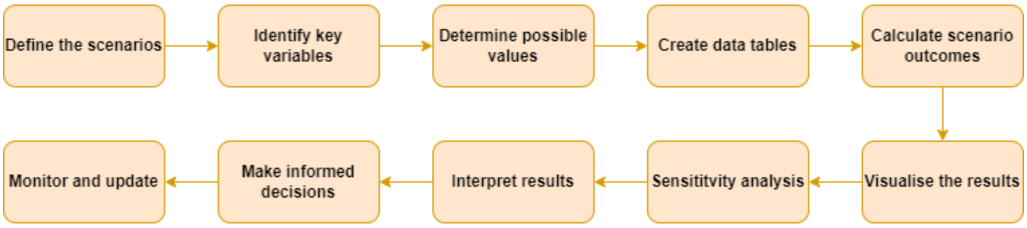


Figure 2: Scenario analysis methodology

3.2 Inventory Management System

The inventory management system focuses on the lower-echelon inventory. The root cause of the company lies within the lower echelon inventory and requires inventory management techniques to manage the acquisition phase of the supply chain.

3.2.1 Conceptual Inventory Management System Requirements

The requirements for the company's inventory management system are to:

- Efficiently manage inventory, including overseeing stock levels, lead times, reorder points, and safety stock.
- Calculate material requirements.
- Align inventory levels with the available capacities.
- Generate reports and analytics about the inventory and production performance.
- Employ an intuitive, user-friendly interface.

3.2.2 Software Selection

Table 4 summarises the software suitable for developing a basic inventory management system.

Table 4: Software comparison

Software	Description	Advantages	Disadvantages
Microsoft Excel	Microsoft Excel is a widely used spreadsheet software developed by Microsoft. Users can create custom inventory sheets, record product information, track quantities, and calculate basic inventory metrics.	• Can be used for MRP, P-model and Q-model systems • Flexible • Cost-effective • Familiarity	• Limited scalability • Manual data entry • Time-consuming to create or modify • Requires technical skills for advanced features • Dashboards are not standard
Katana	Katana is an inventory management software specifically designed for small and medium-sized manufacturers. It provides tools for managing inventory, production, and sales in a centralised platform.	• Can be used for MRP and P-model systems • User-friendly • Centralised control • Real-time data • Dashboards for reporting purposes	• Requires manual monitoring for Q-model systems. • The free version has limitations • Limited customisation • Learning curve
Odoo	Odoo is an open-source ERP platform with MRP functionality.	• Can be used for MRP, P-model and Q-model systems • Comprehensive • Cost-effective • Open-source • Scalability	• High-level complexity • Steep learning curve • Only two modules are free

A weighted criteria table was used to select the most suitable software for an inventory management system. The weights are assigned to the criteria based on their specific significance to the company.

The inventory management system will be designed using Microsoft Excel with Visual Basic Application (VBA) programming. VBA will be used to create a user-friendly interface, automate tasks, and design a dashboard to improve user-friendliness and functionality. The choice was made because the company is already familiar with using spreadsheets for basic inventory and production processes.

Table 5: Software evaluation

Criteria	Weight (%)	Score (Out of 5)	Weighted Score	Score (Out of 5)	Weighted Score	Score (Out of 5)	Weighted Score
		Microsoft Excel		Katana		Odoo	
Ease of Development	15%	2	0.3	4	0.6	3	0.45
Ease of Use	20%	4	0.8	3	0.6	3	0.6
Cost	20%	5	0.8	1	0.2	3	0.6
Customisation	15%	5	0.75	2	0.3	4	0.6
Ease of Customisation	15%	3	0.45	3	0.45	4	0.6
MRP Functionality	5%	3	0.15	5	0.25	5	0.25

Technical Support	10%	3	0.3	3	0.3	5	0.5
Total	**100%**		**3.55**		**2.7**		**3.1**

4. FINAL DESIGN

This section details solutions developed to address identified root causes. It includes two solutions: a scenario analysis for optimal business expansion and an inventory management system for effective monitoring and material requirement planning. These solutions have been refined from their initial conceptual designs with minor improvements.

4.1 Scenario Analysis

The ten-step scenario analysis methodology discussed in the literature review will be followed to complete the scenario analysis.

4.1.1 Define Scenarios

1. **Current state (using new suppliers):** This scenario involves utilising new local raw material suppliers. The company will continue to operate with their existing machines and production process.
2. **Outsourcing production processes:** The company can subcontract specific production processes to nearby shoe-manufacturing companies. The processes that will be outsourced include cutting, lasting, glueing, skiving, sole pressing, quality checking and debossing.
3. **Acquiring new machines:** The company has identified crucial machines that could enhance its production rate. These machines include a debossing press, a sole press, and a three-phase clicker press.

4.1.2 Identify Key Variables

All variables across the various scenarios are held constant, except for the specific variables that require adjustment due to each scenario. The critical variables that will notably impact each scenario are raw material costs, equipment costs, direct labour costs, fixed costs and outsourcing expenses.

4.1.3 Determine Possible Values (Input Data)

All scenarios were calculated for 150, 300, 600, and 1200 pairs sold monthly. The company's objective for 2023 was to sell 300 pairs of slippers per month and double that quantity annually. These quantities provided sufficient data to draw meaningful conclusions.

4.1.4 Create Data Tables

The input data and calculations have not been included in this report due to the proprietary and sensitive nature of the information, which is the company's intellectual property.

4.1.5 Calculate Scenario Outcomes and Visualise the Results

Calculating the unit cost is crucial to a company's operational analysis, offering insights into product production efficiency [17]. The unit cost represents the cost of manufacturing and selling a single product unit. It is imperative to strive for the lowest possible unit cost as it directly impacts profit maximisation. The break-even point (BEP) serves as a vital indicator, revealing the minimum number of products that must be sold for the company to achieve profitability [18]. The BEP is calculated using the weighted sales distribution of the different shapes. Furthermore, it is calculated for the four different quantities to be produced since the variable and fixed costs change as the quantities change. The BEP is calculated as follows:

$$\frac{(Fixed\ Cost + Direct\ Labour + Machine\ Cost)\ x\ \%\ Shape\ Sales\ Distribution}{(Selling\ Price - Variable\ Cost)} \quad (1)$$

The unit cost results are summarised in Figure 3, and the BEP calculations in Figure 4. It is important to note that the company can only manufacture 300 units at the current facility. Therefore, calculations must be made for various output units to determine the best strategy for the future.

Figure 3: Unit cost comparison summary

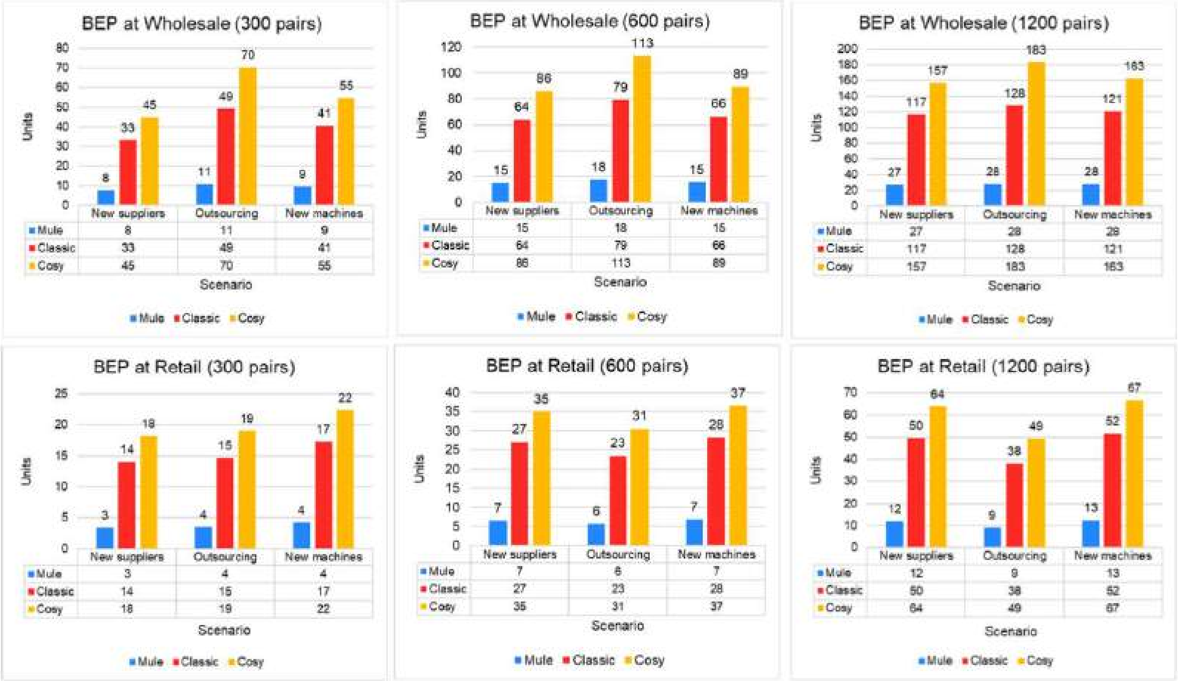


Figure 4: Break-even point comparison summary

4.1.6 Sensitivity Analysis

Sensitivity analysis is performed and discussed in detail in the succeeding verification section of this report.

4.1.7 Interpret Results

Upon analysing the unit cost calculations, it is evident that producing 300 pairs is most efficient using existing manufacturing procedures and new suppliers. Introducing machinery becomes more cost-effective for 600 pairs or more production goals. Outsourcing specific production procedures is prohibitively expensive, resulting in high unit costs and minimal profit margins, even when producing 1,200 pairs for wholesale. The scenario with the new supplier has the lowest break-even point (BEP) for various quantities at wholesale prices, closely followed by the new machinery scenario. However, if products are sold at retail prices, the outsourcing scenario becomes most favourable due to its lower BEP, as the new supplier and machinery scenarios require higher sales volumes to offset labour and machinery costs before becoming profitable.

4.1.8 Make Informed Decisions

The company's plan to enter the retail market by the end of 2024 and produce 1,200 pairs of slippers monthly by 2026 will significantly impact the break-even point (BEP) calculations, primarily due to the shift towards wholesale pricing. Investing in new machinery is deemed worthwhile based on the unit cost and BEP calculations. Flexibility to extend the payback period beyond the initial 12 months is available, mainly if unit cost concerns arise during the project's early phase. This extension will significantly reduce unit costs once the machines are fully paid off, substantially enhancing profit margins on all future products. Furthermore, embracing a machinery-based production approach offers the company greater control over the manufacturing process and mitigates significant risks.

4.1.9 Monitor and Update

Continuous monitoring of the spreadsheets is imperative, and the scenario models must be fine-tuned as new data becomes available to ensure accuracy in a dynamic environment with ever-changing future conditions and volatile variables.

4.2 Inventory Management System

The focus in developing the inventory management system has been on addressing the need for inventory management. The system is tailored to the company's requirements to ensure that it is an efficient inventory and production management tool. The inventory management system has been developed using Microsoft Excel and VBA as outlined in the conceptual design. The data used to build the model is based on two weeks of information provided by the company to ensure the model is relevant and accurate.

4.2.1 Features of the System

An overview of the different system features is provided below, with selected screenshots to explain the functionality without the reader interacting with the system.

a) Navigation Panel

The navigation panel serves as the "home" screen, allowing access to various inventory management system features through relevant icons.

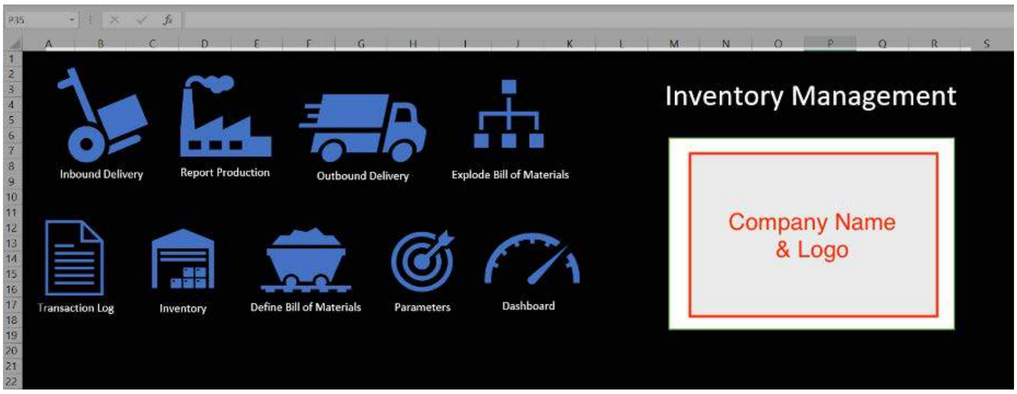


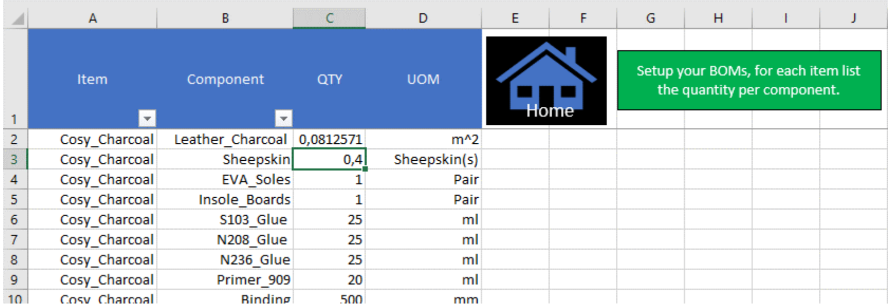
Figure 5: Navigation panel

b) Parameters

A sheet with operating parameters in dropdown lists is used for the parameters function, reducing errors and improving the interface. Users can add parameters like customers and retailers. Defined parameters include raw materials, units of measurement, customers, products, warehouses, shapes, colours, and sizes.

c) Bill of Materials

The Bill of Materials (BOM) lists materials and quantities needed for each product, including a 10% safety factor for material availability and error accommodation. This BOM is crucial for the material availability check feature.



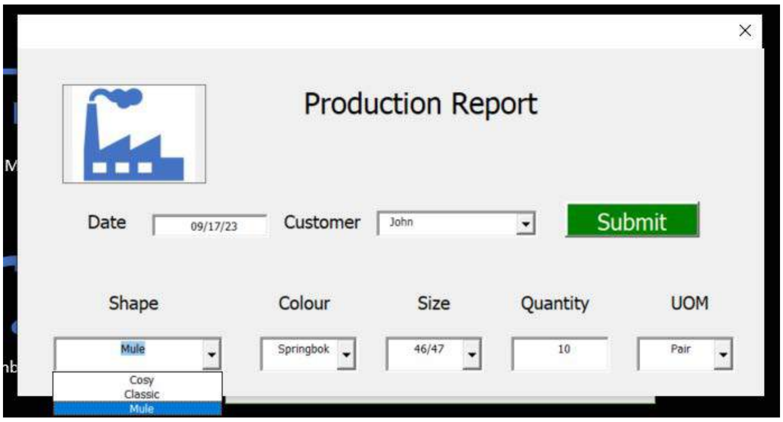
Setup your BOMs, for each item list the quantity per component.

Item	Component	QTY	UOM
Cosy_Charcoal	Leather_Charcoal	0,0812571	m^2
Cosy_Charcoal	Sheepskin	0,4	Sheepskin(s)
Cosy_Charcoal	EVA_Soles	1	Pair
Cosy_Charcoal	Insole_Boards	1	Pair
Cosy_Charcoal	S103_Glue	25	ml
Cosy_Charcoal	N208_Glue	25	ml
Cosy_Charcoal	N236_Glue	25	ml
Cosy_Charcoal	Primer_909	20	ml
Cosy_Charcoal	Binding	500	mm

Figure 6: BOM example

d) Production Order Management

Production orders are added via a user-friendly form in VBA. Upon submission, the system checks material availability, deducts raw materials from available inventory, and updates the finished goods inventory. If materials are insufficient, a warning message appears, and no materials are deducted.



Production Report

Date: 09/17/23

Customer: John

Shape: Mule

Colour: Springbok

Size: 46/47

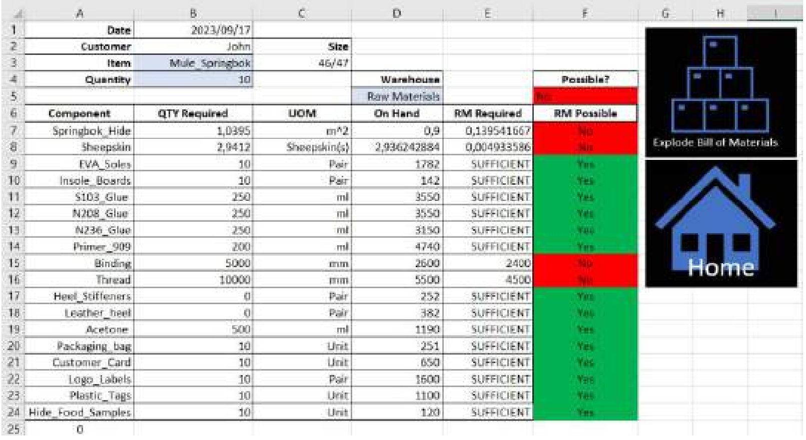
Quantity: 10

UOM: Pair

Figure 7: Production report form

e) Material Availability Check

This feature verifies raw material availability for production, using the BOM to determine requirements and compare with inventory levels. It also functions as a simulation tool for future production and material planning without impacting inventory levels.



Date: 2023/09/17

Customer: John

Size: 46/47

Item: Mule_Springbok

Quantity: 10

Warehouse: Raw Materials

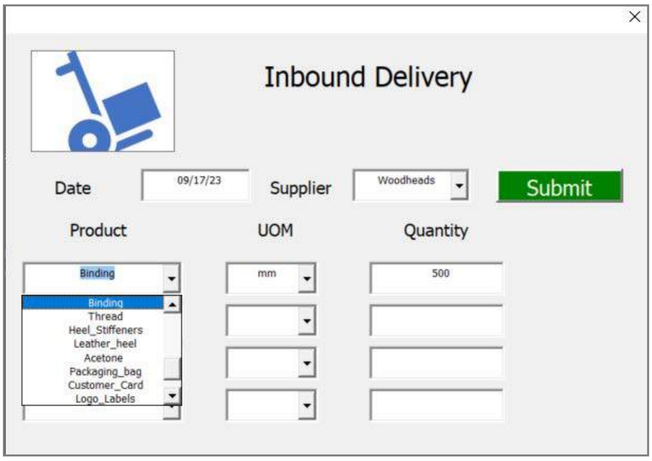
Possible?: No

Component	QTY Required	UOM	On Hand	RM Required	RM Possible
Springbok_Hide	1,0395	m^2	0,9	0,139541667	No
Sheepskin	2,9412	Sheepskin(s)	2,936242884	0,004933586	No
EVA_Soles	10	Pair	1782	SUFFICIENT	Yes
Insole_Boards	10	Pair	142	SUFFICIENT	Yes
S103_Glue	250	ml	3550	SUFFICIENT	Yes
N208_Glue	250	ml	3550	SUFFICIENT	Yes
N236_Glue	250	ml	3150	SUFFICIENT	Yes
Primer_909	200	ml	4740	SUFFICIENT	Yes
Binding	5000	mm	2600	2400	No
Thread	10000	mm	5500	4500	No
Heel_Stiffeners	0	Pair	252	SUFFICIENT	Yes
Leather_heel	0	Pair	382	SUFFICIENT	Yes
Acetone	500	ml	1190	SUFFICIENT	Yes
Packaging_bag	10	Unit	251	SUFFICIENT	Yes
Customer_Card	10	Unit	650	SUFFICIENT	Yes
Logo_Labels	10	Pair	1600	SUFFICIENT	Yes
Plastic_Tags	10	Unit	1100	SUFFICIENT	Yes
Hide_Food_Samples	10	Unit	120	SUFFICIENT	Yes
0					

Figure 8: Material availability check and simulation tool

f) Inbound and Outbound Delivery Management

Like the production order form, the inbound delivery form allows materials to be added to the raw material inventory using dropdown lists for materials and quantities. The outbound delivery form records customer orders and tracks the inventory of finished goods. It alerts users if stock is insufficient to fulfil an order, prompting a check of inventory levels.



Inbound Delivery

Date: 09/17/23

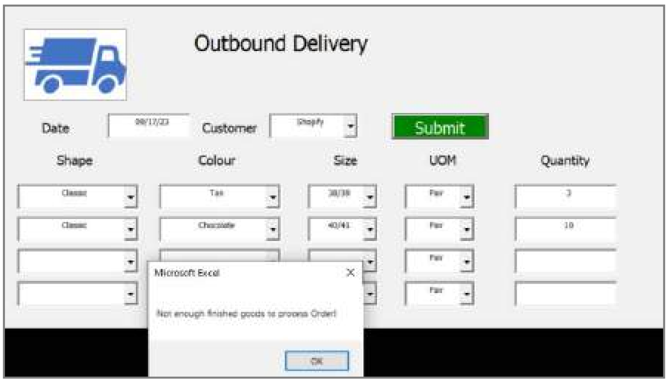
Supplier: Woodheads

Product: Binding

UOM: mm

Quantity: 500

Figure 9: Inbound delivery form



Customer: Shopify

Shape	Colour	Size	UOM	Quantity
Classic	Tan	38/39	Pair	3
Classic	Chocolate	40/41	Pair	10
			Pair	
			Pair	

Not enough finished goods to process Order!

Figure 10: Outbound delivery form

g) Transaction Log

The transaction log records all inbound, production, and outbound transactions, providing data for the inventory sheet via pivot tables. It is not intended for frequent user interaction but can manage errors or manual corrections.

h) Inventory

The inventory feature uses pivot tables based on the transaction log to show stock levels of raw materials and finished goods, aiding supply chain management. Pivot tables can be filtered and adjusted for more detail on the stock on hand.

i) Dashboard

The dashboard summarises valuable information using graphs and pivot tables, providing insights into sales distribution, production quantities, and inventory levels. It includes slicers for period-specific data.

5. VERIFICATION AND VALIDATION

5.1 Verification

5.1.1 Scenario Analysis

The sensitivity analysis verified the scenario analysis by evaluating how variations in crucial input variables affected the break-even point (BEP) for wholesale and retail price scenarios. The variables adjusted included wholesale and retail prices, variable costs, fixed costs, and machine payback periods. The analysis used Excel's 'what-if' function, highlighting base case output cells and comparing changes to these outputs. The realistic and consistent results verified the BEP calculations for all scenarios, confirming that the system could handle changes in wholesale and retail prices, variable costs, fixed costs, and machine payback periods.

Wholesale and retail prices: Adjusting the wholesale and retail prices showed that BEP increased when prices were lowered and decreased when prices were increased. Wholesale prices significantly impacted the BEP, especially in the outsourcing scenario, suggesting that negotiation with retailers to raise wholesale prices could drastically lower BEP.

Variable costs: Changing the variable costs, which include direct material and indirect costs, demonstrated that increased variable costs led to higher BEP and vice versa. The impact was significant when products were sold wholesale in the new suppliers' scenario.

Fixed costs: Altering the fixed costs revealed that lowering fixed costs decreased BEP, and increasing them raised BEP. Fixed costs had a notable impact on BEP when products were sold wholesale.

Machine payback period: Extending the payback period for new machines reduced the monthly BEP, as costs were spread over a more extended period. This reduction could improve cash flow and flexibility in financial management.

Company verification: The scenario analysis was verified through a review and approval process by the company's general manager and stakeholders, who provided input variables and costs, ensuring the results were accurate and reliable.

5.1.2 Inventory Management System

White box testing: White box testing aims to evaluate the system's internal logic and performance. There are two types of white box tests: unit and integration testing. Unit testing focuses on testing individual units or components of the system in isolation to ensure they perform as expected. Integration testing checks the interaction and integration between different units or elements of the system to validate that they work together correctly.

1. **Unit testing:** Unit tests for various system features, such as adding production orders, checking raw material availability, integrating new BOMs, and monitoring real-time inventory levels, were conducted. All tests passed, verifying that individual features worked accurately.
2. **Integration testing:** Integration tests verified that different components of the inventory management system worked together seamlessly. Tests included integrating production order management with material availability checks, inventory deductions with production order management, and the inventory and production monitoring dashboard. All tests passed, ensuring accurate and cohesive system performance.

5.2 Validation

5.2.1 *Scenario Analysis*

Validation survey: A validation survey was conducted using Google Forms to gauge the industry partner’s alignment with the final design. The survey results strongly agreed that the unit cost calculations, BEP calculations, and scenario analysis were reliable and provided valuable insights for decision-making and business expansion.

5.2.2 *Inventory Management System*

Black box testing: Black box testing evaluates the system's functionality and performance from a user perspective through system testing and user acceptance testing.

1. **System testing:** System testing used real-life data to replicate transactions, ensuring all features required by the company were included and thoroughly tested for functionality. The process confirmed the system's performance in real-world scenarios.
2. **User acceptance testing (UAT):** UAT ensured the system met the company's requirements and worked seamlessly. Tests included placing and managing orders, user-friendliness, dashboard insights, inventory level tracking, flexibility, and budget software. All tests passed, validating the system's readiness for future implementation.

6. CONCLUSION

The startup company on which the research project is based has an opportunity to enter the retail market. A business expansion strategy and adequate inventory management are crucial to optimising the supply chain and ensuring the company can enter the retail market soon. Three potential business expansion scenarios were considered, and a scenario analysis was conducted to aid decision-making. This analysis compared the unit cost and break-even points of these three scenarios. Furthermore, an inventory management system was designed to handle raw materials and finished goods inventories better.

In conclusion, the scenario analysis recommends investing in new machinery as the optimal expansion strategy. Implementing an inventory management system holds great potential, considering the company's current need for such a system. Correctly utilising these tools will lead to notable improvements in the startup manufacturer’s supply chain.

7. LIMITATIONS AND RECOMMENDATIONS

The scenario analysis relies on data susceptible to change due to evolving economic conditions, rendering the analysis accurate only if no significant changes occur. Verification of the variables employed in the study is advisable.

The inventory management system is designed to track inventory levels and manage orders cost-effectively. Although it has a feature to verify material availability, it does not create material procurement plans. Investing in MRP software is highly recommended as production rates escalate and become more challenging to manage. It offers enhanced features such as demand forecasting, production planning, material procurement planning, and scheduling.

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THE ANALYSIS OF THE LOGISTICS SUPPORT SYSTEM IN ROAD TRANSPORT

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ABSTRACT

Logistics is a diverse field. It involves information processing, material handling, warehouse storage, customer service, logistics monitoring, and distribution. Logistics services, the transportation of goods through a coordinated organised logistics system are one of the important characteristics of any company. In this paper, the researcher investigates and analyses success factors and challenges that affect the logistics support system in road transport using a systematic review of the literature. The researcher discusses the steps to optimise road transport's logistical support systems. The literature review encompassed scholarly materials such as conference papers and peer-reviewed journal articles. The researcher aims to develop a system that can ensure timely deliveries, which plays a key role in customer loyalty and market reputation. The company may save money attributable to the research because of improved inventory control, more effective supply networks, and new logistics technologies. This paper mainly focuses on the road transport.

Keywords: Logistics, Support systems, Haulage, Systematic literature review, success factors, transport, Improvement.

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[*] Corresponding Author

1 INTRODUCTION:

Logistics system (LS) refers to the actual movement of goods from supplier to customer facilitated by a network of companies, individuals, activities, information, and resources [1]. The logistics support system's major purpose is to maximise the logistics system, which considers all the important factors for the business and helps it to achieve long-term development objectives.

The transportation of goods from one point to another is complicated and expensive. Transport includes the convergence of networks, utilities, logistics equipment, warehouses, and information and communication technology (ICT). The transportation of goods through a coordinated and tightly organised logistics system is one of the important characteristics of any company's logistics system. At company X, the analysis of logistics activities is based on the total cost principle and aims at handling the physical flow of costs effectively and efficiently. A logistics support system needs to be developed to find the most efficient design while considering all trade-offs. The purpose of the logistics support system is to ensure the convergence of the logistics chain with both upstream and downstream costs through the management of the logistics functions to meet the standard of customer services at competitive costs.

According to Voit [2], transport and warehouses are the main elements of logistics, Logistics is attracting more and more interest from a whole range of companies as it has a lot of potential to save capital, time, and effort. The primary task of the logistics support system is to maximise the logistics system which considers all the company's main goals and assists in the achievement thereof. With logistics support, observing cost allocation across the materials and product life cycle is very important.

Technology plays a vital role in managing the logistics of the business, helping companies adapt to changing quality requirements and transfer an ever-increasing number of customer orders [3]. The issues of having a large enough fleet, handling equipment, and warehouse space are being exacerbated by increased demand and the rapid growth in the logistics sector, which is making companies battle to move their goods efficiently. The industry's most apparent obstacle is a lack of skilled labour [4]. A successful logistics support system ensures that suitable goods and services are delivered at the right time to the right consumers at the best quality while reducing costs and rewarding all participants based on value added to the supply chain.

The ever-changing economy is putting growing pressure on the transport system to move shipments faster and cheaper. At company X, congestion and restrictions on product size are the most critical logistics factors. This is a result of both the quantity of goods the transport truck can carry; and the quantity of goods ordered in a certain location. If an order for twelve vehicles is received, Company X's single transport truck will only be able to deliver eight vehicles. The remaining four vehicles will have to wait until four additional orders are accumulated, bringing the total to eight vehicles, at which point the second truck will deliver the remaining vehicles. This results in delays in the delivery of goods to other customers, as the company is unable to dispatch a truck that is not fully loaded. Additionally, it delays the delivery of products from the previous purchase. Traffic congestion is a major problem in most cities, and the shortest path is also not necessarily the best [5]. Company X manually gathered logistics details; they anticipate demand but lack precise information about future developments. Companies use logistics demand forecasting to forecast future demand for goods and services. This entails using analytics and statistical tools to forecast future trends based on previous results, present market circumstances, and possible future events; as a result, the business ended up investing more money than anticipated. This paper aims to use a systematic review of the literature to examine and evaluate the obstacles and success factors that impact the logistical support system in haulage and discusses steps to optimise the haulage’s logistical support systems.

The research questions are:

1. What are the obstacles that impact the road transport logistics support system?
2. What are the success factors required for the road transport logistics support system?
3. What steps can be taken to optimise the road transport's logistical support systems?

2 METHODOLOGY

Gathering and examining pertinent research on logistics support systems in the haulage sector was done through a systematic review of the literature. The review encompassed scholarly materials such as industry reports, conference papers, peer-reviewed journal articles, and more. The researcher used databases from Google Scholar, Web of Science, and Scopus. Some of the search terms used were "*Logistics success factors, and "haulage logistics support"*. The selection of articles was conducted based on their quality of content and relevance to the study problems. Thematic analysis was used in the review process to find recurrent themes and revelations connected to the study's goals.

Based on the steps in Figure 1 below, the number of articles found was reduced from 24600 to 450 articles. After removing duplicates 320 were left. After screening abstracts and titles, 120 papers were selected for evaluation. A quality assessment was conducted on them, considering their contribution to the field, clarity and coherence of conclusions, and relevance to the research questions. Articles that satisfied the required quality requirements following the quality assessment were 70 and were added to the review.

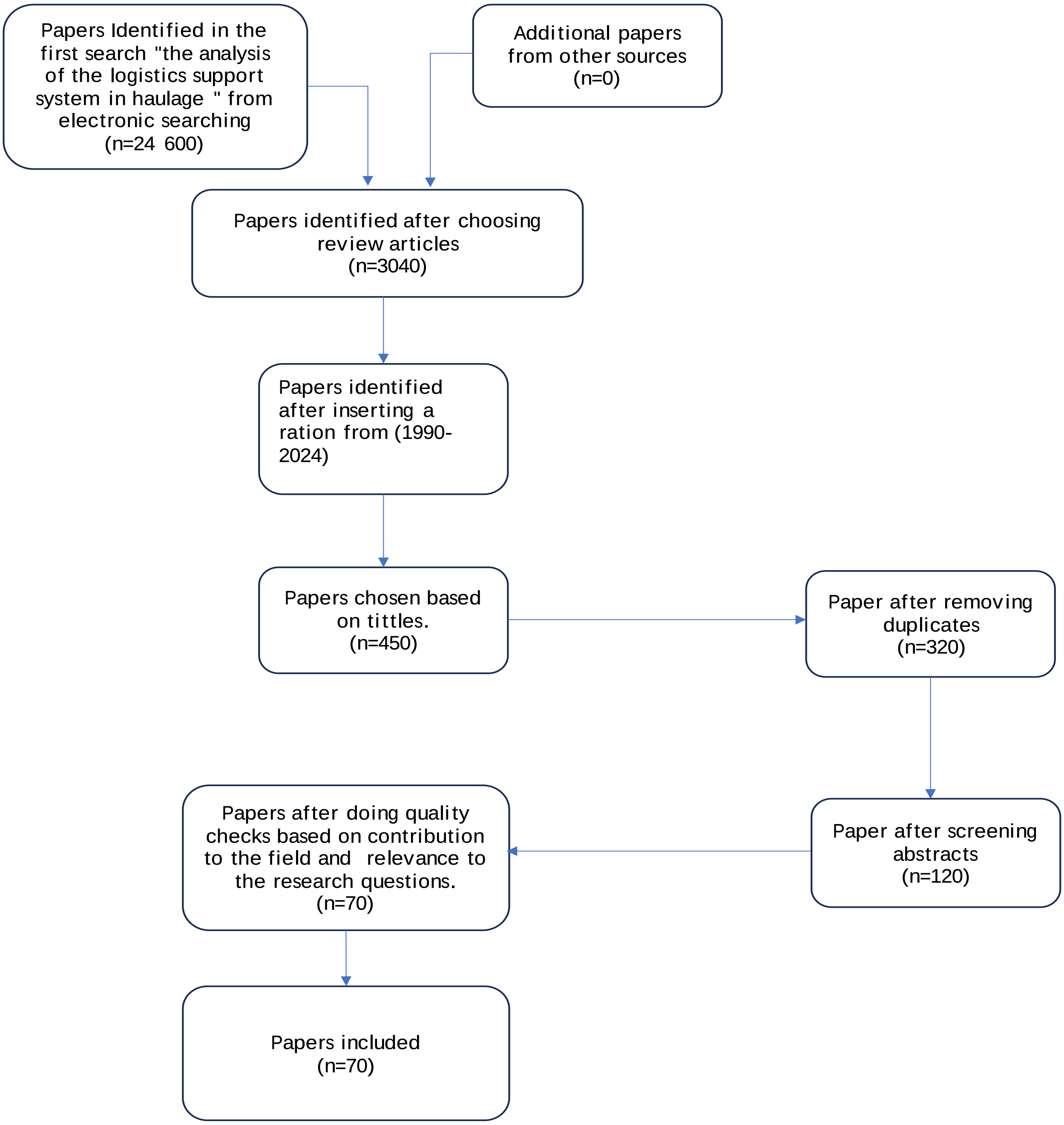

Figure 1: Flow diagram that represents different phases of the systematic literature review.

2.1 Quality Requirements and Inclusion and Exclusion Criteria Used

Tables 1, 2, and 3 provide a full overview of the inclusion and exclusion criteria used in the creation of this research. These tables additionally list the quality requirements that are upheld, guaranteeing that the insights produced into the road transport haulage logistics support system are thorough and significant.

2.1.1 *Research questions.*

Table 1: Inclusion and exclusion criteria for systematic literature review on Research questions.

Inclusion criteria	Exclusion criteria
Studies that address difficulties, impediments, or constraints unique to the road transport haulage logistics support system.	Research that only addresses other modes of transportation or other forms of logistics systems (such as air or maritime freight) and has no bearing on road haulage.
Articles that highlight significant performance metrics, essential success elements, or best practices unique to the road transport haulage logistics support system.	Success criteria for general logistics that are not unique to road transport haulage.
Studies offering plans, techniques, or models for enhancing the road transport haulage logistics support system.	Strategies for optimisation that are limited to non-road logistics transport.

2.1.2 *Literature Sources.*

Table 2: Criteria used for selecting systematic literature review.

Databases	Time Frame
Peer-reviewed journals, respectable trade periodicals, industry reports, conference proceedings, and publications devoted to logistics and road transportation.	Papers that have been written in conference proceedings or peer-reviewed journals, research on logistics support systems in the setting of haulage, and publications that document contemporary developments that date back to the year 1990.

2.1.3 *Study Design*

Table 3: Criteria used for quality checks.

Types of studies	Quality assessment
Reviews, case studies, theoretical frameworks, and empirical research that particularly target the logistics support system in road transport haulage.	Applying standardised instruments for quality assessment, such as PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) or CASP (Critical Appraisal Skills Programmes).

2.1.4 *Ethical Consideration*

- Following the study ethics rules and making sure that sources are properly cited and acknowledged.

3 RESULTS AND DISCUSSION

The objective of this systematic literature review is to investigate several aspects of logistics support systems, with a particular emphasis on the haulage industry. Systems engineering and logistics engineering which include logistics planning, maintenance, training, packaging, storage, transportation, and life cycle costs are among the subsections covered. This analysis additionally explores availability, dependability, maintainability, supportability, and system effectiveness regarding vehicle operating costs. A thorough examination of inventory management, storage and warehouse logistics, organisational logistics chain performance, inventory management strategies, and the economic order quantity is also conducted. By identifying issues in the logistics sector and examining techniques to enhance maintainability, reliability, and availability, particularly within the automotive sector, this review aligns with the research questions: What are the obstacles impacting the haulage logistics support system? What are the success factors required for the haulage logistics support system? What steps can be taken to optimise haulage logistical support systems? Additionally, the review aligns with the objectives of identifying obstacles affecting logistics support systems in the haulage sector, determining critical success factors, and suggesting feasible steps to enhance these systems, thereby increasing their overall efficacy and efficiency.

Logistics handles inventory distribution and customer information from the manufacturer. Logistics includes packaging, inventory, shipping, warehousing, distribution, and technological support for sales [6]. The Logistics Support System (LSS) offers robust online entry and monitoring platforms for all processes of inventory management, material requisitioning, issuing, and receipt. It offers client status and maintenance status monitoring at the service, typically operated by serial number and document number [7].

3.1 Blockchains, IoT sensors, and AI

The concept of supply and demand in the market has evolved because of advancements in information technology, particularly the Internet. Companies are shifting toward adaptive production to increase revenues and satisfy customer demands [8]. As a result, industry 5.0 and the industrial Internet of Things (IIoT) were developed. We must first comprehend the Internet of Things (IoT) to comprehend IIoT. IoT is the expansion of a wide network that allows little human intervention in generating, exchanging, and consuming data by giving network connectivity and computational power to objects, devices, and sensors. IoT offers the ability to remotely gather, analyse, and manage data [8]. Therefore, IIoT refers to the application of IoT technology in manufacturing. IIoT stands for industrial Internet of Things, where industrial data, machinery, equipment, and vehicles are all connected over large networks. Logistics is another complex area of IIoT that can be controlled by IIoT for intelligent and effective supply chain management. A variety of logistical real-world issues have been addressed by the IIoT framework [9]. Blockchain, AI, and 6G are the four primary functional components of IIoT and smart logistics.

3.2 Logistics Engineering.

Logistics engineering is an engineering discipline dedicated to procuring, transporting, storing, distributing, and warehousing materials and final inventory through the scientific organisation. Logistics engineering is a dynamic science that is required to guarantee that the "*item*" is where it is needed, when it is needed, and operating at a reasonable cost. It considers trade-offs in component and system design, repair capacity, training, inventory spares, demand history, storage and distribution points, and methods of transport [10]. Logistics also adds value by raising customer satisfaction and productivity [11].

Between the point of origin and the point of consumption, effective data flow, storage, and product development are put into practice, and regulated to satisfy consumer needs [12]. It is a definition for the management of physical supply management and the distribution of goods, as the main goal of the needs of customers and the determination of benefit to warrant affordability. In this sense, it implies that logistics aims to achieve a quality of service to customers in terms of reliable goods at the right time and in the right place at the right quantity and expense. Sharma [13] argues that logistics is built up and assisted by numerous activities that include functional elements. Some of the components of logistics include the following:

3.2.1 Logistics planning

Interactive planning, organising, and management practices are important to ensure the proper coordination and execution of logistics specifications for any given program [14]. Throughout its life cycle, initial preparation and review contribute to the development of logistics specifications and the overall support of the system.

3.2.2 Logistics maintenance

These activities include the initial provision and procurement of support items, logistics functions related to manufacturing, the installation and checkout of the system and its components at the customer service functions of the user's operational sites, the continuous support of the system throughout its intended period of use, and those functions essential for the retirement and material recycling or disposal [15].

3.2.3 Training and training support

This area covers all personnel, equipment, information, or documents on facilities and related services required for the training of workers, covering both original and replenishment or replacement training. Training equipment such as simulators, mock-ups, special instruments, teaching materials, and computer resources. Software is developed and used as required to support regular site training, and more formal distance education [16].

3.2.4 Packaging, handling, storage, or warehousing and transportation.

This includes all components, special equipment requirements, resistant and disposable containers, and supplies required to support items, to ensure their protection, preservation, effective storage, handling, and or transport. System personnel and parts for repair to ensure the primary mission. Test and support equipment technical data, computer resources, and mobile equipment are also included [17].

3.2.5 Logistics information

This refers to the services required to ensure that an effective and efficient flow of logistics information is given throughout, as well as to the organisations responsible for all the activities that fall under its attention [18].

3.3 Life-Cycle costs (LCC)

The overall cost of ownership of machinery and equipment, including its acquisition, service, repair, conversion, and/or decommissioning costs, is the life cycle cost [19]. LCCs are summaries of the empirically determined cost estimates for all programs, equipment, and disposal costs. The LCC analysis aims to choose the most cost-effective method from a series to achieve the lowest long-term ownership cost.

3.4 Vehicle operating costs.

Any logistics company must be aware of its fleet running expenses. Operating expenses ought to be accessible in one way or another, but a thorough grasp of the transport costs depends on how the costs are calculated [20]. Transport costs are more complex than merely time and distance (km) associated expenses. Devlin,[20] also argues that costs per day and cost per km are combined to form vehicle operating costs because time-related expenses arise even when the vehicle is not being used and because distances differ significantly based on the destination. According to Devlin [20] The following parameters should be taken into consideration when designing the Decision Support System to calculate transport costs:

- Capital expenses for a vehicle, trailer, and crane.
- Costs associated with standing (time)
- Costs associated with mileage (running costs).

3.5 Availability.

Availability is the probability that a system will function as required when required for a task. Availability includes non-operational cycles connected to logistics and maintenance. On the other hand, availability is utilised to determine the system's readiness or the likelihood that a system will be operational when required. Availability aims to maximise the operational time [21].

3.6 Maintainability.

The ease with which a product can be maintained. The ease with which one can identify flaws or their source, fix errors or their source, meet new requirements, improve possible maintenance, or adapt to a changing environment is referred to as maintainability [22]. In its broadest sense, maintainability can be determined by combining variables relating to logistical support, as well as staff work-hour rates, elapsed hours, maintenance speeds, and maintenance costs [22].

3.7 Reliability.

Reliability is the likelihood that a system or component will function as intended over a predetermined period and under predetermined conditions [23]. To maintain the required functionality in the planned operating environment, reliability must be satisfactory. Reliability considerations support all measures of availability. According to Gillespie [22], reliability engineering studies system failures and repairs to improve operational usage by extending design life, eliminating or lowering the probability of failure and safety risks, and decreasing downtime.

3.8 Supportability.

According to Taylor [24], supportability is the degree to which the logistics services and system design components meet the needs of the system. A fully developed system design can meet operational and readiness requirements throughout the system's life cycle at a reasonable cost. When a system exhibits operational appropriateness and affordability, the designs of its parts are considered complete; nonetheless, most aspects of a complete system are subject to change over time [26]. Supportability Engineering is also referred to as Integrated Logistic Support (ILS) [25].

3.9 Dependability.

Dependability is about consistently providing products in the required condition and on time. According to Werbińska,[27], providing a dependable and reasonable price is a key component of reliability in logistics and shipping. The ability of transportation companies to deliver a price that the shipper can rely on is crucial. Logistics players rely substantially on information technology (IT) and electronic data sharing because of problems, including delays, complicated form completion, laws, and border clearance inspections.

3.9.1 Automated storage and retrieval system dependability

The essential elements of automated warehouse facilities with high throughput and storage capacity are Automated Storage and Retrieval Systems (ASRS). ASRSs are the foundation of the warehouse process or the direct source of high-efficiency order-picking [28]. ASRS establishes the physical characteristics of the building, forms the buffer capacity of the warehouse, and is frequently a crucial component of the picking system.

3.9.2 Dependability of Logistics Systems

One aspect of the systems' dependability is their reliability. Because ASRS has the buffering capacity, material handling components to change the material flow, and input and output determined by the qualitative and quantitative material flow structures, it is regarded as a logistics system [28]. Therefore, dependability, rather than the more widely used reliability, is a better method to characterise its overall properties. According to Wasiak [29], a logistics system's dependability can be likened to the technical system's reliability since it gauges how well tasks are implemented over time.

3.10 System Effectiveness.

The total cost of logistics, the quality of the logistics service, the business system's overall performance, the length of time the logistics processes take in the system, and the Caliber of logistics operations are the five main measures of a system's efficiency [30].

3.11 Packaging

Among other factors, packaging affects how efficiently and effectively items move through the supply chain. Packaging needs to be appropriately constructed, and tailored to the needs of the consumer, transport, identification, and applicable rules [31]. Packaging should provide the following purposes in terms of logistics:

- Protective function: The package should be completely compatible with the product's features, both functional and technological, as well as its worth.
- Packaging should be adjusted to the current standardised dimensional system, enable storage, make it easier to construct unit loads, and perform other functions related to storage, transit, and handling that are linked to the packaging's sensitivity to automation and mechanisation of processes.
- Packaging serves as a carrier of information for identification, handling (which includes dynamic complementation), and storage procedures. It also aids in flow control throughout the supply chain.
- Recycling and functions connected to cessation.

According to Szymonik [31], We may categorise packaging based on the specifications related to supply chain participation, the kind of unit load (logistic load), and the marking method that has been employed.

3.12 Inventory Management.

Inventory management is one of the most crucial business operations for a manufacturing organisation. It addresses inventory control along the entire supply chain. The effectiveness of product storage is determined by inventory management operations. Improvements in methods and management principles lead to improvements in moving loads, delivery times, service quality, operating expenses, facility utilisation, and energy conservation. The manipulation of logistics heavily relies on inventory management [32].

Storage facilities are necessary to maintain the distribution system, and the market, and keep the wheels of production rolling [32]. Inventory management is crucial for industrial activities, machinery and plant maintenance, and other operational needs. When inventory levels are high, the organisation's management becomes extremely anxious [33]. This means that management needs to be closely monitoring it. Any increase in the redundancy of operations or machinery brought on by a lack of inventory can result in lost productivity and the expenses that go along with it. Production control in a manufacturing system is usually determined by the physical configuration and capabilities of the equipment, even in very complex and flexible processes involving multiple products. The tools must be set up each time the work changes [34].

The primary goal of inventory management is to support company activities to guarantee the efficient flow of materials, products, and services [35]. The term "*inventory*" here refers to the total number of items in the list; it is the amount of goods or products that a company has on hand to construct a product that will be sold. "*Stock*" refers to a broad category of products or resources available for purchase or use, such as stationery, office supplies, machinery, plant, and consumables.

Finished goods, work-in-progress, and raw material inventories are among the various categories of inventory.

- The inventory of raw materials comprises all the goods that a company buys to process them [32].
- Work-In-Progress Inventory: This is a stage of raw material inventory in between, where the factory is still working on finishing up tasks before moving on to the next processing step [32].
- The stock of finished goods is known as the finished goods inventory. These could include the amount of completed goods in the warehouse or the stock of goods ready to be sent. The organisation's production and sales departments must coordinate to manage stock [32].

3.13 Organisational Logistics Chain Performance.

Careful consideration should be given to inventory management strategies and the effectiveness of the organisation's supply chain to prevent large budgetary expenditures for preserving inventory. By requesting input from customers and ensuring that the concepts of time, location, and money are kept at the best possible levels, an organisation can ensure that its consumers are happy with the services it delivers. For the company to turn a profit or keep its budgetary allocations, the total cost model must be balanced by making sure that holding, ordering, and purchasing expenses are kept to a minimum [16]. The most crucial component of any business is controlling supply chain costs, which can only be done by hiring qualified personnel familiar with inventory management's technical aspects.

In the present world, supply chain management needs to be greatly improved because businesses are competing fiercely with one another. Hiring highly qualified employees and utilising cutting-edge technologies, such as Material Requirement Planning (MRP) and Enterprise Resource Planning (ERP), are necessary to attain the necessary level of efficiency. When staff members are proficient in applying inventory management techniques, which call for demand planning, forecasting, and location, organisational performance will be attained. Inventory management's primary goal is to maximise customer service while minimising the overall cost of all associated expenses to ensure profitable operations [36].

3.14 The Economic Order Quantity (EOQ)

The Economic Order Quantity (EOQ) inventory management methodology is used to identify the ideal delivery size and select the least expensive deliverer, ensuring the lowest possible overall cost of inventory investments. The EOQ model is a method that figures out how much inventory is best to order each time that item's inventory runs out [37]. A higher order quantity lowers ordering frequency and associated costs but necessitates keeping a higher average inventory, which raises holding expenses. Conversely, a lower order quantity lowers the average inventory but necessitates more frequent orders at a higher cost [38].

Transparent cooperation with reliable suppliers of critical inventory can yield substantial benefits under the Vendor-managed-Inventory (VMI) approach, particularly in large-scale production management. In a vendor/customer relationship, VMI allows the vendor to plan, monitor, and control inventory for their clients [39]. The vendor assumes responsibility for maintaining inventory levels within predetermined ranges while the client focuses on increasing demand accuracy [40].

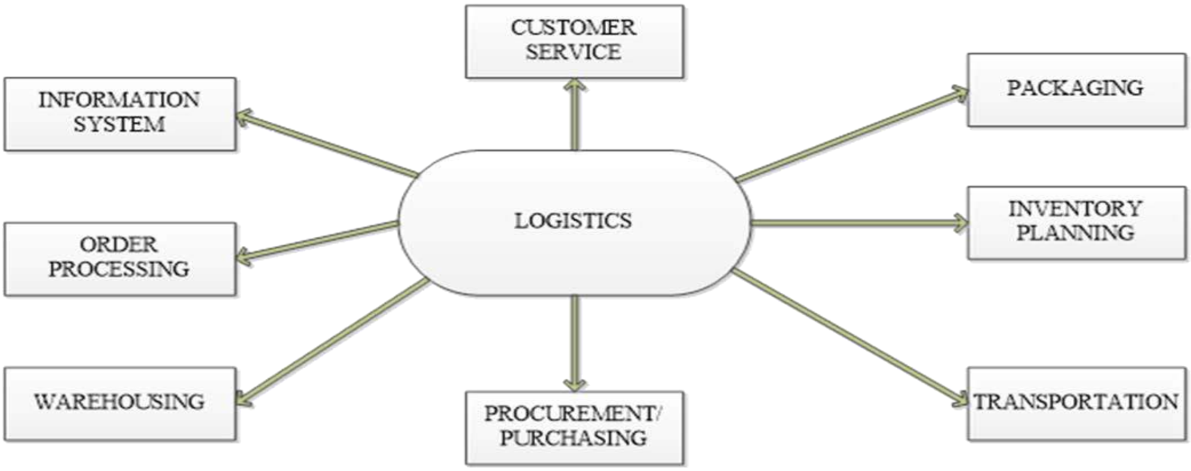

Figure 2: Logistics components

3.15 Success Factors and Challenges that affect the Logistics Support system in haulage.

In the haulage industry, the logistics support system plays a critical role in determining transportation operations' efficacy, performance, and efficiency. This study endeavours to accomplish two principal goals: initially, pinpointing the crucial elements and hindrances impacting logistics support systems within the haulage industry, and secondly, suggesting workable measures to improve these systems. This study discusses world-class practices that have proven to be successful in improving and provides insights into the present difficulties and success factors in haulage logistics through a thorough evaluation of the literature.

Identification of Issues in the Logistics Sector

- Economic Fluctuations: The haulage industry is susceptible to changes in the economy, including fluctuations in fuel prices and swings in consumer demand. The planning and execution of logistics are affected by economic volatility [41].
- Regulatory Limits: Logistics companies face delays and higher operating expenses due to diverse and non-uniform regulatory frameworks across different countries [41].
- Infrastructure Challenges: The research discovered that the effectiveness of haulage operations is severely compromised by inadequate infrastructure, such as badly maintained routes and a lack of warehousing facilities [42]
- Environmental Issues: Given that many of the processes used in the logistics industry are not viable in the long term, there is growing pressure on the industry to lower its ecological impact [43]
- Technological Gaps: A lot of haulage companies still operate with antiquated technology, which makes fleet management, scheduling, and tracking inefficient [44].
- Security Risks: Frequent problems that jeopardise the integrity of logistics operations include cargo theft and security breaches. Although putting strong security measures in place is crucial, it is highly resource-intensive [44].

Techniques to Enhance Maintainability, Reliability, and Availability

- Preventive maintenance programs: Consistent and methodical maintenance plans help haulage vehicles last longer and experience fewer unplanned problems [45].
- Training and Development: Funding ongoing employee training guarantees that staff members are competent in utilising new technology and abiding by logistics management best practices [46].
- Adoption of Advanced Technologies: The availability and dependability of haulage services can be greatly improved by putting in place GPS tracking, computerised scheduling systems, and real-time data analytics [47].
- Collaborative Networks: Creating partnerships and strategic alliances can result in resource sharing, enhanced optimisation of routes, and increased dependability of services [48].
- Strengthening Infrastructure: To invest in and maintain top-notch infrastructure, governments and business entities should work together. Infrastructure projects can be successfully financed through collaboration between the public and private sectors [42]
- Regulatory Integration: The complexity and expense of compliance can be decreased by working to harmonise rules between different locations. Logistics operations can run more smoothly with the support of international collaboration and standardisation measures [41].
- Improving Security Measures: Security risks can be reduced by putting in place cutting-edge security technology including biometric systems, RFID monitoring, and surveillance systems. Regular risk evaluations and security audits are also essential [44].

Handling Issues Particular to the Automotive Sector

- Improved supply chain coordination can result in shorter lead times and more effective inventory management between production departments and logistics departments (In this case supply chain management, parts control and, material handling) [49].
- Customisation and Flexibility: Creating logistics solutions, including just-in-time delivery systems, that are specifically designed to meet the demands of the automotive industry can boost productivity [50].
- Sustainability Practices: Reducing fuel usage and using electric or hybrid trucks are two examples of eco-friendly logistics strategies that can be used to solve environmental issues. Another strategy is to optimise delivery routes [51].

The results of this systematic literature analysis demonstrate that, although human skills and technology integration are essential for effective logistical assistance, barriers like economic swings and regulatory hurdles represent serious risks. By taking proactive steps like using cutting-edge technologies and harmonising regulations, these barriers can be overcome, thereby greatly improving the effectiveness and efficiency of logistics systems in the haulage industry.

4 RECOMMENDATIONS AND CONCLUSION

4.1 Investment in Infrastructure

- It is recommended that greater funding be promoted for harbours, bridges, and other transportation infrastructure. Presentations to the government to release funds for this can be made because this sector attracts investors and strengthens the national economy. Haulage operations will operate more efficiently and with fewer delays as a result.

- Upgrading and maintaining current infrastructure regularly is necessary to meet the needs of modern logistics.

4.2 Addressing Environmental Issues

- It is recommended to adopt sustainable behaviours, such as driving fuel-efficient trucks, planning routes to cut emissions, and making investments in alternative energy sources, should be emphasised.
- Green logistics initiatives: It is recommended to support the implementation of laws that promote these initiatives, particularly those that provide financial rewards to businesses that reduce their environmental effect.

4.3 Regulatory Reforms

- Regulation Simplification: It is recommended that administrative barriers be lowered and compliance increased, and regulations across various locations be harmonised and simplified.
- It is recommended that legislation be advocated that promotes effective logistical operations without sacrificing environmental and safety requirements and requires active engagement with lawmakers.

4.4 Technological Advancement

- Adoption of Advanced technology: To improve the effectiveness and dependability of the logistics support system, it is recommended to make investments in cutting-edge technology like GPS tracking, automated warehouses, and data analytics.
- Training and Development: It is recommended to put in place programs to teach employees how to use new technology and keep up with the most recent developments.

4.5 Economic Stability Measures

- The development of comprehensive risk management techniques is required to limit the impact of variations in the economy on haulage operations.
- It is recommended to encourage the government or financial institutions to provide financial support and incentives to logistics companies in times of economic recession.

4.6 Enhancing Security

- Better Security Measures: To protect products in transit, it is recommended to invest in security measures, including surveillance systems, safety facilities, and strong protocols.
- Cooperation with Law Enforcement: To improve the security of haulage operations and encourage cooperation between logistics firms and law enforcement organisations.

4.7 Optimisation Steps

- Process Optimisation: To reduce waste and boost the effectiveness of logistics processes, it is recommended to apply lean management techniques.
- Supply Chain Cooperation: To improve logistics operations, it is recommended to promote increased cooperation and information exchange throughout the supply chain.
- It is recommended to establish plans for continuous improvement to evaluate and improve the logistical support system regularly.

4.8 Future Research Directions

- Impact of Emerging Technologies: It is recommended to Examine how transport logistics may be affected by cutting-edge technologies like blockchain, artificial intelligence (AI), and the Internet of Things (IoT).
- Case Studies on Best Practices: To find best practices and reproducible techniques, it is recommended to do case studies on businesses that have effectively overcome logistics issues.

Through the resolution of these issues, companies can strive to establish a logistical support system for the haulage sector that is more effective, dependable, and sustainable.

Deteriorated roads might result in more expensive auto maintenance and longer travel times. This can be greatly reduced by advocating for public and private funding for infrastructure upgrades, such as constructing new warehouse facilities and repairing damaged roads. Regulations and consumers are looking more closely at the environmental impact of the logistics industry, which means that more sustainable methods must be adopted. Nonetheless, these issues can be successfully addressed by implementing green logistics techniques, such as the use of fuel-efficient trucks, route optimisation to reduce fuel consumption and the integration of renewable energy sources into logistical operations.

Decision-making and customer satisfaction are impacted when antiquated technologies are used because they lead to inefficiencies and a lack of real-time visibility into logistical operations. Modern logistics technology can significantly increase operational efficiency. Examples of these technologies include IoT devices, sophisticated fleet management software, AI-driven analytics, and warehouse management systems (In this case, an example is Mainframe). Delivering specialised logistics solutions that meet the unique needs of the automotive sector can greatly improve customer satisfaction and service quality. Gaining a competitive edge can come from creating adaptable logistics plans, such as just-in-time delivery and modular logistics solutions, that can be tailored to the different demands of manufacturers.

5 CONCLUSION

This report emphasises how important it is for the haulage business to have a strong logistical support system, especially when it comes to tackling the issues the haulage is facing. This study offers a road map for improving logistics services availability, maintainability, and dependability by pinpointing problems and offering specific solutions. The adoption of cutting-edge technologies, enhanced infrastructure harmonisation of regulations, and sustainable practices are essential for propelling the haulage logistics sector's future growth and efficiency.

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APPLYING THE PDCA CYCLE TO SCOPE 3 GHG EMISSIONS REPORTING IN THE SOUTH AFRICAN MINING INDUSTRY

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ABSTRACT

Scope 3 emissions are indirect emissions occurring along the value chain of industries such as mining. With the focus mainly being on Scope 1 and Scope 2 emissions, Scope 3 emissions are fast becoming a concern within greenhouse gas emissions reporting. Scope 3 emissions reporting comes with challenges in accuracy, transparency and completeness which impact the quality of Scope 3 inventories published. These principles are affected by poor data availability and data gaps. This study applies the Plan-Do-Check-Act (PDCA) cycle to Scope 3 emissions reporting in South African mines to improve the quality of Scope 3 inventories within this sector. The PDCA cycle incorporates aspects such as identifying the required information, clearly categorizing activities and conducting materiality assessments. Applying this to a case study showed that the inventory could be expanded from reporting three categories to reporting ten categories. Justifications are also given for excluded categories to improve the overall reported inventory.

Keywords: Scope 3 emissions reporting, accuracy, transparency, completeness, PDCA Cycle

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1 SCOPE 3 EMISSIONS REPORTING LANDSCAPE

Greenhouse gas (GHG) emissions from human activities are a significant driver of climate change. These emissions are classified into Scope 1, Scope 2, and Scope 3 emissions. Scope 1 emissions are direct emissions occurring from an organisation's core activities whilst Scope 2 and Scope 3 emissions are indirect [1]. Scope 2 emissions stem from the organisation's energy consumption, while Scope 3 emissions arise throughout the organisation's value chain.

In South Africa, the current GHG inventory primarily consists of Scope 1 emissions across various industries [2]. The reporting of Scope 1 and Scope 2 emissions is relatively straightforward, given the availability of quantifiable data. [3], [4]. Companies within the agriculture, energy and mining sectors are at the forefront of GHG emissions reporting. Notably, mining is a vital component of South Africa's economy, contributing approximately 25% to provincial GDP in the Northwest, Limpopo, Northern Cape and Mpumalanga [5].

The mining sector with its extensive value chain, involves numerous third-party interactions, ranging from sourcing material, processing and distributing. Consequently, Scope 3 emissions are inevitable within mining companies. While reporting Scope 1 emissions is mandated by law, the disclosure of Scope 3 emissions remains voluntary, contingent on the company's discretion [1].

Scope 3 emissions reporting also faces various challenges, particularly regarding data quality and double accounting [6]. The accuracy of reported emissions heavily depends on the data supplied by the third parties within the value chain [7], [8], [9]. Data gaps often necessitate the use of estimates and industrial averages, compromising the precision of emissions reporting. Additionally, existing Scope 3 emissions guidance leaves critical aspects such as determining relevance and materiality to the reporting organisation's discretion.

Scope 3 emissions are broad, and they are comprised of 15 categories, divided into upstream and downstream emissions. Upstream emissions (categories 1-8) originate from purchased materials and services used by the company. Downstream emissions (categories 9-15) arise from the selling, distribution, and end-of-life treatment of the products [10]. Listed in Figure 1 are the 15 categories considered under Scope 3.

	UPSTREAM		DOWNSTREAM
1	Purchased goods and services	9	Transportation and distribution
2	Capital goods	10	Processing of sold products
3	Fuel and energy-related activities	11	Use of sold products
4	Transportation and distribution	12	End-of-life treatment of sold products
5	Waste generated in operations	13	Leased assets
6	Business travel	14	Franchises
7	Employee commuting	15	Investments
8	Leased assets		

Figure 1: Scope emissions categories divided into upstream and downstream

The Corporate Value Chain Accounting Standard (Scope 3 Standard) is the most widely recognised framework to quantify Scope 3 emissions [1]. Although guidance is available, Scope 3 emissions reporting is proving to be more complex compared to Scopes 1 and 2 [3], [4]. Even with challenges, the Scope 3 standard has assisted in informing Scope 3 specific emissions disclosure guidance such as the Carbon Disclosure Project (CDP) climate change questionnaire. However, the quality of data disclosed can vary significantly, depending on the robustness of the data collection process and cooperation from value chain partners.

Despite Scope 3 emissions reporting being voluntary, multiple multinational mining companies have already taken steps towards quantifying and reporting their Scope 3 emissions. Climate change reports, sustainability reports and CDP climate change questionnaires of the leading mining companies in Africa [5] were sampled to assess how they report their Scope 3 emissions. Table 1 summarizes the disclosed Scope 3 inventories by these companies. The review aims to assess the extent to which the 15 Scope 3 categories are reported.

Table 1: Scope 3 inventories of various mining companies in Africa

Mining companies	Ore focus	1. Purchased goods and services	2. Capital Goods	3. Fuel - and energy-related activities	4. Upstream transportation and Distribution	5. Waste generated in operations	6. Business travel	7. Employee Commuting	8. Upstream leased assets	9.Downstream transportation and Distribution	10. Processing of sold products	11. Use of sold products	12. End-of-life treatment of sold products	13. Downstream leased assets	14. Franchises	15. Investments
1. Goldfields [11]	Gold	■	□	■	□	■	■	■	□	■	□	■	□	□	□	□
2. Anglo American [7]	PGMs, Coal etc.	■	■	■	■	■	■	■	□	■	■	■	■	□	■	■
3. Anglo Gold Ashanti [12]	Gold	■	■	■	■	■	■	■	□	■	■	□	□	□	□	□
4. Harmony [13]	Gold	■	□	■	□	□	■	□	□	□	□	□	□	□	□	□
5. Sibanye Stillwater [14]	Gold, PGMs	■	■	■	■	■	■	■	□	■	■	□	■	■	■	□
6. Implats [15]	PGMs	■	□	■	■	■	■	■	□	■	□	□	□	□	□	■
7. Northam Platinum [16]	Platinum	■	■	■	■	■	■	■	□	■	■	□	□	□	□	■
8. DRD Gold [17]	Gold	□	□	□	□	□	■	□	□	□	□	□	□	□	□	□
9. Pan African Resources plc[18]	Gold	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
10. Jubilee Metals Group [19]	PGMs, Chrome etc.	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□

Reported ■ Not reported □

South Africa is the world's largest platinum producer [20], [21] and it is within the top 10 gold producers in the world [22], [23]. Since the mining companies in Table 1 have a similar ore focus, the expectation would be for them to have a similar trend in their inventories. However, the inventories vary greatly from one company to another.

Companies nine and ten do not report on their Scope 3 emissions whilst the remaining companies report on their Scope 3 emissions to an extent. The emissions distribution lies mostly in the upstream categories. Since mining companies produce intermediate products, the emissions occurring downstream tend to become the upstream emissions of the buyer [9]. Company eight holds the smallest inventory with one category reported. Thus, the Scope 3 emissions may be under-reported for this company. The inventories also vary from one company to another depending on their emission reduction goals, the materiality, and relevance criteria applied to each Scope 3 category [24].

Companies one through six hold larger inventories and have disclosed plans to continuously improve their Scope 3 emissions reporting [7], [8]. Such improvements require engagement with value chain partners. By encouraging data measurement and management in the value chain, the quality of data can be improved. Uncertainties can be eliminated and then the accuracy of the emissions will improve. Thus, mining companies will be able to apply the data in setting emission reduction targets and inform their decision-making when sourcing suppliers [3], [25].

The Scope 3 Standard acknowledges trade-offs occurring within Scope 3 emissions reporting. This results in the reporting company having to choose between *good practices* such as comparability and relevance [1], [24]. A reporting company can choose to report on what is relevant to their emission goals and targets over making their Scope 3 inventory comparable to another company. There are several opportunities to improve Scope 3 reporting to match the quality of Scopes 1 and 2. This can be done by considering quality improvement methods that allow repeated exercise to achieve a specific goal.

2 TRANSPARENCY, ACCURACY AND COMPLETENESS OF SCOPE 3 REPORTING

Transparency, accuracy and relevance are considered *good practice* principles[†]. An inventory that follows *good practice* contains neither over nor underestimates and uncertainties are reduced as far as possible [26]. Transparency means that sufficient information is disclosed to make the data understandable [26]. Accuracy focuses on the quality of data disclosed, addressing uncertainties, and whether there are neither over nor underestimates in the inventory. Completeness is focused on the level of coverage and inclusion of all relevant GHG emissions and removals [26].

If these principles are not met in reporting, the inventory comes into question on whether it is a proper representation of the company's emissions profile and if this data can inform decision-making. The Scope 3 Standard, the IFRS-S2[‡] standard and ISO 14064-1[§] were used as sources for developing evaluation criteria that inform transparency, accuracy and completeness [1], [27], [28].

The evaluation criteria are focused on the reporting requirements which all align within the standards. It is mentioned that Scope 3 data shall be reported in CO_2-equivalent[**] tonnes per category. Additionally, any excluded categories must be accompanied by justifications for their exclusion. Providing justifications is one of the ways to satisfy completeness. The method behind the reported data shall also be disclosed as far as possible. These reporting requirements ensure transparency and accountability in emissions reporting. Along with transparency, the data reported must show a certain level of consistency. That is, the boundary chosen must be consistent with that applied in Scopes 1 and 2 to avoid overlap and double accounting in the GHG emissions. A historical record of the emissions also supports consistency and transparency however this may not apply if an company has not begun

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[†] *Good practice* principles include transparency, consistency, accuracy, comparability, completeness and accuracy. Relevance is considered over comparability in Scope 3 emissions reporting as the standard was only designed to accommodate comparability internally

[‡] The IFRS-S2 Standard informs the financial risks related to climate disclosures and was adopted from the Task Force on Climate-related Disclosures (TCFD) guidance.

[§] ISO 14064-1 provides reporting and accounting guidance on GHG emissions.

[**] CO_2-equivalent is a unit of measure to compare different GHGs on the basis of their global-warming potential.

reporting. Data assurance is also assessed as it shows whether the data can be trusted, and adheres to the method the company applied.

To review these *good practices* within the Scope 3 emissions reporting landscape, the sustainability reports were assessed on the extent the disclosed Scope 3 inventories follow the principles of transparency, accuracy and completeness. The evaluation criteria discussed above and the results from the sampled reports are summarized in Table 2.

Table 2: Scope 3 reporting review

Company	**1. Goldfields**	**2. Anglo American**	**3. Anglo Gold Ashanti**	**4. Harmony**	**5. Sibanye Stillwater**	**6. Implats**	**7. Northam Platinum**	**8. DRDGold**	**9. Pan African Resources plc**	**10. Jubilee Metals Group**
Data reported in metric tons of CO_2 equivalent per category	■	■	■	■	■	■	■	■	□	□
Excluded categories are given with justifications	■	■	■	□	■	■	■	□	□	□
Calculation methodology disclosed per category	□	■	□	□	■	■	■	□	□	□
The boundary chosen is consistent with Scope 1 and Scope 2	■	■	■	■	■	■	■	■	□	□
Materiality criteria disclosed (quantitative/qualitative) and justified	■	■	□	■	■	■	■	□	□	□
Historical record of at least 1-2 years of emissions	■	■	□	■	■	■	■	■	□	□
Any uncertainties with reported emissions disclosed	■	■	□	□	■	■	■	■	□	□
Assurance on Scope 3: Reasonable or limited	■	■	□	■	■	■	□	□	□	□
Fulfilled	■	**Not Fulfilled**								□

Companies nine and ten do not have any information related to Scope 3 emissions in their sustainability reports. It is a reporting requirement to disclose reasons behind the categories that have been excluded from the inventory [27], [28], [1]. Only four companies give reasons/justifications for the excluded categories. The most prevalent reason is that the category does not apply to that company. The materiality criteria are disclosed as a materiality approach that adopts a double materiality stance. Double materiality considers the financial aspect and the Environmental Social Governance (ESG) aspect when determining what should be reported.

It is assumed that the general material approach is also applied when quantifying Scope 3 emissions [24]. Considering that only four out of ten companies adhere to methodology disclosure and provide justifications, transparency is not entirely fulfilled in Scope 3 emissions reporting. The completeness of the Scope 3 inventories also becomes a concern. If companies are not adhering to full disclosure, it cannot be deduced whether the reporting company has included all relevant GHG emissions in its inventory.

Companies one through seven have a historical record of Scope 3 emissions reporting. These companies show consistency in reporting, as they also provide restatements for any changes in data. Companies one, two, five, six, seven and eight also disclose the challenges and uncertainties with some of the Scope 3 data reported. This includes where industrial averages or estimates were used and the plans for improvement in reporting that category. Assurance statements were reviewed to determine whether Scope 3 emissions are included in the process. Assurance proves that the data is trustworthy and reliable enough to inform decision-making. Companies one, two, four, and five included Scope 3 emissions within their assurance, conveying compliance with the outlined methodologies for Scope 3 emissions reporting.

Companies two, four and five meet all the reporting requirements in the criteria. The remaining companies lack transparency in method disclosure and materiality criteria. This puts the relevance of the data to the company into question. Not fulfilling all the reporting requirements also means uncertainties are not disclosed to stakeholders. Poor focus on Scope 3 emissions reporting also means that the companies that are not fully reporting on this scope, miss out on emission mitigation opportunities occurring in their value chain [3], [4]. Companies that do not quantify their Scope 3 emissions risk collaborating with suppliers who have a high carbon footprint. This, in turn, increases the reporting company's Scope 3 carbon footprint which adversely affects emission reduction strategies.

The inadequate reporting of Scope 3 emissions is further exacerbated by the challenges with data availability. The mining companies highlight several challenges as the data quality and availability are influenced by third parties and not within their control [10], [20], [25], [26]. The Mining Council of South Africa (MCSA) recognises the impacts of climate change and has called for its members to commit to reducing their emissions and implementing mitigation mechanisms [29]. The main commitment is to collaborate with supply chain partners towards reducing Scope 3 emissions.

This however cannot be done if there are still challenges within the Scope 3 reporting landscape. Furthermore, research into Scope 3 emissions reporting is gaining momentum. The preliminary review conducted in Table 2 showed that not all the *good practice* principles are met in Scope 3 reporting. There is a need for a framework that addresses the challenges in Scope 3 emissions reporting while also uncompromising with *good practices.* For the literature review, the following research questions were applied to assess the studies:

- Why is it important to report on Scope 3 emissions?
- Who are the legally liable parties in reporting Scope 3 emissions?
- Is the study applicable to mining companies?
- How are Scope 3 emissions defined by reporting disclosures?
- How can a standardised reporting methodology be developed?

Google Scholar, SpringerLink and Elsevier were the main academic search engines used to source the relevant literature. The key statements used were "Scope 3 emissions in the mining industry", "Scope 3 emissions reporting", and "ESG". The search yielded eight articles relevant to this study. A state-of-the-art matrix summarizes the main articles and their niche.

Table 3: State-of-the-art matrix summarizing the literature on Scope 3 reporting

SOURCE		Reference	Reporting disclosures on Scope 3	Legally liable parties	Importance of reporting Scope 3 emissions	Methodology development	Applicable to mining value chain
1	B. Ackers and S.E. Grobbelaar, (2022)	[30]	▤	▤	■	▤	▩
2	Y.A. Huang, C.L. Weber, and H.S. Matthews	[25]	■	■	▩	▩	▤
3	M. Schmidt, M. Nill and J. Scholz, (2022)	[9]	▩	▤	▩	▤	▤
4	S. E. Greene (2017)	[3]	▩	■	▩	■	▩
5	A.G.S. Gous (2018)	[31]	■	▩	■	▩	▩

6	M. van Heerden (2017)	[32]	■	■	■	▦	▦
7	J. Patchell (2018)	[4]	▦	▦	▦	▦	■
8	G. Shrimali (2021)	[6]	▤	▦	▦	▤	▤
▦	In the study	▤	Somewhat in the study	■	Not in the study		

Five articles cover the importance of reporting Scope 3 emissions with the common motive being a holistic approach to emissions mitigation [3], [4], [6], [9], [25]. Huang, Weber and Matthews [25] discuss the lack of focus on Scope 3 emissions and how it is estimated that these emissions can even account for up to 75% of emissions for an industrial value chain. Currently, companies are focused on mitigating their Scopes 1 and 2 emissions which contribute significantly less to overall emissions.

A GHG inventory consisting of all three scopes provides companies with an accurate and transparent outlook on their emissions. Schmidt, Nill and Scholz [9] emphasise the importance of quantifying Scope 3 emissions as most countries are working towards carbon neutrality and how the challenges in Scope 3 reporting may compromise meeting these goals.

This puts into question the legal liability set for Scope 3 emissions as they are voluntary. Gous [31] touches on the carbon tax landscape in South African mines and considering that the carbon tax bill is a legal requirement set out for industrial companies, the same is possible for Scope 3 emissions. Imposing a legal requirement for Scope 3 reporting may improve the number of companies reporting on these emissions. This will positively affect data availability as companies will have to implement measurement strategies to quantify emissions accurately. Ackers and Grobbelaar [34] conducted a study on the integrated reporting landscape in South African mines. The article highlights how the legal reporting requirements for companies listed on the stock exchange have moulded the quality of data published in sustainability reports.

Four studies apply to the mining value chain focusing on aspects such as the current Scope 3 landscape [3],[30], data management processes [32] and how this sector approaches reporting emissions-related requirements such as carbon tax and section 12L [31]. Schmidt et. al. [9], Greene [3] and Patchell [4] provide a general overview of the reporting disclosures and are not specific to the mining sector however, mining companies are included within their sampling. The studies scrutinize the reporting requirements of various Scope 3 guidelines including the Science Based Target Initiative (SBTi), CDP, the Scope 3 Standard and ISO 14064-1. They also highlighted how downstream categories may be more suited for the end users than the reporting companies as double accounting may occur. Huang et. al. [26] discuss the need for specificity per sector to improve accuracy.

Since most guidance is general, Scope 3 emissions reporting needs specificity to streamline reporting [25]. Value chains tend to overlap with other industries and this can confuse the responsibility allocation of emissions due to multiple sectors interacting [6]. To remedy this, Huang et. al. suggest an accounting methodology using the Input-Output Life-Cycle Assessment (IO-LCA) to quantify Scope 3 emissions. Huang et. al. [26] discuss building on tools previously used. The IO-LCA method relies on sectoral aggregation resulting in average data being used which can affect the accuracy of Scope 3 emissions. Schmidt et. al [9] adopt a multiregional model into the Input-Output analysis to consider the geography, supplier levels and the sector the reporting company belongs to. The Multiregional Input-Output model (MRIO) employed does require region-specific data. For developing countries, this model may be a challenge to use considering the data gaps that may be encountered.

The IO - LCA, and MRIO models have their shortcomings concerning their application in Scope 3 emissions reporting. Both models require granularity in the data, and since data availability is already a challenge for Scope 3 emissions reporting. Van Heerden [32] applies a different approach by using the PDCA cycle to develop a detailed environmental data system that analyses, manages, and continually improves ESG reporting for mining companies. The data management process relies on an auditing aspect which assures the continued accuracy that ESG data requires [32]. The process emphasizes addressing any findings via investigations within the mining companies. Similarly, Gous [31] developed an approach for quantifying carbon tax by applying certain elements from the requirements for section 12L quantification and reporting. Gous solved issues that affected *good practice principles* in the carbon tax landscape. Gous highlighted how one management approach can make use of elements in guidance that are already available to develop a process that addresses challenges in other GHG reporting areas. Gous and van Heerden addressed data limitations in the South African mining landscape.

The environmental data management process outlined by Van Heerden is mainly focused on Scope 1 and Scope 2 emission data in the mines. Considering that Scope 3 requires continuous review, the PDCA cycle can be applied to address data gaps, data availability and methodology inconsistencies as it is a fundamental concept of continuous improvement aiming to improve quality [33]. Other methods such as Define-Measure-Analyse-Improve-Control (DMAIC) work better with eliminating unproductive steps.[33]. Which would be suitable for an already well-developed process. Most of the other methods are fact-based and rely on specific data and that is already a challenge in Scope 3 emissions reporting. The PDCA cycle is favourable to apply in Scope 3 emissions reporting as it has shown successes with streamlining Scopes 1 and 2 reporting in the mining context.

3 THE PDCA CYCLE ON SCOPE 3 REPORTING

The PDCA cycle is a technique which can be applied to a process or system without stopping any moving parts in the process [33], [34]. The PDCA cycle consists of four phases i.e. Plan, Do, Check and Action. The Plan phase is focused on identifying the problem, root causes and weighing possible solutions. In the Do phase, the possible solutions given in the plan phase are implemented and the results are gauged for viability [35].This includes preliminary data collection related to the identified problem. The Check phase is for data analysis of the compiled data set. It also assesses the extent to which the goals that have been set during planning have been achieved and if it would be feasible to implement the planned solution on a large scale. Another PDCA cycle can be done within the check phase as the Act phase can only come into action once the results from the Do phase are satisfactory. The Act phase considers the full implementation of the outlined process. The PDCA Cycle is summarized in Figure 2 with the steps taken and the outcome for each phase.

3.1 PLAN

The first step to Scope 3 reporting is to review the reporting requirements according to the various standards. Reviewing other guidance such as the ISSB-S2, SBTi and Global Reporting Initiative (GRI) along with the Scope 3 Standard, ensures that the constructed dataset will satisfy multiple reporting requirements. Scoping what other companies with a similar ore focus are reporting gives the company an idea of where the potential emission hotspots may lie within the value chain. The Plan phase is mostly related to research and identifying the challenges that might be encountered moving forward.

Considering the *good practice* principles and reporting requirements for Scope 3 emissions, an evaluation criterion was developed. The evaluation criteria were developed as a tool for gauging whether the Scope 3 inventory satisfies the reporting requirements and adheres to *good practice*. To reduce the broad scope, all elements reported under Scopes 1 and 2 can be eliminated for consideration in Scope 3 reporting. Materiality is also informed by the reporting guidelines, and this is mostly given as a recommendation on what to consider when developing materiality criteria [1], [24]. To ensure as much data is collected as possible, all Scope 3 categories are considered initially material [24].

3.2 DO

This phase is focused on data collection according to the categories. It is favourable to collect primary data from tier 1 suppliers [1]. This data can be emission factors related to the commodity and/or emission quantities if available. As the data quality decreases, companies can make use of secondary spend-based data and industrial averages. Spend-based data is widely accepted as the lowest data quality that can be used to estimate Scope 3 category emissions [1]. The simplest calculation methodology to quantify emissions is to make use of equation 1 [1], [24].

$$Activity\ data\ \times Emission\ Factor = tCO_2e\ emissions \tag{1}$$

In the formula, *Activity data* is physical quantities of the activity or commodity, *Emission Factor* is the CO_2 equivalent emissions released from the activity or production of the commodity, and the emissions produced are given in CO_2-equivalent units. This unit of measurement is calculated using the Global Warming Potentials of the GHGs recognised by the Kyoto Protocol [36]. Once data collection is complete, a preliminary Scope 3 GHG inventory can be calculated.

3.3 CHECK

This phase scrutinizes the Scope 3 inventory produced in the do phase and the materiality thereof. This materiality assessment considers financial and environmental risks related to reporting each category informed by the various reporting standards [1]. All categories not relevant to the company can be eliminated and the focus can be on improving the quality of the remaining categories. Internal controls can be planned accordingly to reduce findings when the data is audited externally. The inventory can then be presented in the form of quarterly reports within the reporting year. A continuous cycle of reporting ensures that the data is constantly reviewed and verified. This also simplifies implementing improvement measures. The evaluation criteria in Table 2 can be used to track if the inventory still complies with the reporting requirements.

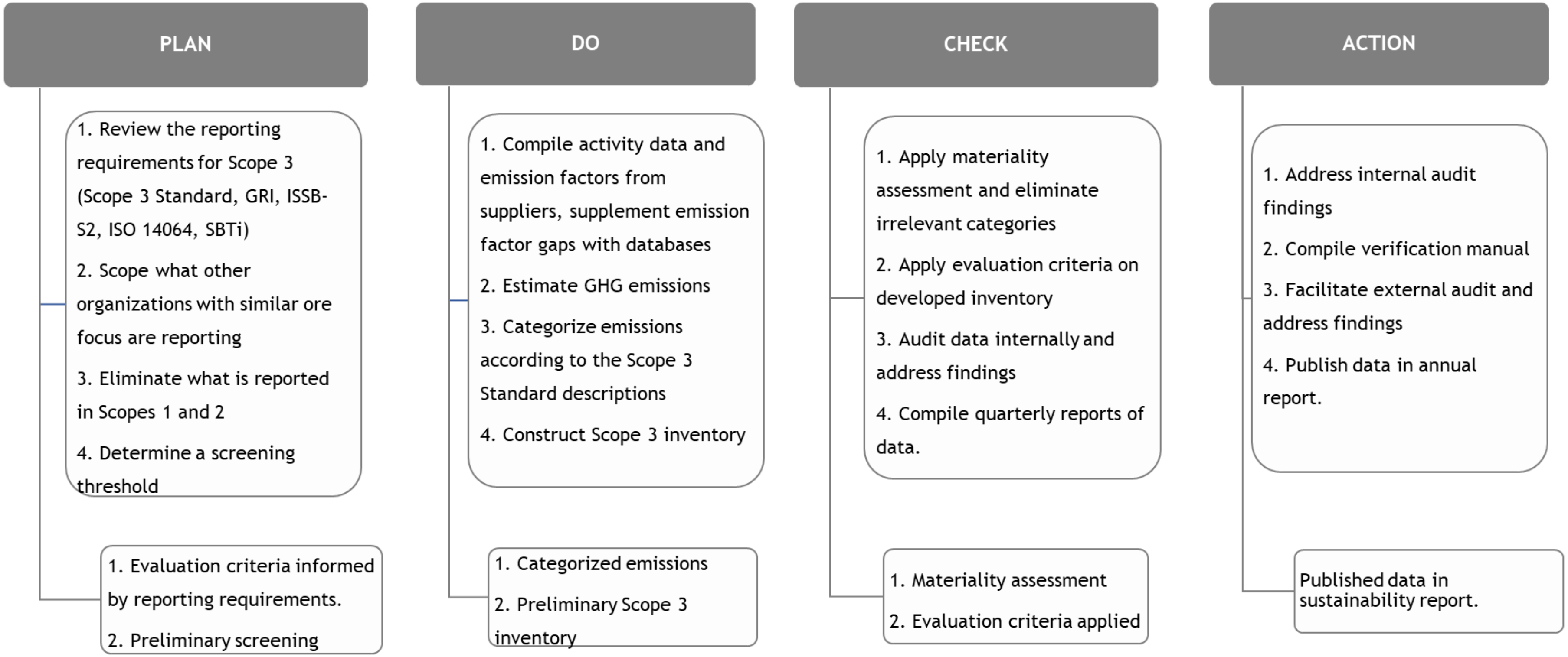

Figure 2: PDCA Cycle process for Scope 3 reporting

3.4 ACTION

It is a requirement for material topics to undergo some form of external assurance [1], [28]. Sustainability reports include a statement of assurance from external auditors to support the accuracy, transparency and relevance of data published in the sustainability reports. Assurance ensures that the identified improvement areas are given more attention, and the data is compliant with publishing standards. These steps, if carried out on a continuous year-on-year cycle can eliminate most of the inconsistencies within the Scope 3 inventory.

4 IMPLEMENTATION AND RESULTS OF THE PDCA CYCLE METHOD

This study employs mixed methods. The qualitative aspect focused on applying the PDCA Cycle in the current Scope 3 reporting landscape whilst the quantitative aspect aligns with the steps outlined in the “Do phase”. On a case study basis, the PDCA cycle was applied on a Scope 3 inventory of mining company G. Mining company G is gold-focused with more than 15 operational business units. The PDCA Cycle in section 3 was applied following the outlined steps per phase.

4.1 PLAN

The evaluation criteria developed from reporting requirements were used to assess the current Scope 3 inventory. and the results are shown in Table 4:

Table 4: Evaluation criteria for Company G’s Scope 3 inventory

Mining Company G		
Evaluation Criteria	**Y**	**N**
Data reported in metric tons of CO_2 equivalent per category.	■	
Excluded categories are given with justifications.		■
Calculation methodology disclosed per category.		■
The boundary chosen is consistent with Scope 1 and Scope 2.	■	
Materiality criteria disclosed (quantitative/qualitative) and justified.		■
Historical record of at least 1-2 years of emissions.	■	
Any uncertainties with reported emissions disclosed.		■
Assurance: Data has undergone some form of external audit process.	■	
Result: Company G does not meet all reporting requirements.		

Mining company G’s current Scope 3 inventory adheres to certain reporting requirements. However, transparency is not fully adhered to as uncertainties with the data are not addressed. Similar challenges in completeness and relevance also arise with mining company G. A detailed calculation methodology and justifications for excluded categories are not given. As a step towards remedying the shortcomings in fulfilling the reporting requirements, the inventory was also gauged against the International Council of Metals and Mining (ICMM) Scope 3 guidance heat map [24]. Table 5 shows mining company G’s inventory against the heat map along with four other mining companies that have the same ore focus.

Table 5: ICMM heat map against Scope 3 inventories

Mining companies	**Ore focus**	**1. Purchased goods and services**	**2. Capital Goods**	**3. Fuel - and energy-related activities**	**4. Upstream transportation and Distribution**	**5. Waste generated in operations**	**6. Business travel**	**7. Employee Commuting**	**8. Upstream leased assets**	**9.Downstream transportation and Distribution**	**10. Processing of sold products**	**11. Use of sold products**	**12. End-of-life treatment of sold products**	**13. Downstream leased assets**	**14. Franchises**	**15. Investments**
ICMM	Precious Metals	▓	▒	▓	▒	▒	□	□	□	▒	▒	□	□	□	□	▒
A. Harmony	Gold	▦	░	▦	░	░	▦	░	░	░	░	░	░	░	░	░
B. Goldfields	Gold	▦	░	▦	░	▦	▦	▦	░	▦	░	▦	░	░	░	░
C. Sibanye-Stillwater	Gold, PGMs	▦	▦	▦	▦	▦	▦	▦	░	▦	▦	░	▦	▦	▦	░
D. Implats	PGMs	▦	▦	▦	▦	▦	▦	▦	░	░	▦	░	░	░	░	▦
Company G	Gold	■	■	■	■	■	■	■	░	■	■	░	░	░	░	■

Legend		
	▓	significantly greater than 5% of total Scope 3 emissions [24]
	▒	around 5% of total Scope 3 emissions, both below and above threshold [24]
	□	lower than 5% of total Scope 3 emissions [24]
	▦	Category reported
	░	Category not reported
	■	Potential category to report

From Table 5, it can be deduced that gold mining companies tend to report upstream categories 1 to 7. For downstream, categories 9, 10 and 15 are commonly reported. Considering that the sampled companies have the same ore focus, mining Company G has the potential to report ten categories. The ten potential categories for Company G also align with the emission hotspots outlined in the ICMM heat map. The heat map shows that high to medium emissions occur in categories 1 through 5 whilst downstream emissions lie in categories 9,10 and 15. These categories form part of the identified potential categories. The plan phase ensures that the completeness of Company G's Scope 3 emission inventory is high by considering 67% of the categories that could be reported. By reviewing each category, improvements to Company G's inventory can be identified and data collection can take place. A categorisation process (guided by Scope 3 Standard descriptions) was applied to group the available data into the relevant categories.

4.2 DO

The previous phase identified additional categories hence, data collection must take place. The most readily available data is through a financial data management system. This database stores all transactions that take place within Company G. The database provides quantities of goods purchased and expenditure on services. The database can be used to quantify category 1 and category 2 emissions. For other categories, data was received from the supplier. For categories without primary data, emission factors were sourced from trusted emission factor databases such as the United Kingdom's Department of Energy Food and Rural Affairs (DEFRA) database [37] to supplement the data gap. Table 6 summarizes the data type obtained per category, the calculation method and the source of emission factors.

Table 6: Data collection per category

Category		**Data obtained**		**Calculation method**
		Activity data	**Emission Factor(s)**	
1	Purchased goods and services	Financial database	DEFRA, CcalcC	Average-data
2	Capital goods	Financial database	Ecoinvent	Average-data
3	Fuel and energy-related activities	Supplier invoices	Supplier-based	Supplier-specific
4	Upstream transportation and distribution	Delivery notes, helicopter running hours	DEFRA	Distance-based
5	Waste management	Waste manifests	DEFRA	Waste-type specific
6	Business travel	Travel agency Carbon emission reports	Supplier-based	Supplier-specific
7	Employee commuting	Survey on travel patterns	DEFRA	Distance-based
8	Upstream leased assets	N/A	N/A	N/A
9	Downstream transportation and distribution	Helicopter running hours/ shipping vehicle consumption data	DEFRA	Fuel-based/Distance-based
10	Processing of sold products	Mine production sheets	Supplier-based	Average-data
11	Use of sold products	N/A	N/A	N/A
12	End-of-life treatment of sold products	N/A	N/A	N/A
13	Downstream leased assets	N/A	N/A	N/A
14	Franchises	N/A	N/A	N/A
15	Investments	Investee Scope 1 and 2 emissions data	N/A	Investment-specific

The data was obtained from Company G and through reaching out to their tier 1 suppliers. Primary data is mainly emissions data directly from the supplier and it was obtained for category 3 and category 6. For category 3, energy usage data was obtained from supplier invoices and the emission factor was calculated from the supplier's integrated report emissions data. For the other categories, the most common activity data available was from delivery notes and invoices providing data on volumes and quantities. A relevant emission factor is then sourced from DEFRA's database.

The most common calculation method applied is the average data method. The average data method uses *equation 1* [1]. Categories 2, 7, and 15 may require long-term data collection and can only be quantified with estimates as a temporary action. Category 7 emissions are calculated by collecting data on travel patterns from employees. Since Company G is large, data collection must be done per business unit for accuracy. Category 15 requires emissions data from joint ventures. It is important to consider that some joint ventures may not have emissions data available. Category 2 is another complex category as capital assets must be known, and data related to assets is usually spend-based. Spend-based emission factors are not readily available and usually require further data collection.

4.3 CHECK

Once the inventory is complete, a materiality assessment is applied to refine the data so that it includes only emissions relevant to Company G. The materiality assessment adopts the double materiality stance. The Scope 3 Standard suggests elements companies can use to inform their materiality and relevance. These include size, influence, risk, stakeholder concern, outsourcing and sectoral guidance [1]. The reporting company can develop the criteria to fit their emissions management strategy or according to their set goals. The materiality assessment developed includes financial materiality, quantitative materiality, and ESG-related concepts such as reporting impact and relevance to Company G’s emission reduction targets.

Quantitative materiality is focused on the number of emissions whilst financial materiality is focused on whether that category can affect the operational budget of the business units within the company. The ESG-related risks focused on the impact in Company G’s Scope 3 inventory, whereby if a category contributes as little as 1%, it can be included in the inventory. The smallest contribution is considered to provide Company G with a clear and complete representation of how their Scope 3 inventory currently stands.

Out of the fifteen categories, all ten categories identified in Table 5 were considered relevant and material to report. Table 7 summarises the materiality assessment outcomes according to the factors considered. Much of the upstream categories appear relevant to operational activities as the day-to-day running of the business units results in emissions contributed to those categories. However, categories such as business travel are influenced by Company G’s managerial aspect. Category 8 is the only upstream category excluded from the inventory due to the emissions being accounted for in Scope 1. The downstream categories are mostly not relevant to Company G, or the emissions can be deemed negligible.

Table 7: Results from applied materiality criteria

Category		Materiality Criteria Result
1	Purchased goods and services	Quantitatively material
2	Capital goods	Relevant to the company’s operational activities
3	Fuel and energy-related activities	Quantitatively material and relevant to operational activities
4	Upstream transportation and distribution	Relevant to the company’s operational activities
5	Waste management	Relevant to the company’s operational activities
6	Business travel	Relevant to the company’s operational activities
7	Employee commuting	Relevant, can change Scope 3 inventory by ±1%
8	Upstream leased assets	leased assets usage accounted for under Scope 1 and Scope 2
9	Downstream transportation and distribution	Relevant to the company’s operational activities
10	Processing of sold products	Relevant to the company’s operational activities
11	Use of sold products	Not relevant, once refined Gold produces negligible emissions, negligible direct and indirect use-phase emissions

12	End-of-life treatment of sold products	Not material, gold is an intermediate product with a long life and once processed, it produces negligible emissions.
13	Downstream leased assets	Not relevant, no downstream leased assets
14	Franchises	Not relevant, mining company G has no franchises
15	Investments	Relevant, can change Scope 3 inventory by ±1%

The detailed disclosure of methodology can include plans to use disclosures such as the CDP climate change questionnaire to detail the emissions methodology which also gives insight into the quality of data given in the questionnaire through a rating system [38]. The internal auditing of the data can include assurance on whether the outlined reporting and quantification procedures are adhered to and if the quality of data presented is a proper representation of the Scope 3 emissions of Company G. The company can decide the level of assurance required for their material topics [39]. A continuous reporting cycle of the emissions can be implemented to eliminate inconsistencies and ensure the data is following the outlined procedures of reporting.

4.4 ACTION

This is the final implementation phase of the cycle. by applying the PDCA Cycle framework, it was identified that certain categories needed specific attention due to insufficient data. As a temporary action, estimates were used where possible. A permanent action must be implemented long-term for these categories to address the data gaps. The data collected for this study spans over 12 months. Table 8 summarizes the percentage change in emissions per category post-application of the PDCA Cycle on mining company G’s Scope 3 inventory.

Table 8: GHG Emissions quantified

Category		Contribution	Contribution after PDCA	Permanent actions required
1	Purchased goods and services	52.61%	44.9%	Inclusion of a broader scope of relevant products and services in the category
2	Capital goods	-	-	Record of capital goods purchased, quantities and cost.
3	Fuel and energy-related activities	37%	36.5%	Inclusion of energy-related fuel emissions
4	Upstream transportation and distribution	-	1.4%	Record delivery details on products used by the company to report more accurate emissions
5	Waste management	-	16.5%	Quantified emissions on waste with available data
6	Business travel	0.5%	0.3%	Supplier-based data obtained and used over averages
7	Employee commuting	-	-	Survey distribution to employee population per operation
8	Upstream leased assets	-	-	N/A
9	Downstream transportation and distribution	-	-	Included in category 10 emissions

Category		Contribution	Contribution after PDCA	Permanent actions required
10	Processing of sold products	-	0.4%	Quantified emissions from the third-party carbon emissions and production report
11	Use of sold products	-	-	N/A
12	End-of-life treatment of sold products	-	-	N/A
13	Downstream leased assets	-	-	N/A
14	Franchises	-	-	N/A
15	Investments	-	-	Liaise with joint ventures to obtain carbon emissions data

Categories 1,3 and 6 were quantifiable as they were already included in Company G's Scope 3 inventory. Improvements were focused on completeness and updating to a more accurate methodology. Category 1 showed a 20% change and category 3 showed a 10% change in emissions reported post-application of the PDCA Cycle framework. Category 6 showed a 22% decrease post-application of the PDCA framework. This was due to updating the methodology from estimates to actual carbon emissions quantified by the supplier. Categories 4, 5, and 10 were previously not accounted for in Company G's inventory and showed a contribution of 1.4%, 16.5% and 0.4% respectively.

For category 4, certain data was available and supplemented by industrial averages. To reduce the uncertainty occurring with the data, permanent actions must include data collection on the outstanding gaps. Categories 2, 7 and 15 had insufficient data for estimated calculations. Thus, a planned permanent action was to implement data collection strategies whilst also disclosing plans to report emissions on these categories. Category 2 requires a record of purchased capital goods, their quantities and the cost related to these purchases. Category 15 requires carbon emissions per joint venture as mining company G's equity share is known. Categories 2 and 15's data requirements are dependent on the data provided by the third parties.

5 CONCLUSION

Scope 3 emissions reporting is gaining momentum in ESG. These value chain emissions are broad and can account for even up to 75% of an organisation's overall emissions. With the mining sector having a large value chain, Scope 3 emissions can be significant and if left unmanaged, they can jeopardise set emission reduction targets. Although Scope 3 emissions reporting guidance is complex, most mining companies have taken a step towards quantifying these emissions. However, the Scope 3 inventories produced can compromise principles of completeness, transparency, accuracy and relevance by not meeting reporting requirements.

Studies have highlighted significant gaps in the Scope 3 emissions reporting landscape. A PDCA cycle-based case study on mining Company G showed that their Scope 3 inventory should include ten categories. Improvements were achieved by implementing the planned steps in the PDCA framework. The entire Scope 3 inventory was reassessed with the reported categories' completeness being improved. Such steps resulted in more accurate data reported for categories 1,3 and 6. Additionally, Categories 4,2,5, 7, and 10 were quantified and included in the Scope 3 inventory as they were considered relevant to Company G.

The materiality assessment applied addressed the relevance of each category and informed the level of transparency. Determining justifications for the excluded categories also improved transparency. Temporary actions done to quantify categories 2,4 and 7 need to be addressed by implementing the permanent actions outlined for data collection. It is recommended that the company implement participation in methodology disclosure programmes as a quality assurance step and to gauge the quality of the methodologies employed. The reporting requirements were met by detailing materiality criteria, providing justifications for excluded categories, disclosing uncertainties in reported categories and planning full methodology disclosure by participating in disclosure projects.

Overall, the PDCA framework can be implemented to guide an company in Scope 3 emissions reporting. The PDCA Framework was developed for continuous improvement which is essential in Scope 3 emissions reporting. The incorporation *of good* practice guidelines ensured that the reporting requirements were fulfilled.

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APPLICATION OF FAILURE MODE AND EFFECTS ANALYSIS IN A ONE-PIECE FLOW MANUFACTURING SET UP: A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

This work aimed to analyse the application of Failure Mode and Effects Analysis (FMEA) in a manufacturing environment. This study reviewed 143 books published between 1985 and November 2023.

The criteria for selecting the books were keywords, publication window, English language, document type, and relevancy to manufacturing. Twenty-five books were analysed and cited in this systematic review.

The study revealed that FMEA was applied in manufacturing industries as a risk and problem-avoidance tool. FMEA addressed industry challenges such as safety, cost of poor quality, and product complexity to remain competitive. Most studies applied probabilistic fuzzy algorithms to address challenges associated with failure mode identification, evaluation, decision making and reporting. FMEA data credibility remains expert dependable or probabilistic fuzzy.

This study is the first systematic review of FMEA in the manufacturing sector. It is recommended that future studies focus on the FMEA data input mechanism and live documented risk.

Keywords: Systematic Review, FMEA, Fuzzy set concepts, Fuzzy algorithms, IFHWED, ITHWD, Trapezoidal Fuzzy Numbers, VIKOR, Interval 2-tuple Linguistic, Analytic Network Process, Spherical Fuzzy Sets, FWLSM, FWGM, Rough set theory, TODIM, Cloud Chocket weighting, BWM, CMT, ICWGT, SMAA, Fuzzy Shannon, MOORA, MCDM, RFUCOM-RTOPSIS, DUARN, and FUCOM.

1 INTRODUCTION

FMEA is a methodology that identifies and prevents potential problems [1]. It includes characteristics like failure mode, effect, cause, cause prevention, severity, occurrence, detection ranking, and risk priority number (RPN) [1].

Over half a century, FMEA tools have evolved in the aerospace, automotive, and defence force industries and are now explored in the food manufacturing industry [2]. Most studies focused on applying FMEA methodology and its relationship with other quality concepts, such as problem-solving, quality control, quality function deployment, and safety risk management.

During the discussion, the researcher covered the implementation of FMEA in the early stages of the project and product design to enhance the design reliability. The searcher also touched on the challenges in FMEA, such as disagreements in evaluation criteria, rating and ranking methods over the years.

Figure 1 shows the focus areas of books and articles reviewed and dictates the research directions taken for the present debates. They included 21 books and 29 papers that studied the application of FMEA and presented case studies following the traditional FMEA procedure along with other quality techniques. Ten books and ten papers focused on FMEA methodology. Five books and one paper discussed risk management, while five books and six papers covered problem-solving and the integration of FMEA with quality tools. Three papers addressed machine efficiency, and the rest of the four books and nineteen papers emphasised the challenges of the FMEA methodology.

It also provides the overview of books and articles reviewed highlights based on books and articles screening characteristics as follows:

- FMEA characteristics covered all books that address the severity, detection and occurrence limitations and suggest innovation illustrations.
- FMEA Descriptions are books and articles reviewed that focus on the FMEA theory, definition, and explanations of advantages and shortfalls.
- FMEA Methodology characteristics emphasise reviewed works that address the procedural drawback and integrate fuzzy techniques to innovate the traditional methods and simultaneously address the conventional limitations. It includes developed frameworks.
- FMEA applications focus on practical methodology implementation and evaluation of effectiveness based on objectives set to address the problem.

In Table 1, the defined characteristics were grouped and summarised with references.

The FMEA application topics led to a scientific discussion on risk identification, evaluation, assessment, rating, ranking, and prioritisation. The team addressed team incompetence, subjective inconsistency, impreciseness, and vagueness in the analysis and evaluation using fuzzy techniques [2], [12], [53]. Figure 2 illustrates the fuzzification techniques and methods to address some of the limitations of conventional FMEA. The ratio of the fuzzy method applied, as encountered in each paper and book reviewed, is represented in colour cording as per legendary on the figures (Refer to Figure 2).

The paper is divided into Methodology, Results and Analysis, Discussion, and Conclusion. To find weaknesses and get a comprehensive review, I searched the Scopus and EBSCOhost databases using the keyword “the application of FMEA in manufacturing”. The study included examining published books or book chapters from 1985 to 2023 from Scopus to gain a theoretical understanding of the subject and articles from January 2019 to July 2024 from EBSCOhost to understand the current debates, even though some books had recent case studies.

A book discussed the FMEA software structure, covering preparation, user interface, team accessibility, real-time input during meetings, system structure linkage, FMEA documentation, and test or control plans with team member access [54].

A book discussed the FMEA software structure, covering preparation, user interface, team accessibility, real-time input during meetings, system structure linkage, FMEA documentation, and test or control plans with team member access [54].

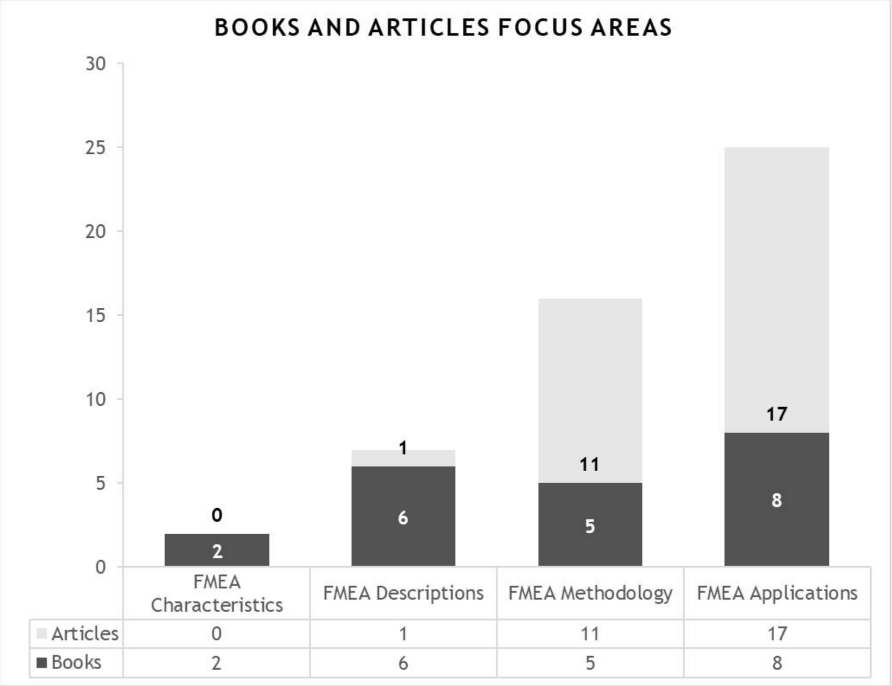

Figure 1: Reviewed Books and Articles Highlights

Table 1: Books and Articles Review Summary.

Characteristics	Books	Articles	Book's References	Article's References
FMEA Characteristics	2	0	[7], [22]	
FMEA Descriptions	6	1	[11], [12], [15], [16], [20], [21]	[24]
FMEA Methodology	5	11	[3], [4], [5], [6], [18],	[25], [26], [30], [32], [42], [43], [44], [47], [48], [50], [51]
FMEA Applications	8	17	[1], [8], [9], [10], [13], [14], [17], [19],	[23], [27], [28], [29], [31], [33], [34], [35], [36], [37], [38], [39], [40], [41], [45], [46], [49],
Total	21	29		

Therefore, the present research intended to show a systematic review of 143 book chapters, among which 25 books were deemed acceptable for citation based on defined merit and 59 paper articles, of which 29 were referenced.

This research aimed to evaluate the methodology of applied FMEA for risk identification, assessment, decision-making, and documentation in manufacturing. The study seeks to understand the evolution of FMEA and the present status of FMEA methodology to identify future areas for exploration.

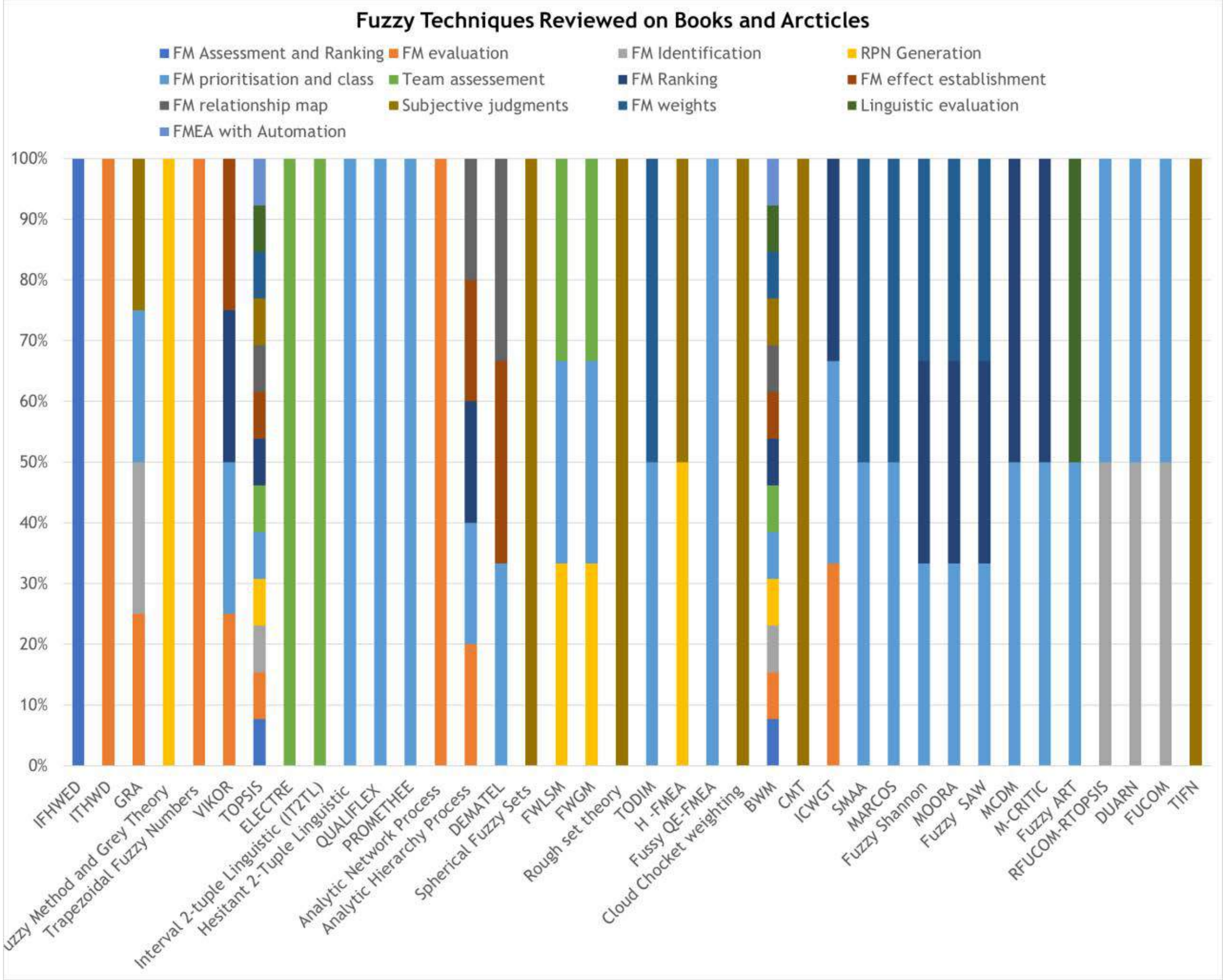

Figure 2: Fuzzification Techniques

2 RESEARCH METHODOLOGY

The review approach follows the PRISMA protocol, including search keywords, information sources, and screening criteria [51]. The search work followed five selection criteria such as:

- Search keywords “Application of FMEA in Manufacturing Assembly line" OR "Implementation of FMEA in Workstation" OR "Failure Mode and Effect Analysis" in two main databases such as Scopus and EBSCOhost
- The search criteria were as follows:
  - Scopus:
    - Results from narrowed from 1985 to the 20th of November 2023 and English work only.
    - Articles, journals, and lecture notes were not considered in this study; only English books and book chapters were focused on them,

        - The abstracts of the selected search were screened for FMEA or Risk Management in a Manufacturing Environment context,
        - Complete books and book chapters were chosen and downloaded for a detailed study.
    - EBSCOhost:
        - Results from January 2019 to July 2024 and English.
        - The focus was on paper journals and conference articles, but lecture notes, newsletters and books were excluded.
        - The rest of the screening criteria were like the Scopus search process.

The search was limited to Scopus and EBSCOhost; other search engines, like Elsevier, Social Science Citation Index, Science Direct, and Google Scholar, were only explored if the results were redirected to any of the listed engines.

The Scopus and EBSCOhost search results were saved in the database for gradual analysis.

The author studied relevant material as per the selection process in Figure 3, with defined inclusion and classification criteria with the intended idea of the context of FMEA or risk management application within the manufacturing environment. The author conducted the work analysis to classify all applicable work gathered.

All content work was reviewed in depth, the focus was on methodology and reference records were kept and documented to draw a relationship and conclusion.

Scopus search criteria methodology results were respectively: 5 688, 143, 45, 36 and 25; and EBSCOhost: 3678, 59, 39, 29 and 29 as per figure 3. In total, 54 research works were considered in this review.

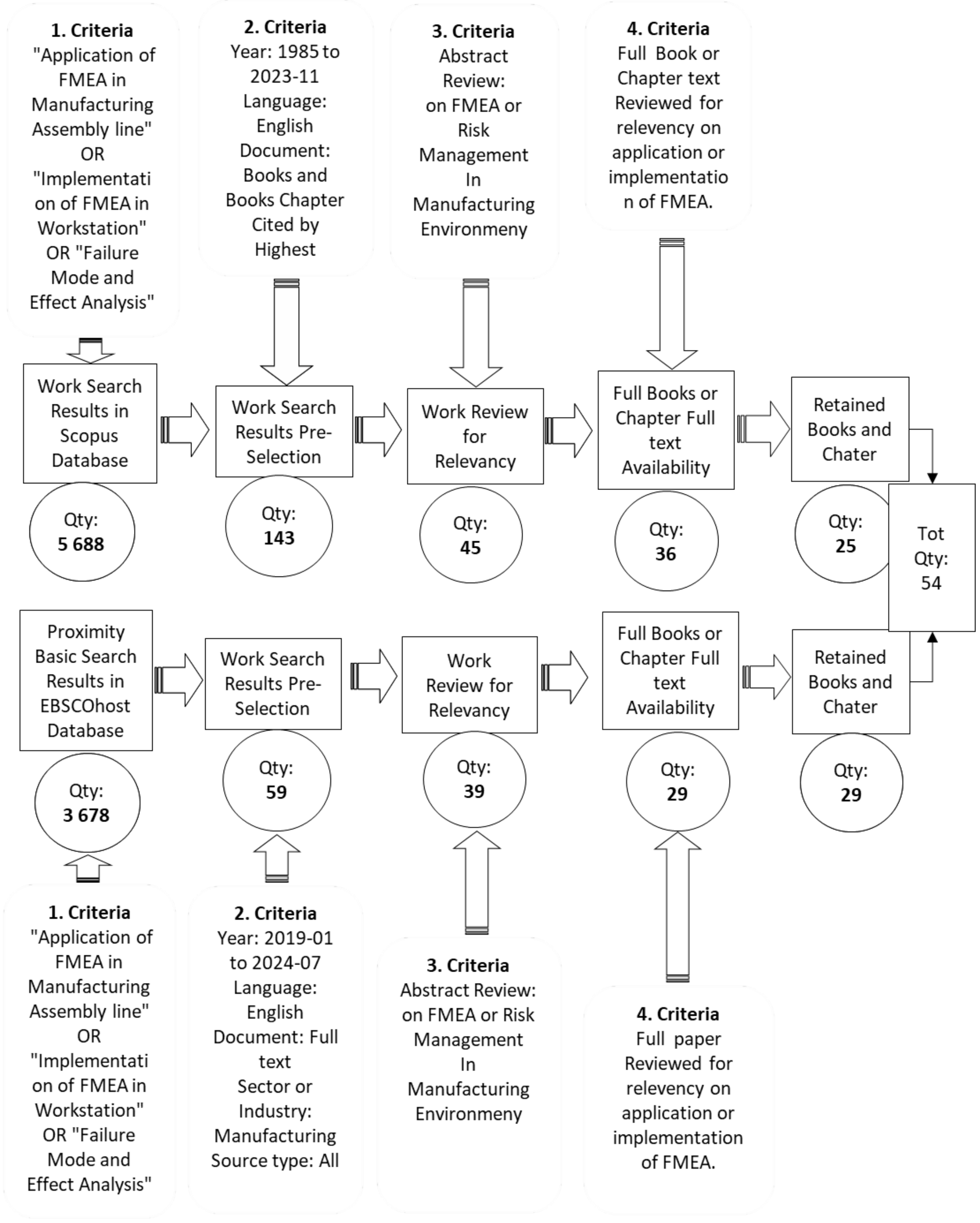

Figure 3: Literature Review Protocol

3 RESULTS AND ANALYSIS

3.1. Debates on FMEA Procedure

Issar and Navon co-authored a book chapter in 2016 that discussed the FMEA methodology and the proactive assessment of potential failures to enhance quality in organisations [3]. The FMEA process involved developing the scale tables for S (Severity), O (Occurrence), and D

(Detection) risk factors tables, then examining the process or product and determining the sub-processes or components, respectively [5]. To sort potential failures by their potential effect, there is a need to segregate them [3],[5],[6]. In FMEA, potential failures are estimated to be high to low potential effect factors [3],[5],[6]. FMEA steps are: brainstorm potential failure modes, list potential effects, rank effects by severity/occurrence/detectability, calculate RPN, develop an action plan, work on the plan, and review RPN reduction [3],[5],[6]. Ngian and Tay proposed the application of FMEA to cases where risk ratings are missing [5]. Signoret and Leroy (2021) discussed the FMEA procedure, which involves study preparation, breaking down the system into items or operations, defining relationships between elements, gathering relevant requirements, and preparing FMEA documentation to align with FMEA objectives [6].

In Food manufacturing, hazard analysis is referred to as self-regulation, self-control, and quality assurance [4]. GMPs ensure safe food production and handling, minimising contamination risks and maintaining quality [4]. GMP procedures ensure that raw materials and ingredients are suitable [4]. HACCP systems involve hazard analysis, risk management, and optimisation measures [4].

The key FMEA contributors in the mid-1900s are listed in Table 2.

Table 2: Key FMEA Contributors

Industry	Year	Product	Method	Reason	Author
Aerospace	1960s	Aircraft	Design methodology	Design Methodology	Apollo
Automotive	1970s	Automobile	Improve production and design	Safety and regulations in production and design	Ford
Defence	1980s	Military	Standardisation implementation process	Improvement	Military Standard
Various	1990s	ISO9000 Series	Standardisation implementation process	Recommend for design review	ISO
Automotive	1994s	SAE J1739	Application of design and process FMEAs	FMEA and guidance	USA OEMs

Figure 4 shows the reviewed books published over the years; even though the search covered books from 1985, the rest of the books were eliminated based on retainment criteria. These provide insight into the relevancy of the work covered. Eleven books were over ten years old, and fourteen were ten years recent (refer to Figure X). The traditional FMEA has been applied on a bigger scale throughout the manufacturing industries regardless of other innovative approaches; it has been a challenge to combine the newly agreed approach and roll it out to all industries.

The papers reviewed were grouped within the past five years of publication, and here, recent debates are both fuzzification solutions for conventional FMEA and FMEA integration with other TPM and quality tools. Sixteen papers discussed the probabilistic solutions and thirteen traditional approaches to quality challenges, TPM, machine and tool reliability and health and safety.

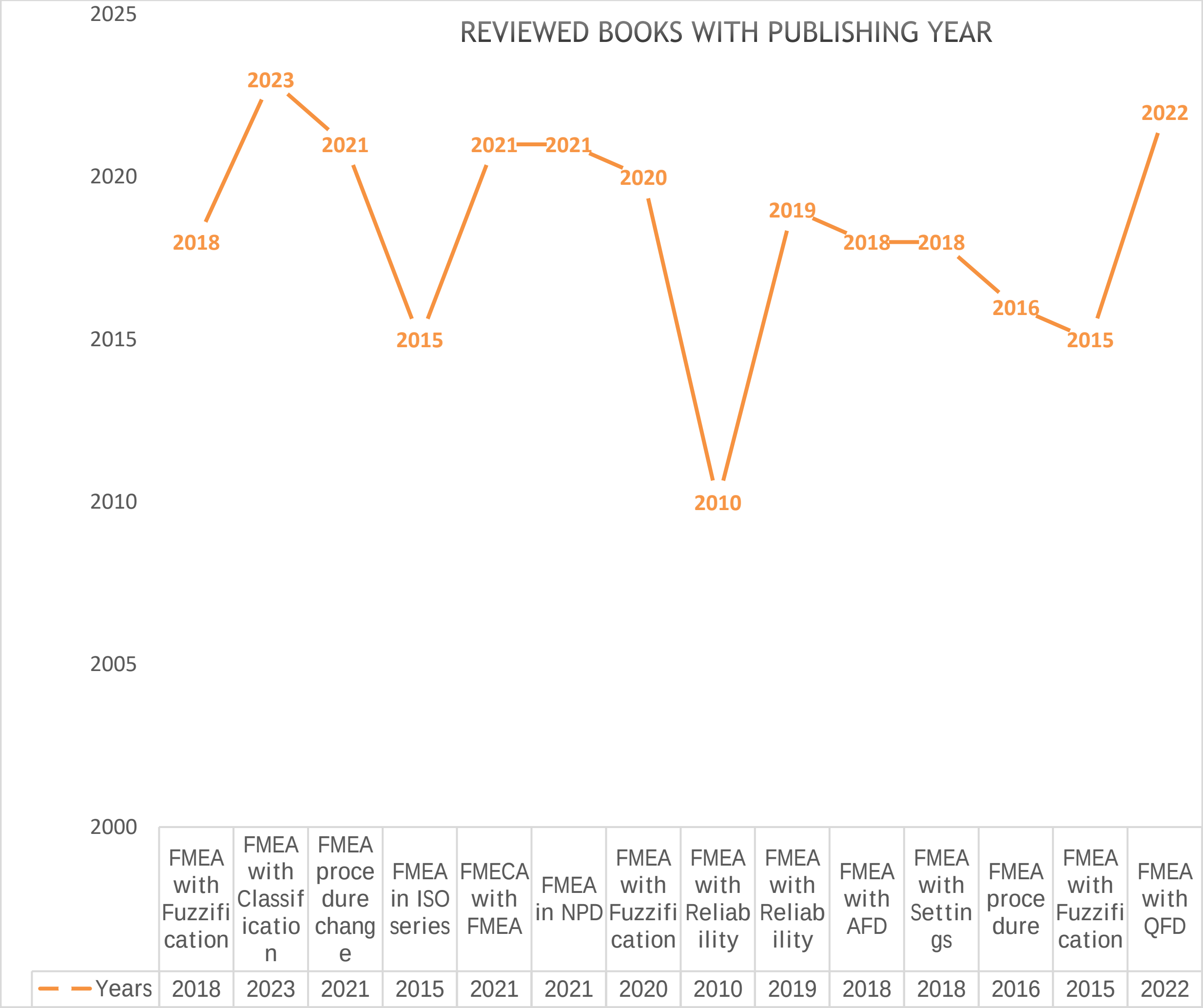

Figure 4: Literature Review Protocol

3.2. FMEA in Conjunction with Quality Tools

FMEA is critical in NPD for short product lifecycles, changing technology, and evolving customer demand in a competitive environment [11]. A combination of quality tools for NPD, including QFD, FMEA, Pareto Analysis, and Poka-Yoke techniques, is used [11]. These tools ensure that our products are of the highest quality by identifying and addressing potential issues early in the development process [11]. Pareto analysis prioritises RPN for corrective actions in FMEA, reducing subjectivity [11]. FMEA used three factors to calculate RPN: O, D and S [11]. The RPN methodology prioritised failure modes to allocate resources more effectively [11]. To prioritise Poka-yoke principles, one can perform FMEA [10]. FMEA used elimination, detection, and mitigation principles for parameters O, D, and S, respectively. Pareto analysis is a technique that identifies the most important causes of a problem [11].

The FMEA systems thinking model can identify quality issues and view production processes from a safety perspective [55]. The FMEA process is subjective and influenced by personal views and experience [55]. Additionally, QFD is a tool used to assess customers' needs and turn those needs into specific technical features, often using matrices [55]. The QFD methodology now includes safety risk management, examining system-user-environment interactions and implementing preventive measures for hazards [55]. By evaluating design options from a functional view, safer and more durable solutions can be chosen through the Functional-FMEA before moving to D-FMEA or P-FMEA [55]. Addressing issues early is more cost-effective than doing so later and presents an opportunity to consider automation [55].

Root Cause Analysis (RCA) is a methodological approach to identifying a problem's underlying cause or failure [7]. RCA investigations are conducted when something goes wrong to determine its cause-and-effect trail. It helps determine what happened, why, and what can be done to prevent it from happening again. Pareto Charts are used in RCA to visualise the frequency of problems or causes [7],[11]. A cause-and-effect diagram identifies potential causes of a problem or quality issue [7]. It visually represents how various factors affect a specific outcome [7].

Globalisation has increased competition, pressuring companies to meet diverse consumer needs [9]. Traditional post-production defect identification is costly. Companies now use a preventive approach based on ISO quality standards, introducing the FMEA tool to anticipate and address potential failures during program development stages [9]. This saves time and money by detecting errors early and preventing them in the final product or process [9].

When components fail to meet minimum performance levels, their materials and performance requirements must be assessed based on various criteria, such as optical properties, mechanical strength, and aesthetic values [8]. Predicting product lifespan involves measuring environmental stresses and identifying potential failure modes [10]. Assessing the economic impact of component failure is crucial when defining performance requirements [8]. Differentiating between short-term and long-term exposure to environmental stresses helps identify potential failure modes. Testing methods are chosen based on the estimated risk level [8].

Reliability engineering, quality control, and RDM aim to prevent failures [13]. FMEA is a method that identifies potential consequences of failure modes [13]. Products must be made insensitive to noise factors for failure-free operation, necessitating their inclusion in DFMEA [13]. A case study at Volvo Car Corporation by Ake Lonndvist shows that FMEA and RDM address the same technical issues when noise factors are considered as causes of failures [13].

Dhillon's Design for Reliability chapter stresses the importance of considering reliability in engineering system planning, design, and operation [15]. Doing so reduces failures, improves safety, lowers maintenance and life cycle costs, and decreases inventory needs [15].

The book "Data Centre Handbook" discusses reliability in design theories, emphasising the importance of analysing different solution topologies [10]. It uses methods such as SPOF, FTA, FMEA, and FMECA to ensure a robust design [10]. The book also highlights that less complex designs are more reliable and require less training [10].

The book "Maintenance for Industrial Systems" explores the key to productivity and competitiveness in the industry [14]. It emphasises analysing and mitigating failures, reevaluating potential reliability issues, and focusing on the customer's perspective for measurable improvements in product and process reliability [14].

The FMEA results include a description of the failure mode and the selected guideword from a standard list, along with effects and criticality rankings [19]. FMEA is a method to identify and prevent potential problems in a product or process before they occur. It considers both likelihood and severity of failure modes [19]. SFMEA assesses software failures, SFMECA enhances software reliability, and SFTA is used in software development to discover defects [19]. Bi-directional safety analysis (BDSA) thoroughly evaluates design safety and can demonstrate that the software design is free of critical flaws that could contribute to hazards [19]. Software Reliability Engineering aims to improve the reliability of software systems and can reduce the cost and labour of fault analysis using automated toolsets [19].

The traditional FMEA methodology focuses on analysing failure issues and typically does not consider other factors, such as availability and costs [18]. This new approach introduces a new index based on machine tool availability and customer costs related to failure time, making it more reliable than traditional FMEA results [18]. The tools used in this study have proven to be helpful for the efficient and cost-effective design of machine tools [18].

It has been argued that Anticipatory Failure Determination (AFD) and FMEA are two methods for identifying potential failure modes [20]. AFD, also known as anticipatory failure prediction, analyses mechanical faults to identify potential failure modes and propose solutions [20]. Designers need to understand fault mechanisms to minimise product failures [19]. The cost of fixing a product failure during planning, production, and use can be 10, 100, and 1000 times more than during conceptual design [20]. FMEA can be used to prevent product and process issues beforehand [20].

Many efforts have been made to develop systematic approaches to service life prediction of components, parts of components and materials so that all essential aspects of the problem will be considered [21]. In almost all existing systematic methodologies for service life prediction based on accelerated life testing, four basic themes appear performance analysis, failure analysis, laboratory ageing testing, and mathematical modelling for service life prediction [21]. Predictive FMEA is the starting point for service life prediction from accelerated life test results [21].

A sensitive investigation of FMEA by Laszlo Pokoradi aimed to show how the change in any system parameter influences the resultant reliability value of the whole system ([22]. This method considered that the customer had defined severities. A case study of wheel speed and sensor risk analysis showed this method [22]. The Authors proposed prospective scientific research related to applied mathematics and risk management, including the study of risk assessment methodologies and the possibilities of using their betterment [22].

The following methods have been used with FMEA to address product and process quality issues: design of experiments, ANOVA analysis, total productive maintenance, overall equipment efficiency, Six Sigma, statistical process controls, and measurement system analysis [31],[33],[41],[43],[50].

The author intended to understand the general application of FMEA in a manufacturing environment and specifically in a one-piece flow production setup. After an intensive review of the research results, the author realised that there is no discussion in both databases that discusses the FMEA in conjunction with the one-piece flow manufacturing line.

3.3. Fuzzification

The theories of uncertainty and multi-criteria decision-making (MCDM) were reviewed and classified into five main groups: distance-based, compromise ranking, outranking, pairwise, and hybrid methods [2]. Distance-based MCDM methods use several techniques to evaluate and prioritise failure modes, including Intuitionistic Fuzzy Hybrid Weighted Euclidean Distance (IFHWED) and Internal 2-tuple Hybrid Weighted Distance (ITHWD) for risk evaluation, Service-Specific FMEA and GRA for identifying potential failure modes, and FM-GT for determining RPNs [53]. Cloud chocket weighting is used to fuse random and uncertainty risk, and GLDS with Chocket integral is based on cloud distance [32]. The listed techniques are all probabilistic in addressing the inconsistency of output [2],[53]. Three Multi-Criteria Decision-Making (MCDM) methods, i.e., VIKOR, TOPSIS, and Trapezoidal Fuzzy Numbers (TFN), are used to prioritise risk factors and failure modes [2],[53]. The triangular fuzzy number for the selection of rating indicator combines selection matric for qualitative environmental (QE) indicator, a Method for estimating the treat priority in considering the QE [30]. TIFN implementation costs are described by pre-defined linguistic terms, which are the TIFN models, and the solution to this problem is found by using GA [48]. A new ELECTRE-based method with an ELECTRE-based with Interval 2-tuple Linguistic (IT2TL) environment was proposed for FMEA team assessment—hesitant 2-tuple linguistic and extended QUALIFLEX methods for risk priority [2],[48]. Linguistic variables are used to assess the level of failure modes and the relative importance of risk factors using interval-valued triangular fuzzy numbers. Both subjective and objective weights of risk factors are determined using fuzzy AHP and the extended VIKOR method. Comprehensive weights of risk factors are obtained via ICWGT, and the fuzzy VIKOR method is used to rank the risk priority of failure modes [37].

BWM, SMAA, MARCOS, Dempter-Shafer, BWM-SMAA, and SMAA-MARCOS were used to address failure weights and prioritisation [38].

PROMETHEE sorts of failure modes into priority classes [2]. Multi-attribute Failure Mode Analysis (MAFMA) is a pairwise comparison MCDM method that integrates the Analytic Hierarchy Process (AHP) for O, S, and D criteria, Expected cost and Analytic Network Process (ANP) for risk assessment [2]. Hybrid MCDM methods integrate Fuzzy TOPSIS and AHP to rank risks, while Fuzzy AHP, entropy, and Fuzzy VIKOR are used to determine weight and prioritise risks [34],[44]. Other methods, such as VIKOR, DEMATEL, and AHP, BWM, are used to assess the impact of failure modes [2],[34],[44]. Improved methods combining DEMATEL and AHP with Fuzzy evidence reasoning (FER) and grey theory for effective FMEA prioritisation and failure mode analysis [2],[25],[53]. A combination of MGT and GRA may characterise grey theory to generate RPN to have Grey FMEA (GFMEA) [25].

LZNs are used to represent the FMEA team members' cognitive information and reliability. A weighted entropy measure based on fuzzy entropy and LZNs is developed to obtain risk indicators' weights [23]. The generalised TODIM method with LZNs is constructed to determine risk priority orders of failure modes, effectively simulating the FMEA team members' psychological characteristics [23] Fuzzy FMEA, Fuzzy Shannon, Fuzzy multi-objective optimisation based on ratio analysis (MOORA), TOPSIS, and Fuzzy SAW to identify and weigh the most significant barriers, order of preference by similarity to the ideal solution for prioritising and ranking the barriers with each method [45]. In the integrated RFUCOM-RTOPSIS FMEA model, DUARN and FUCOM are considered for failure modes identification and prioritisation in industries [52].

M-CRITIC method is employed to assign weights to the identified risk factors, which indicates their level of importance in analysis. Additionally, the recently proposed Alternative by Alternative Comparison (ABAC) method is used to derive the risk priorities of failure modes [47].

The nature of risk, uncertainty, and subjectivity observed in risk assessment identify and prioritise potential failure modes and their effects [53]. These risks deal with uncertain information as well as highly subjective judgments of experts [24],[53]. Uncertainties may come from various sources, such as lack of knowledge, vague assessments, fragmented expert judgments, or interpersonal uncertainty [53]. To prioritise FMs and their effects, a complete theory and tools must address modelling and qualitative risk assessment, including subjective factors and uncertainties [53]. Fuzzy rule-based approaches of artificial intelligence have been widely studied for risk assessment [24],[53]. They provided consistent handling of qualitative and quantitative data, flexible and realistic combinations of risk factors, and customisation of the risk assessment function for a specific product, process, or system [53]. Rule-based approaches are limited because experts must design and maintain a rich set of if-then rules, which is costly and time-consuming [53]. It is important to note that an incomplete rule base can lead to biased or even incorrect inferences [24],[53]. The failure modes cannot be prioritised or ranked as rules with different antecedents that have the same consequence [24],[53]. Rule-based approaches, which can be subjective, costly, and time-consuming, may not always be the best choice [53].

Multicriteria approaches are necessary for FMEA under uncertainty to handle modelling issues and uncertainties inherent in the assessment process [53]. Common approaches in this field include GRA, aggregation operators, fuzzy TOPSIS, evidential reasoning, intuitionistic fuzzy sets, fuzzy AHP, rough set theory, cloud model theory (CMT) and possibility theory [23],[50],[53].

GRA allows assigning different weights to S, O, and D, providing better distinction among decision alternatives [25],[53]. TOPSIS ranks failure modes according to risk factors S, O, and D, integrating fuzzy AHP with fuzzy TOPSIS to determine realistic risk factor weights [53]. The fuzzy adaptive resonance theory is used to conduct failure modes classification based on the assessment results of S & O, S & D and O & D obtained by the GRA [50].

Evidential reasoning (ER) can model quantitative and qualitative attributes using a distributed framework [53]. The fuzzy AHP uses hierarchical structuring, pair-wise comparison, and prioritisation principles [53]. Rough set theory handles imprecise and subjective judgments without assumptions or additional information, providing a more rational framework for risk evaluation [53].

Various methods, such as Fuzzy Weighted Geometric Mean (FWGM) and fuzzy weighted most miniature squares model (FWLSM), are employed to prioritise and aggregate the assessment of failure modes effectively [53]. Possibility theory is also utilised to handle incomplete, imprecise, and uncertain information, capturing partial ignorance [53].

An application on infant car seat design using spherical fuzzy sets to resolve vagueness and impreciseness in terms of severity, occurrence, and detection value [12]. The extension of ordinary fuzzy sets creates spherical fuzzy sets that integrate neuromorphic and Pythagorean fuzzy sets [12]. Single-valued and Interval-valued spherical fuzzy sets have specific parameters for membership, non-membership, and hesitancy [12]. Single-valued and interval-valued spherical Fuzzy FMEA Methods are defined for analysing FMEA using SVSF numbers for severity, probability, and detectability components [12].

The FMEA software should be user-friendly and allow real-time input during meetings [54]. It should connect system structure, documentation, and test/control plans seamlessly [54]. Proper planning for meeting logistics is crucial, as is team training on FMEA methodology [54]. Understanding system and process hierarchy is important [54]. Easy access to failure mode information is necessary, and project boundaries should be agreed upon [54]. The right cross-functional team is crucial, along with documenting assumptions and ground rules [54]. The FMEA procedure includes identifying impact severity, preventive measures, detection controls, and recommended risk reduction actions [54].

3.4. Benefits

FMEA Improves product/service quality, reliability and safety; strengthens image and competitiveness to help increase customer satisfaction; reduces time and cost of product development; sets priorities for improvement actions; helps identify critical features; facilitates the identification and prevention of errors; helps define corrective actions; help select the best solutions in the production process at an early stage; and facilitate the determination of cause-effect relationships [16].

FMEA's weakness is its inaccurate ranking score calculation for a failure mode due to its non-linear scoring of occurrence and linear scoring of detection [17]. The different failure modes, each with unique characteristics and impacts on the three RPN attributes, can be expressed as the same RPN value [17].

3.5. Disadvantages

Problems in the Application of FMEA were: the construction of an FMEA can be expensive and time-consuming; the amount of data can be significant; it can become complicated and unmanageable unless there was a reasonably direct relationship (simple concatenation) between cause and effect; it is easy to make mistakes during the analysis; it may not be able to handle timelines, restore processes, change environmental conditions easily; contrasting factors complicate the identification of priorities; and some of the critical factors responsible for failures are difficult to determine [16].

The Ford FMEA handbook defines severity scores, with 2 indicating slight annoyance and five indicating customer dissatisfaction [17]. A flawed system treats failure modes A and B as equals [16]. Severity is ranked on a 1-10 ordinal scale based on subjective judgment. Detection is subjective and relies on the assessment team's expertise [17]. Multiplying ordinal values is meaningless due to differing interval values [17]. The RPN formula is inaccurate for prioritising failure modes [17].

3.6. Summary

The results of the application of FMEA in manufacturing show that the focus remains on innovating the concepts of traditional FMEA and using the tool as a problem-solving. Most of the reviews illustrated information about the use of FMEA with Quality tools and TPM techniques. Fuzzy set theories have been deployed to address the limitations found in traditional FMEA. Fuzzification methods are probabilistic approaches to address risk evaluation, prioritising failure mode for identifying and evaluating potential failure modes, and vague assessment. Lastly, one chapter of the book explains the application of FMEA software. This application is from the user interface, team member access and real-time information input from the meetings.

4 DISCUSSION

The findings indicate that past studies have applied the FMEA in various manufacturing sectors, from automotive, aerospace, steel, and food, as a problem-solving tool, resulting in business profitability, competitiveness, safety, and environmental risk. The application was based on theoretical, probabilistic and fuzzification.

Many studies have brought a comprehensive overview of FMEA in manufacturing with key emphases on methodology limitations solutions, which were traditional and fuzzified, and with minimal studies in FMEA application software systems. Hence, this study contributes to the manufacturing industry by opening a loophole for further study focusing on FMEA software applications. These aspects have not been brought to light in other works. The theories illustrated and summarised contribute to the theoretical contribution and bring many ideas for academic researchers. Likewise, different data analysis methodology types can diversify the discovery in future work and enrich the results. Finally, the application of FMEA software is required for Future studies.

After reviewing 143 book chapters, 59 papers, and detailed studies of 25 books and 29 articles, it was found that the FMEA applied procedure is traditionally dominated. Most studies revised the FMEA process with fuzzy set theories to address uncertainty, subjectivity, decision on prioritisation and FMEA software in insignificant numbers. Another study’s key focus was to address manufacturing defects, machine inefficiency, and ineffectiveness using FMEA methodologies.

Extending these theories could result in significant research in these areas. Fuzzy sets of FMEA can be combined with real-time data input to reflect more on ground realities. It combines probabilistic data analysis for decision-making but is fed by real-time data. Twenty-one books and 29 papers lack a data input and analysis mechanism that reflects the actual condition.

The FMEA project is conducted at the beginning of the system/product production or launch. The review reacts to high scrap rates and pricing adjustments to stay competitive by minimising manufacturing costs and non-value-added activities. Three books and eighteen papers focused on probabilistic approaches based on Fuzzy sets theories to address the methodological loopholes related to risk identification, rating criteria, and ranking, as well as a decision-driven approach to determine which risk to address in priority. Various mathematical models were developed based on one study gap to another. These fuzzification techniques and data inputs remain computerised scenarios set up by experienced and field expert individuals. In most cases, computer or software programmers develop this system with less field exposure, resulting in many errors that must be considered in future studies. One book gave us the feel of FMEA software application utilisation processes, from preparing an FMEA project to implementation in a working environment. There are no details about the application settings and data processing based on the action inside the software; however, the application remains human-dependable because of all the FMEA characteristic items from failure mode, failure effects, failure causes, severity, occurrence, detection and RPN value. Many works around these input data are subjective and sometimes vague, as these challenges were partially addressed by fuzzy sets theories.

Therefore, future studies should address the drawbacks mentioned above to maximise this tool's ability to be proactive and not reactive to day-to-day problems faced by industries.

The uncertainty, subjectivity, and decision-making application of the FMEA procedure compared to traditional FMEA processes remain the key elements of this study in the manufacturing sector. These can improve the overall FMEA application output, enabling businesses to have robust systems with minimum or acceptable risk. Integrating these techniques into FMEA software will further help with the issue of application time and reporting.

5 CONCLUSION

The most substantial findings of our analysis related to the various uses of the FMEA procedures by reliability and engineering researchers to elaborate on the advantages and disadvantages of applying the tools in various industries, from automotive to food manufacturing and system/product design. All 25 books and 29 papers refer to the application of the FMEA process to establish system, subsystem or component potential failure modes, their effects on the surrounding, from which causes, and which failure modes should be addressed at the beginning systematically to have a cost-benefit, defect-free, competitiveness system. A lot of FMEA books and papers had traditional baseline procedures; surprisingly, only one book chapter illustrates the intervention of software application FMEA, which has a smooth linkage between system or product structure, document generator and quality control or control plans with the capacity to allow team members access, ability to initiate search command, link all electronic documents and easily configurable profiles and interfaces.

The diligent review presents numerous limitations related to the margin of error that are still evident for rating and ranking based on probabilistic fuzzy sets. Data collected to conduct analysis were computerised, which means they may not be the authentic true reflection of reality or manualised human dependability with the possibility of a high margin of error. The books were explained in depth with various case studies and examples for a better insight into the subject. Moreover, articles from journals and papers were also reviewed.

Both books and papers reviewed did not narrow down the application or implementation of FMEA in specific manufacturing or production types, such as one-piece flow, as per the intended search key.

The extended study can consider other databases and selection types during the review. However, this study's interest was in the English language, which does not consider other non-English speaking nations and FMEA methodology applications.

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THE IMPACT OF RELIABILITY-CENTRED MAINTENANCE ON TOTAL COST OF OWNERSHIP OF MEDIUM VOLTAGE EXPLOSION-PROTECTED INDUCTION MOTORS

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ABSTRACT

The criticality of explosion-protected medium voltage motors is observed throughout various industrial applications and the petrochemical industry is no exception. However, their ability to perform at optimum functional efficiency and productivity are often compromised by the implementation of inadequate maintenance strategies, or the inadequate application of correct maintenance strategies.

This research investigated the cost of ownership impact derived from the implementation of a reliability-centered maintenance strategy for induction motors. The main objective was to analyse and compare the direct financial implications of different maintenance approaches.

The results highlighted the significant cost reduction possibilities in the total cost of ownership, achievable through a change in maintenance strategy. The study also indicated that there is misalignment between the asset stakeholders in terms of maintenance strategy understanding and execution, pointing to governance shortcomings that can be addressed through administrative controls such as updating policies and procedures, and proper communication and training.

Keywords: Maintenance management practices, Reliability-centered maintenance, Total cost of ownership

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1 INTRODUCTION

1.1 Background

In a petrochemical plant that refines crude oil into final products such as petrol, diesel, jet fuel, and liquified petroleum gas (LPG), most areas within the production facility are classified as hazardous and explosive, and equipment installed in these areas needs to comply with local explosion prevention legislation. In such areas, reliable infrastructure, and especially explosion-protected medium voltage motors, due to the number of installed units in such a facility, goes a long way in providing assurance to senior management. However, management of such a facility is not always sure whether current maintenance practices reduce total cost of ownership of these assets, or whether it is costing the company money to provide assurance. If the latter is true, then the question needs to be asked whether an alternative approach to maintenance, such as Reliability-centred Maintenance (RCM) can be implemented to provide assurance and to reduce the total cost of ownership on medium voltage induction motors.

Total cost of ownership (TCO) is a topic discussed to great lengths in literature, and books on maintenance best practices have been written (Smith and Hinchcliffe [1]). However, it is a field that is seldom understood by maintenance managers and practitioners. Reliability-centred maintenance (RCM) has become a term loosely used in the industry, but is it truly understood and applied in a correct manner, or is the term used as an umbrella term for preventive maintenance that merely increases reliability (Basson [2])? Not encountering the principles of TCO and RCM in a maintenance role as an electrical engineer or maintenance manager in a petrochemical refinery, raises questions about the limited exposures of these principles, and if exposure is there, why the reluctance from maintenance managers to implement them.

There is a myth that RCM practices need to be applied to all assets being managed, which creates the illusion of extreme costs with limited benefit to the company (Smith and Hinchcliffe [1]). This approach is a knife that cuts both ways, whether implemented or not. Avoiding RCM practices due to the cost puts a facility like a hazardous petrochemical plant at risk due to unreliable assets, which can lead to downtime and severe costs in terms of loss of production or infrastructure damages. On the other hand, when implemented as a blanket approach it can be extremely costly and take a long time to implement, which has a negative financial impact on the firm, as well as reduce resource availability to attend to critical maintenance activities. A blanket approach also prolongs the rollout of RCM and delays positive reliability outcomes that can be used as justification methods to apply for further capital.

1.2 Research problem

Every engineering discipline has certain best practices that can ideally be implemented if financial and human resources are not a constraining factor, but as Goldratt and Cox [3] elaborated on the theory of constraints, these constraining factors cannot be ignored, and a balance should be found between best maintenance practices and the cost implication thereof. The RCM methodology is perceived as one of these best practices for maintenance as an engineering discipline (Smith et al. [1]). This study aimed to integrate RCM into maintenance practices within a petrochemical explosive refinery, in an attempt to reduce the total cost of ownership (TCO) for the enterprise.

The RCM methodology was developed in the 1960s in response to a request by the Federal Aviation Administration (FAA) for more reliable and safer airplanes that were in development (Smith et al. [1]). The success of RCM lead to the implementation at nuclear installations, off-shore oil extraction, and chemical processing plants. A refinery is a high risk chemical plant due to the volatile liquids that are present in nearly all equipment. The petrochemical plant that was the focus for this study has a satisfactory reliability but the cost of maintenance indicated an investigation to consider other maintenance approaches like RCM.

A preliminary investigation into the theories of RCM and TCO suggest that these practices are either not implemented at all, or an extremely small portion thereof is implemented unwittingly. Both these outcomes could be due to a lack of knowledge about the subject matter and could be overcome by publishing the results of this study. The proposition is that these practices are not implemented due to the perceived cost implication thereof which forms the basis of this research i.e., to reduce the cost of ownership through the implementation of RCM practices effectively.

1.3 Objectives

The main objectives of this research project were:

- Determine the current maintenance practices implemented on medium voltage (MV) explosion-protected induction motors at a petrochemical plant and how these practices differ from accepted RCM practices.
- Identify the gaps between RCM best practices and the current maintenance approaches implemented at the petrochemical plant and the reasoning behind them.
- Quantify the possible reduction in the maintenance part of the total cost of ownership on MV explosion-protected induction motors by implementing RCM practices at the firm.

2 LITERATURE REVIEW

2.1 Introduction

The electronic journal platform Emerald Insight was used for the literature study. The main search terms were “Reliability-centred maintenance” and “Total cost of ownership”. The following sections discuss the main results of the literature study.

2.2 Overview of maintenance practices

Maintenance is the industrial practice of intervention to maintain an asset in a condition that it can be utilised to its full productive capacity (Gulati [4]). If maintenance is not carried out on an asset, the asset owner runs the risk of losing partial or full functionality of the asset capabilities, which affects the return on the capital investment made in acquiring the asset.

Moubray [5] touched on the development of maintenance through various generations, and in more recent years, Gulati [4] described this same maintenance paradigm shift which aims to provide capacity assurance, rather than just availability assurance. Capacity targets are set by management, taking into account the asset's design capacity. If downtime prevents an asset from achieving its targets, and an increase in maintenance cost could reduce downtime up to a level that provides higher returns, the application for additional funds to increase maintenance activities becomes easily justifiable.

Although various firms are adopting their own approach to maintenance strategies and practices, they all share the same basic requirement i.e., to maintain the capacity of their assets at a level that satisfies the operational demand of the firm.

A list of various maintenance approaches are defined below:

- **Condition-based or predictive maintenance**: Activities that are guided by the actual condition of the asset or component (Campbell and Reyes-Picknell [6]).
- **Corrective maintenance**: Activities performed on assets to correct defects before or after functional failure.
- **Operator-based maintenance or Total Productive Maintenance (TPM)**: A cost-effective approach where asset operators perform basic maintenance activities (Suzuki [7]).

- **Prescriptive maintenance**: A maintenance approach that combines asset degradation detection with outcome-focused recommendations to restore asset condition (Choubey, Benton and Johnsten [8]).
- **Preventive maintenance**: Scheduled or periodic maintenance which involves regular time-based inspections or conducting of prescribed maintenance services (Choubey et al. [8]).
- **Failure-finding maintenance**: An approach that identifies hidden part failures that are not known or visible at the time of the inspection (Campbell and Reyes-Picknell [6]).
- **Pro-active maintenance**: A collective term used to describe maintenance strategies or approaches that are based on the replacement of parts proactively.
- **Reactive maintenance**: Activities performed after complete- or partial failure, which results in sub-optimal performance levels (Choubey et al. [8]).
- **Reliability-centred maintenance** (RCM): Methodology that is utilised to determine the specific maintenance requirements of a physical asset in its operating context (Basson [2]).
- **Risk-based maintenance** (RBM): The risk of functional failure is the main criterion in the allocation of resources and maintenance efforts (Sacco et al. [9]).
- **Run-to-failure maintenance (RTF)**: Allows functional failures to occur before maintenance is conducted on the component. (Choubey et al. [8]).

2.3 Failures and failure consequences

Basson [2]) describes a failure of a mechanical component, which gets exposed to deteriorating conditions such as fatigue, wear, and corrosion, as a significant deviation from its original condition that results in the equipment or component to no longer meet the required performance standards. Maintenance practices are not implemented to prevent this failure process, but for asset managers to cope with it and reduce the consequences of the two types of failures, namely functional and potential failures. Predicting failures based on age is possible when assets are exposed to a constant level and type of stress and if the component’s initial resistance to stress is known. However, inherent defects in equipment make initial resistance unknown and can vary from component to component, even in the case of identical components (Moubray [5]). In the event of induction motors that are physically coupled to driving equipment, stresses induced onto the motor from the drive-end side through the coupling are not constant and vibration and temperature affect the extent of deterioration of the motor condition. These fluctuating stresses and variances in initial resistance to stress make the predictability of failures of these assets difficult to directly link to operational age.

The type of asset being managed, the consequences of failure, and the risk appetite of the business and asset manager neccessitate the development of maintenance strategies. Reliability engineering practices are more commonly implemented on high-consequence systems or assets. The cost-saving of an RCM strategy is mainly due to the prevention of failures, decrease in production losses, and a decrease in serious injuries or fatalities. Tortorella [10] defines a high-consequence system or asset as one where the failure consequences are so severe that they dominate the decision-making toward prevention.

2.4 Reliability-centred maintenance

Reliability-centred maintenance (RCM) is described as a specialised methodology that is implemented by reliability, maintenance, and safety engineers. Practitioners and engineers use RCM to develop effective maintenance strategies and action plans to define activities necessary to achieve, maintain or restore the required operational functionality of physical assets. Strategies involving hard-time overhauls of machinery as a form of preventive maintenance are not always effective. The reliability of an asset is not always proportional to the operational age of the asset (Nowlan and Heap [11]). Various authors have described the detailed RCM process in the past 2-3 decades (Fouche [12], Selvik and Aven [13], Smith [14]).

According to Nowlan and Heap [11], maintenance programs involving RCM can be developed based on four distinct groups of preventive maintenance tasks. These tasks comprise:

- Regular interval inspections to detect potential failures.
- Rework at a time based on a predetermined age limit.
- Discard at a time based on a predetermined life limit.
- Inspections of items to detect potential failures.

These four tasks are used to detect single as well as multiple failures and maintenance engineers and/or managers need to determine which items are applicable and for which a task will be effective. For example, for a potential failure of a component to be detected through scheduled inspection, the component needs to have a sub-component that will show signs of deterioration that can be detected through inspections. The same applies to the other types of maintenance tasks. The effectiveness of the task needs to be determined by not only determining whether the task can be done (applicability) but also by determining whether the implementation of the task will add value by improving reliability (Basson [2]).

This study aimed to not only reduce cost through the implementation of RCM practices on MV induction motors in petrochemical applications but also to reduce cost by limiting RCM implementation to maintenance significant items (MSI) as defined by Tang et al. [15]. They developed a framework to assist maintenance engineers and asset managers to identify maintenance significant items that the RCM process can be applied to. RCM cannot be seen as a set of blanket maintenance principles that have to be applied to all maintenance items, due to the cost of implementation (Smith and Hinchcliff [1]).

The RCM methodology, developed by Nowlan and Heap [11], originated from the analysis of three important questions that assist in identifying items that are worthy of implementation of RCM principles:

- What are the causes of a failure occurrence?
- What are the consequences if the failure does occur?
- How can preventive maintenance contribute towards reducing the probability and/or consequences of a failure?

NASA [16]documented a decision process that relies on historical data and the specific application or firm’s risk tolerance.

The clear objective of the implementation of RCM is, therefore, to reduce consequences of failures by actively analysing asset or system conditions and to base maintenance decisions and/or maintenance strategies on such information, to save lives, increase profitability and sustain environmenally healthy operations.

Several other maintenance approaches (or strategies) are available as alternatives to RCM. Some examples are Total Productive Maintenance (TPM) which is a people-centred approach, Business-centred Maintenance which is business or profit centred, and Risk-based Inspection (RBI) which uses risk in determining inspection intervals. The benefit of RCM is that it is well established in high-risk industries and many case studies are available in industry (Campbell and Reyes-Picknell [6].

2.5 Total cost of ownership

Ellram [17] described total cost of ownership (TCO) as a tool applied to understand the real cost of an asset and not only consider the purchase price. The cost elements of TCO include all stages of the asset life i.e, acquisition, possession, utilisation, and the retirement and disposal of the asset. TCO has been around for quite some time (Jackson Jr. and Ostrom [18], Harriman [19]). However, adoption of the principles is slow, possibly due to practitioners not fully understanding the benefits of a TCO analysis.

The terms lifecycle cost (LCC) and TCO might be misunderstood as synonyms, but where LCC takes the entire asset life cycle into account, TCO is more concerned with the part of LCC post-purchasing. TCO can be calculated using the simplified formula in Equation 1 (Barbusova et al. [20]), but is then expanded into Equation 2**Error! Reference source not found.** which provides more detail on each of the terms in the equation.

Like RCM, a TCO analysis cannot be implemented across all assets bought by a firm, due to the complexity and resources needed to obtain the required information. Cost factors considered for each asset can be unique and can include any one or a combination of the following cost elements), namely cost of procurement, competencies of the supplier in terms of research and qualification, asset loading, transportation, receiving, inspection, order rejection, asset replacement costs, maintenance costs, and disposal costs.

$$TCO = \sum Cost_{ownership} + \sum Cost_{service} + \sum Cost_{disposal} \quad \ldots (1)$$

$$TCO = Cost_{initial} + Cost_{operation} + Cost_{maintenance} + Cost_{downtime} + Cost_{production} - Cost_{remaining\ value} \quad \ldots (2)$$

Bearing failure is one of the most common causes of motor failure. Such failures and repair costs add to the TCO of the asset and implementing an RCM analysis on this subcomponent can reduce the cost considerably. Reduced failures lead to increased availability and can lead to several other advantages such as reduced risk for personnel safety, environmental risk, and indirect costs due to production losses (Hodowanec, [21]).

3 RESEARCH METHODOLOGY

3.1 Background

Data was obtained at a petrochemical refinery in South Africa, The focus was on explosion-protected medium voltage (MV) induction motors, and how RCM practices could possibly reduce the TCO of these assets. The study involved three parts.

- Investigate existing maintenance practices for explosion-protected, MV induction motors, and how it compares to the RCM approach in existing literature.
- Determine how TCO theory can be applied to MV induction motors.
- Establish whether TCO could be reduced by implementation of RCM.

3.2 Research design

Primary data was obtained through structured questionnaires. A quantitative approach was also used to determine what the current TCO of a typical medium voltage induction motor was. Qualitative data was gathered by studying existing maintenance strategies and procedures at the refinery and how this related to theory on RCM. Quantitative data was also obtained on actual expenditures on MV induction motors, and how RCM practices could be utilised to reduce the TCO and improve the return on investment of these assets.

3.3 Data sampling

Limited maintenance and cost data was available for 51 MV motors of a section of the plant. However, more detailed data for one of the 51 motors was available and it was therefore selected for this study. This decision was based on the amount of recent data that was available for this motor due to maintenance interventions. These 51 motors have a similar design but different usage cycles. A more in-depth study should involve more motors if sufficient reliability and cost data is available. The choice of one motor was also due to limited time available for a Masters project.

Qualitative data was also obtained from electrical maintenance managers within the petrochemical refinery. The sample also included senior electrical representatives including the senior manager (electrical and instrumentation), area manager (electrical maintenance), chief technician/engineer (electrical maintenance), and foreman (electrical maintenance).

4 RESULTS

4.1 Data gathering and analysis

A questionnaire was distributed to the identified populations via e-mail due to the difficulties in geographical location. Data in the questionnaires were transferred to an Excel worksheet for analysis and interpretation. The survey was conducted anonymously.

4.2 Demographic information

Some 63% of respondents were from the middle- to lower management positions within the electrical maintenance division. Some of the responents have 6-9 years experience while 75% of respondents have more than 15 years of relevant experience in maintenance and management of MV explosion-protected induction motors. All the respondents were involved in the implementation and/or development of maintenance strategies for MV induction motors, with 83% being involved on a higher level than just the implementation of strategies.

4.3 Maintenance strategies and comparison with RCM practices

One goal of the questionnaire was to determine the current maintenance practices that are used for MV explosion-protected induction motors at the plant and how they differ from RCM practices. The respondents were therefore asked to link a set of predetermined maintenance strategies with some components of MV motors. The response to this question is shown in Table 2. A brief explanation of each strategy mentioned in Table 2 is given in Table 1 and was provided with the questionnaire.

Table 1: High-level maintenance strategy descriptions

Heading	Term	Description
Ad hoc	Ad hoc maintenance	As and when required, or unplanned. No fixed strategy
RTF	Run-to-Failure	Risk is tolerable and acceptable. Wait for asset or part failure before maintenance is performed.
RM	Reactive Maintenance	Do maintenance after partial or full functional failure
CBM	Condition-based (Predictive) Maintenance	Maintenance based on online condition monitoring information showing degradation and predicting failures
TBM	Time-based Maintenance	Fixed interval maintenance
FF	Failure-finding	Failures are not known until they must work (e.g. trip system) and regular inspections are done to identify these hidden failures.
PAM	Pro-active Maintenance	Components are pro-actively replaced to improve reliability

Table 2: Existing maintenance strategies for various MV motor components

		Ad hoc	RTF	RM	CBM/ Predictive	TBM/ Preventive	FF	PAM
Component	**Stator**	*17%*	0%	0%	0%	67%	0%	17%
	Rotor	*17%*	0%	0%	0%	67%	0%	17%
	Bearings	0%	0%	0%	33%	83%	0%	33%
	Shaft	17%	0%	0%	0%	67%	0%	17%
	Frame	17%	0%	0%	0%	67%	0%	17%
	Terminal Box	17%	17%	0%	0%	67%	0%	17%
	Cooling system	17%	17%	0%	0%	67%	0%	17%
	Protection devices	0%	0%	0%	17%	50%	33%	50%
	Control equipment	17%	17%	17%	17%	17%	33%	50%
	Condition-monitoring devices	0%	0%	17%	17%	33%	0%	50%
	Lubricators	0%	0%	0%	17%	83%	17%	33%
	Main cabling	17%	33%	17%	0%	33%	17%	17%
	Control cabling	33%	33%	17%	0%	33%	67%	17%

Two major gaps, when compared to RCM strategies, were identified from the data in Table 2.

Firstly, the time-based maintenance strategy is used on all components listed, except for control equipment, condition monitoring equipment, and control cabling. The failure-finding strategy is used for these situations. The time-based maintenance tasks are done through the shutdown strategy of the organisation. The MV motors are stopped at fixed intervals which allows easy implementation of time-based maintenance strategies, with limited interruption of operational availability other than the planned downtime.

Secondly, the data are spread across the various maintenance practices for similar components, which could make sense when the sample population is spread across various organisations or operating entities, but this was not the case with the sample population participating in this research. All respondents were from the same organisation and departmental division of the organisation, and under the same management. In making sense of these identified gaps, the sample population's exposure to RCM had to be determined, as well as the approach followed when developing new or revised strategies.

Repondents were also asked what approach they would use to roll out a change in strategy for a specific component of the motor. About half of the respondents indicated that they would use a blanket approach for the specific component across the entire asset group. The other half indicated that they would follow an RCM-based approach. An analysis of the data obtained in the questionnaire indicated that not all the respondents were entirely sure of the meaning of the term “reliability centred maintenance” and that there was some “misinterpretation”.

Respondents were asked which factors they would consider if a new maintenance strategy is to be implemented. The results of this survey are shown in Figure 1. The ‘cost of maintenance’ related to a new strategy and ‘actions suggested after a root cause analysis’ were indicated as the most important factors to be considered.

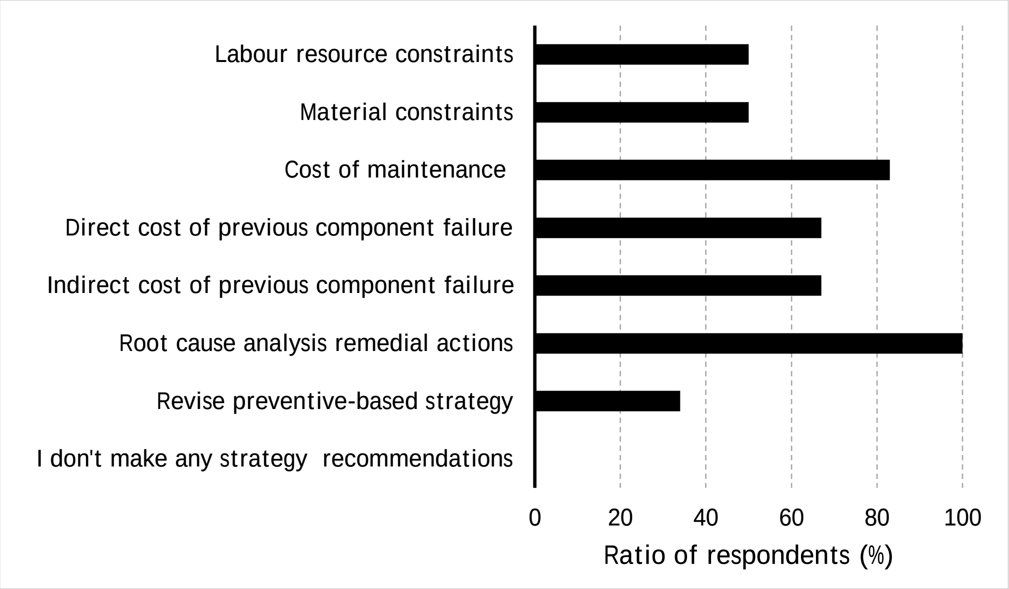

Figure 1: Factors considered when making maintenance strategy recommendations

4.4 Cost of ownership and the influence of maintenance strategies

A maintenance strategy for an asset, although being an expense, is implemented to provide financial benefit to the asset owner through increased asset availability that leads to increased throughput rates. In addition to the financial benefits, the correct maintenance strategy leads to increased asset reliability, reduced plant instability, and reduced risk to personnel safety.

Some questions in the questionnaire aimed to achieve the following objectives.

- To quantify the possible reduction in the maintenance part of TCO on MV explosion-protected induction motors by implementing RCM practices.
- To determine to what extent TCO best practices are implemented in the maintenance of MV induction motors?

These questions were targeted at the more senior electrical maintenance management officials who are responsible for the development and management of the maintenance budget. The respondents indicated that the budget for the maintenance and reconditioning of MV induction motors was between R250 000 and R500 000, which is less than 5% of the annual electrical maintenance budget. Most of the maintenance budget is spent on preventive maintenance activities with 83% of the respondents indicating that more than 50% of the activities are preventive maintenance activities.

Hodowanec [21] said indirect losses frequently account for the majority of the cost of an inefficient and ineffective maintenance strategy. To evaluate the true impact of asset failures in an organisation, a system should be in place that can measure and capture these indirect losses. Most respondents indicated that such a system exists at the refinery.These indirect losses are not budgeted for in the Electrical or Engineering operational budgets, but rather in the Operations budget through reduced annual throughput.

Quantifying the indirect losses are necessary to clearly illustrate the monetary effect that a more suitable maintenance strategy could have for an organisation, but from the mixed results of the data acquisition, it is clear that this value is not readily available to all, and the perceptions of the respondents varied considerably.

This scattered response led to a deeper analysis of secondary data contained in the company's Enterprise Resource Planning software, SAP, that indicated the cost of unplanned failures. A single asset from the 51 assets of interest was singled out due to the availability of data on this asset.

The motor of interest is the driver of the Diesel Unifier (DU) charge pump that supplies the DU unit at the refinery with feedstock and is an 11kV, 1100kW, explosion-protected induction motor. The DU is used to produce diesel as an output product for a specific region within South Africa and has a nameplate rating of 201 m^3/h.

With a specific interest in TCO, which includes maintenance cost and cost of lost production due to unplanned downtime, the following data was retrieved from the organisation’s SAP database between 2010 and 2021:

- Asset acquisition in 2010: R 955 892
- Cost of manual grease canister in 2010: R129
- Cost of manual grease canister in 2021: R411

The annual cost of greasing , based on the maintenance strategy, is indicated in Figure 2.

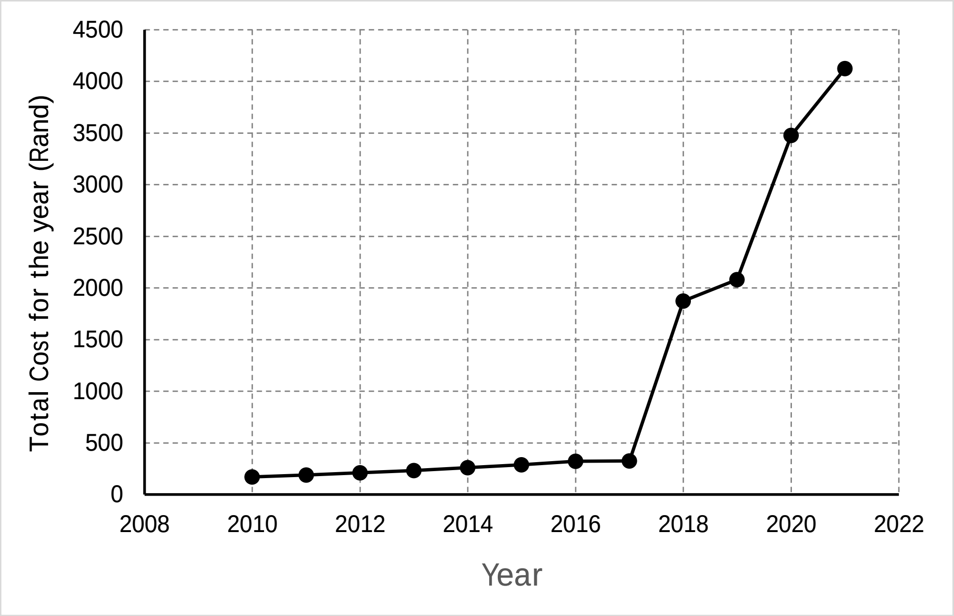

Figure 2: Estimated cost of greasing per annum -DU charge pump motor

A clear increase in greasing costs was seen in 2017. At the time of acquisition, the bearing greasing strategy was a time-based manual greasing strategy, and a preventive time-based strategy of motor reconditioning after a maximum of 10 years. The motor was sent for reconditioning in 2017 and an industry-accepted automatic grease lubrication strategy was adopted as a best practice, which resulted in a yearly increase in greasing cost from R326 in 2017 to R1872 in 2018.

Subsequent to the change in greasing strategy, the preventive maintenance cost (excluding greasing) was limited to the reconditioning costs of 2017, with a dramatic increase in bearing failures and reactive maintenance cost of repairs. These maintenance expenditures can be observed in Figure 3.

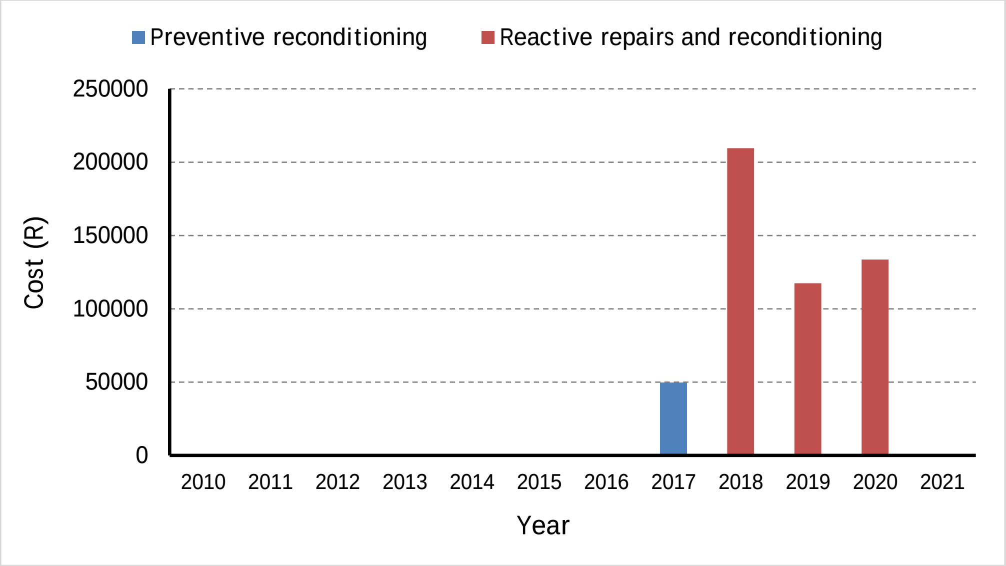

Figure 3: Annual preventive vs reactive maintenance - pump motor

A clear step in the direct cost of failures can be seen post-2017 after the maintenance strategy was adjusted, indicating an incorrect adjustment was made. As mentioned, this adjustment was made based on industry recommendations around best practices, without performing a detailed analysis of the asset greasing requirements and implementing a fit-for-purpose asset-specific maintenance strategy, which would have been more in line with RCM principles.

After multiple failures and investigations, as well as original equipment manufacturers (OEM) consultations and evaluations of site-specific data, the cost of failures and operational downtime, led to the strategy being re-adjusted in 2021 to an asset-specific strategy. This was a combination of maintenance strategies ranging from time-based recommendations of the OEM to CBM, relying on live monitoring of motor health which included bearing temperatures and vibrations. These changes in strategies can be confirmed by the maintenance tasks captured on this asset between 2012 and 2021, with a clear step in the types of activities performed on this asset since 2017, when referring to Figure 4.

Due to the bearing failure mode, the focus was on the greasing strategy and Figure 2 illustrates the specific asset's greasing cost increase. The first change in strategy from manual greasing to automatic lubrication is seen in 2018 after the planned shutdown in 2017 where the planned reconditioning cost amounted to R49 644 and was kept unchanged for 2 years. During these two years, the direct cost of motor failures increased from zero to R209 607 and R117 416 in 2018 and 2019 respectively. A further modification was made to the greasing strategy in 2019 which resulted in a dual (manual and automatic) greasing strategy. This change did not have the desired effect in terms of unplanned failures which amounted to a further cost of R133 647 in 2020.

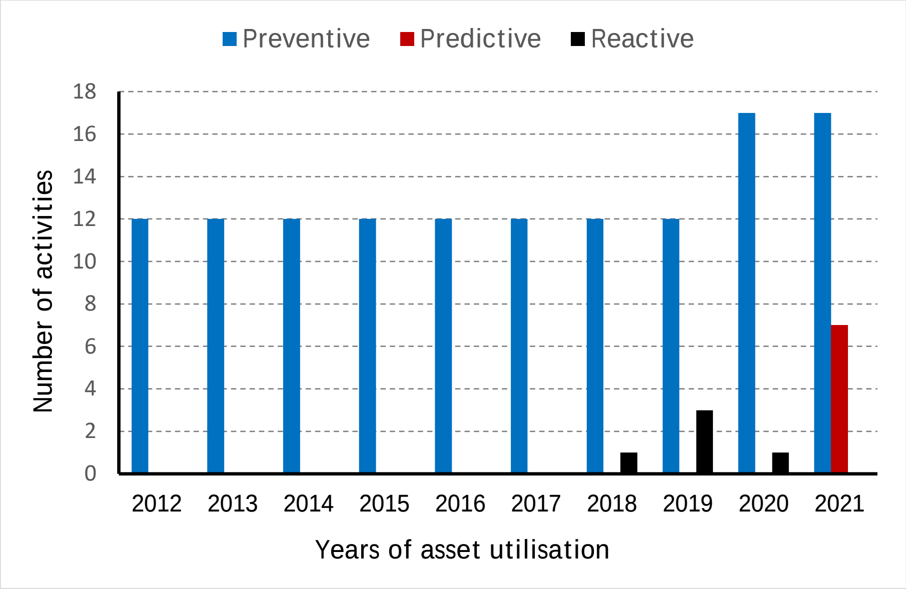

Figure 4: Maintenance activities performed between 2012 and 2021 - pump motor

Condition-based monitoring with daily bearing vibration and temperature verifications in addition to the greasing strategy led to the conclusion that the bearings were still being starved of grease and indicated a greasing frequency above the current strategy at the time and was therefore adjusted accordingly while maintaining daily condition-based monitoring. This led to the increase in predictive activities seen in 2021 in Figure 4. The effect on cost can be observed in Figure 5. Although the annual greasing cost initially increased, it stabilised once a working strategy was obtained and the direct cost of maintenance due to planned and unplanned maintenance and repair activities decreased to zero when referring to Figure 6.

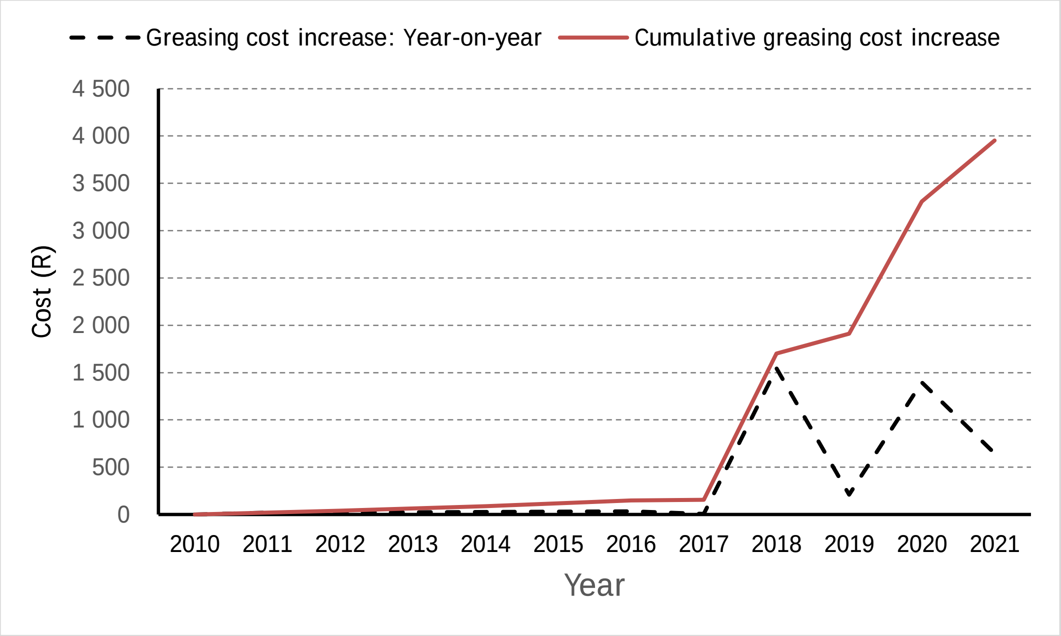

Figure 5: Greasing cost variations, year-on-year between 2010 and 2021 - pump motor

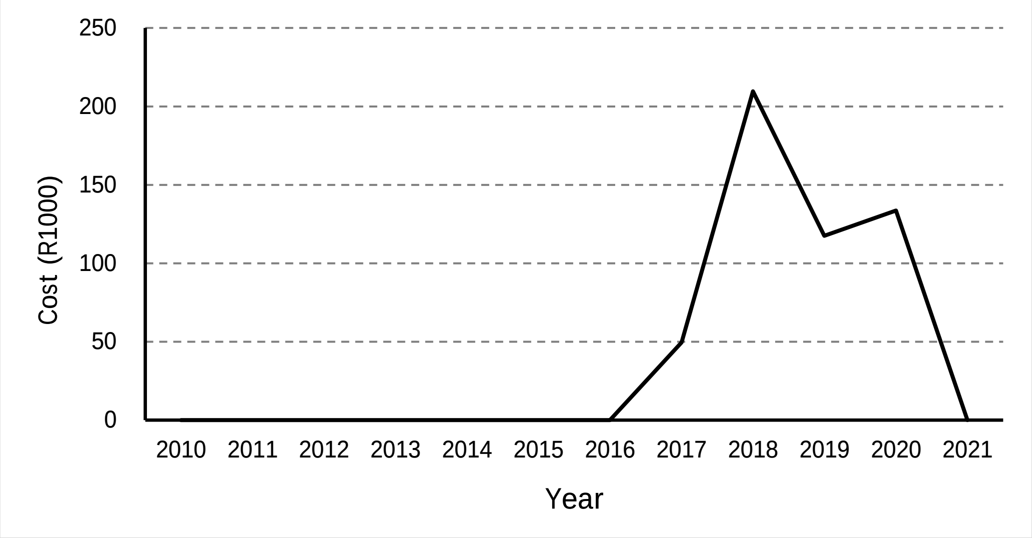

Figure 6: Direct cost of maintenance, excluding greasing - pump motor

All these planned and unplanned downtimes of the unit was tracked on a monthly utilisation report by the Operations department with the indirect losses indicated on the utilisation chart within the report. A failure of this asset in November 2021 lasted one week from the motor trip until the asset was back on site and recommissioned after the bearing replacement, shaft repairs, and other damage repairs. The downtime resulted in an indirect operational loss of R3,7 million for the week.

4.5 Summary

A substantial cost saving can be achieved by preventing asset failure through an RCM-based approach. The cost of implementation is negligible if compared to the annual cost saving. A detailed cost analysis is required for each asset type on the plant to realise the full economic benefit.

Since implementation of the new maintenance strategy, the motor has been available for use 100% of the planned time and the slight increase in the number of maintenance activities and cost substantiates the proposition that the cost of ownership can be significantly reduced through an increase in asset uptime and reduction in plant downtime, through the implementation of an RCM-based maintenance strategy.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of results

The study aimed to understand the current maintenance strategies used for MV induction motors at a petrochemical plant. However, the outcome of the study indicated unexpected results in the sense that the results were widespread amongst personnel of the same division, maintaining the exact same group of assets. The discrepancies between RCM practices and the existing maintenance practices on MV explosion-protected motors at the petrochemical plant partaking in this study do exist in the sense that some participants indicated that a blanket approach in terms of asset class and/or component level was implemented during the roll-out of maintenance strategies.

Further aims of the study were to determine the extent to which the total cost of ownership (TCO) of the asset group of interest could be altered through the implementation of an RCM-based maintenance strategy when focusing on maintenance significant items. The results were quantified with actual data and indicated that a change in maintenance strategy does not guarantee an immediate improvement, but continuous monitoring and evaluation of the effectiveness of the change is required to ensure continuous improvement. Since TCO was only determined for one motor, the findings cannot be generalised for other types of motors or different sized motors.

5.2 Research significance

The findings of this study indicate that maintenance mangers and practitioners should consider careful selection of maintenance strategies. A change of strategy can lead to cost savings in operations which can offset the cost of implementation. The study also revealed that many maintenance workers do not have a clear understanding of the RCM strategy and basic education and training is therefore required that the maintenance significant items can be identified for a possible change in strategy.

5.3 Recommendations

The following actions are suggested for future studies:

- Expand the participating population to include various firms that use MV induction motors from various suppliers. Determine how the maintenance strategies vary between different industries and companies and whether cost benefits differ from one company to another if RCM had been implemented.
- Expand the population to include firms other than the petrochemical industry, to make the comparison between the various industries and whether their strategies and interpretation of RCM differ compared to those of the petrochemical company used in this study.

The results showed that many maintenance workers on the plant have a different understanding of what the RCM methodology entails. It is recommended that these workers enrol for a basic RCM training course to familiarise themselves with the fundamental aspects of the methodology and the implementation of the basic principles.

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AGILE SERVICE SYSTEMS ENGINEERING: A SYSTEMATIC APPROACH TO DESIGNING CUSTOMISED DIGITAL SOLUTIONS IN THE FINANCIAL SERVICES INDUSTRY

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ABSTRACT

Users of services increasingly require a more customised user experience, and historically, the banking industry needs to respond to these changes due to the legacy system of systems. To address this, service systems engineering has evolved as a disciplined, systematic, service-orientated and client-centric approach. Financial service organisations have also started adopting agile development practices with mixed results in terms of their effectiveness. This research aims to develop and evaluate an agile service systems engineering artefact that fosters value co-creation in a socio-technical environment that can be used to systematically design digital service systems in a financial services organisation to rapidly deploy highly customised client value propositions. The design science research methodology is used to design, develop and test the conceptual framework. The conceptual framework designed seeks to address these problems by adhering to the following principles: the agile architecture of the system, the design process is socio-technical where value is co-created, and the process is measurable.

Keywords: service systems engineering, agile software development, agile systems engineering, socio-technical, value co-creation.

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1 INTRODUCTION

According to Xu et al. [1], human civilisation has experienced five distinct ages: hunter-and-gatherer, agricultural, industrial, information worker, and the current emerging age of wisdom. The last two ages have shifted from manual, physical work to developing products and services using human capital. Over the past few years, the global economy has transitioned from a physical capital-based economy to a service-oriented one, contributing to over 78% of the United States' gross domestic product in 2006 [2]. This shift has necessitated an interdisciplinary approach between society, science, organisations, and engineering. Additionally, end-users increasingly demand personalised and customised user experiences to meet their evolving needs.

To remain competitive in the rapidly changing economic environment driven by disruptive technological innovation, organisations must continually enhance their products and services, offering an attractive client value proposition [2]. According to Pineda et al. [2], Service Systems Engineering (SSE) has emerged as a systematic, service-oriented, and client-centric approach to address these challenges. SSE involves various stakeholders and resources to design and deliver services that meet client needs. A service system can be viewed as a socio-technical system combining resources (actors and information) that co-create value, guided by a client value proposition [3].

Financial Services Institutions (FSI), especially banking organisations, have been disrupted by technology startups that rapidly challenge their traditional business models by leveraging technology to offer highly customised value propositions for clients. However, FSIs face challenges in implementing new systems effectively, such as complex integration of a system of systems (SoS), frequent reconfiguration of value, and the need for highly agile forms of software development [4]. To adapt, FSIs have started adopting agile software practices from technology startups. Agile software development methods include extreme programming, generic agile, scrum, lean software development, and other customised versions of Agile [5]. However, the standardisation of these methodologies across industries and the benefits of Agile methods require further evidence [6].

The primary objective of this research paper is to develop a conceptual framework that can be implemented within the FSI to address the challenges they face. This framework aims to provide a systematic approach to designing digital service systems that can rapidly deploy highly customised client value propositions. A scoping review was done on the extant literature on SSE and software development lifecycle (SDLC) methodologies to develop this framework. A conceptual framework was created using a grounded theory analysis of the significant features of the reviewed literature relevant to FSI and the issues they experience when implementing new technology. A mixed methods evaluation approach is proposed to evaluate the conceptual framework.

The subsequent section will focus on the literature reviewed and provide a condensed summary of the key features/issues/processes and frameworks in SSE and software development. These findings will then be used in section 3 to produce a conceptual model framework to address the issues highlighted in this section of the paper. The research design for this paper is presented and discussed in section 4. This section details the method used for the conceptual development of the framework and the proposed validation approach to be used. Lastly, in section 5, a conclusion is provided, and future research actions and recommendations are given.

2 LITERATURE SURVEY

2.1 Systems Engineering

Systems Engineering (SE) emerged in 1937 within the British military for air defence, with formal standards established by 1969. Initially focused on physical systems, SE expanded to include space shuttles, cyber-physical systems, and service systems. The International Council on Systems Engineering (INCOSE) was formed in 1995, and the SE Body of Knowledge was published in 2012 [7]. The Federal Aviation Administration defined Systems Engineering as "a discipline that concentrates on the design and application of the whole (system) as distinct from the parts. It involves looking at a problem in its entirety, taking into account all the facets and all the variables and relating the social to the technical aspect." [8]. Due to the growing service sector, SSE, an offspring of SE, was proposed by Tien and Berg [9] in the early 2000s.

2.1.1 Service Systems Engineering

Böhmann et al. [3] state that SSE addresses service systems from life cycle, cybernetic, and customer perspectives. They further highlight research challenges in SSE, such as engineering service architectures, interactions, and resource mobilisation, focusing on flexibility, cyber-physical contexts, and advanced models.

Based on the literature reviewed, these frameworks emphasise that iterative and agile approaches to developing systems in SSE are being used or proposed. They also highlight the need for different levels of abstraction or perspectives [10, 11]. All the frameworks reviewed include steps related to requirements analysis, service concept design and evaluation. See Table 1 for a summary of SSE's design principles and process steps from the reviewed literature's presented models and frameworks.

2.1.2 Agile Systems Engineering Framework (ASE)

ASE combines agile principles with SE, emphasising flexibility, rapid development, and iterative design. Key metrics include response time and cost to change, making it suitable for dynamic environments [7]. An INCOSE project explored agile software, firmware, and hardware systems engineering processes in real-world cases in the field [12]. This project has resulted in an ASE life cycle model framework, see Figure 1; as Dove and Schindel [13] put eloquently: "You can't have an agile engineering process if it doesn't engineer an agile product (and vice versa)". The following agile architecture design principles complete the ASE framework [7]:

- Reusability principles.
    - Encapsulated modules
    - Facilitated interfacing
    - Facilitated reuse
- Reconfigurability principles.
    - Peer-to-peer interaction
    - Distributed control and information
    - Deferred commitment
    - Self-organisation
- Scalability principles.
    - Evolving standards
    - Redundancy and diversity
    - Elastic capacity

Table 1: Design Principles and Processes of SSE Frameworks.

Model/Framework	Design Principles	Process Steps
Recombinant Service Systems Engineering (RSSE) [14]	1. Socio-technical systems 2. Adding/removing internal/ external resources 3. Access to external resources 4. Agile Process	1. Problem recognition 2. Idea management 3. Requirements analysis and resource solution identification 4. Business model re-design 5. Service concept design 6. Service concept evaluation 7. Service concept implementation 8. Formalisation of learning
Multilevel framework for SSE [10]	1. Iterative and validating design process 2. Multilevel perspective	1. Problem formulation 2. Building 3. Intervene 4. Evaluate 5. Reflect
TRIGGER [15]	1. Actor-based service system reconfiguration 2. Adaptive service system reconfiguration 3. Activity-based service system reconfiguration	1. Customer value constellation 2. Job map 3. Service blueprint 4. Liberation from constraints by digitisation
Service Systems Development Process (SSDP) [16]	1. Service system needs 2. Service system interactions	1. Service need 2. Service design and development 3. Service transition/deployment 4. Service operations 5. Continuous service improvement
Model Driven Service Engineering (MDSE) [11]	1. Servistisation. 2. Virtual organisations 3. MDSE architecture	1. Service system definition 2. Develop business service modelling level 3. Develop technology-independent modelling level 4. Develop technology-specific modelling level 5. Implement and manage the service system

2.2 Software Development Life Cycle models

SDLC models define the software or systems development stages [17]. These models can be distilled into four core steps: (1) specification, (2) design, (3) validation, and (4) evolution [18]. Standard SDLC models include: (1) Waterfall, (2) Prototype, (3) Rapid Application Development (RAD), (4) Evolutionary Development, (5) Incremental, (6) Iterative, (7) Spiral, and (8) Component-based software engineering. However, this paper focuses on the most prevalent models according to Munassar and Govardhan [18], as shown in Tables 2 and 3.

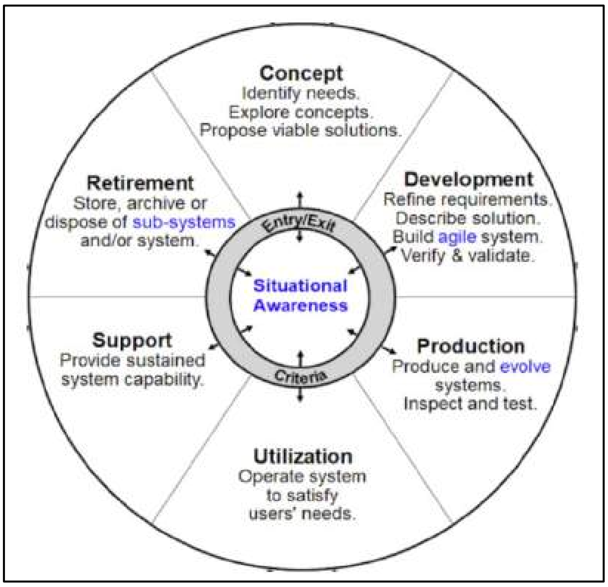


Figure 1: ASE Life Cycle Model Framework [13].

2.2.1 Traditional SDLC Models

All the traditional SDLC models reviewed share the following standard process steps: (1) requirements gathering and analysis, (2) design, (3) implementation, (4) testing, (5) deployment and (6) maintenance. A summary of how these key features differ between models can be seen in Table 2.

Table 2: Summary comparison of key features of Traditional SDLC models.

Feature	Waterfall	Iterative	V-Shaped	Spiral
Process Definition	Needed [19]	Needed [19]	Needed [18]	Needed [19]
Requirements specification	Start [20]	As needed [21]	Start [20]	Start [20]
Cost	Low [20]	Expensive [20]	Expensive [20]	Expensive [20]
Probability of Success	Low [19]	Medium[19]	Medium [18]	Medium to low [19]
Project Size	Medium [21]	Long [21]	Small [18]	Long [21]
Project Complexity	Low [21]	Medium [21]	Low [18]	Medium [21]
Flexibility	Rigid [20]	Flexible [21]	Rigid [18]	Flexible [20]
Value co-creation	Start only [20]	Continuous [20]	Start only [20]	Continuous [20]

2.2.2 Agile Software Development Models

Agile methodologies emerged from the 2001 Agile Manifesto, emphasising individuals and interactions, working software, customer collaboration, and responsiveness to change [22]. Agile principles include frequent delivery of valuable software, welcoming changing requirements, and maintaining a sustainable development pace. Agile methods face criticism for needing more architectural focus, challenges in large-scale applications, and potentially needing to be better chosen for specific real-world projects [6, 23]. A summary of key features can be seen in Table 3.

Table 3: Summary comparison of key features of Agile SDLC models.

Feature	Agile	SCRUM	SAFe	DevOps
Process Definition	Partial [18]	Planning & closure [19]	Continuous [23]	Process standardisation [24]
Requirements specification	As needed [18]	During sprint [19]	During sprints [23]	Defined [24]
Cost	Expensive [18]	Expensive [19]	Very Expensive [23]	Undetermined
Probability of Success	High [19]	High [19]	Undetermined [23]	Undetermined
Project Size	Small-medium [18]	Medium [19]	Enterprise [23]	Enterprise [24]
Project Complexity	Medium [18]	High [19]	High [23]	High [24]
Flexibility	Highly Flexible [18]	Flexible [19]	Flexible [23]	Flexible [24]
Value co-creation	Continuous [18]	Continuous [19]	Continuous [23]	Continuous [24]
Risk Mitigation	Continuous throughout iteration [25]	Continuous [19]	Risk driven iterations [26]	Continuous testing and monitoring [24]

2.3 Analysis of Overlap of Key Features

The overlap of Agile SDLC and SSE framework features can be seen in Table 4. This comparison highlights the need for a more practical application of SSE framework features in practice regarding cost, probability of success and project size.

There is a substantial overlap between process definition, requirements specification, project complexity, flexibility and value co-creation features of both Agile models and SSE frameworks. Additionally, there are overlaps in iterative and incremental development approaches in both SSE and Agile SDLC. There is also a substantial similarity in both approaches to collaboration/stakeholder involvement throughout the development process (value co-creation). Lastly, both approaches strongly focus on the customer value proposition and how best to achieve this in the shortest time.

Table 4: Comparison of key features of Agile SDLC and select SSE frameworks

Feature	**Agile**	**RSSE**	**Multilevel framework for SSE**	**ASE Framework**
Process Definition	Partial	Yes	Yes	Yes
Requirements specification	As Needed	Yes	Yes	Yes
Cost	Expensive	Not Measured	Not Measured	Not Measured
Probability of Success	High	Not Measured	Not Measured	Not Measured
Project Size	Small-Medium	Agriculture	Not Defined	Not Defined
Project Complexity	Medium	Complex	Complex	Complex
Flexibility	Highly Flexible	Flexible	Flexible	Highly Flexible
Value co-creation	Continuous	Continuous	Continuous	Continuous

3 CONCEPTUAL MODEL FRAMEWORK

A conceptual model framework is proposed based on the problems experienced by FSI and the literature reviewed. The conceptual model aims to address the issues experienced by organisations in the FSI when implementing agile projects in complex SoS environments. The conceptual model framework was inspired heavily by the ASE Life Cycle Model Framework presented by Dove and Schindel [13], with changes to the process steps and rationale, discussed in more detail in the following subsections.

The section below will focus on the design principles of the conceptual model framework and explain its relevance in solving problems experienced by organisations in the FSI, as well as its applicability to those organisations. The section after that will detail each of the process steps of the conceptual model framework and the rationale for each one, with examples of its applicability where possible. A graphical representation of the conceptual model framework, Measurable Agile and Socio-technical (MAST), is presented in Figures 2 and 3.

3.1 MAST Framework Design Principles

The design principles chosen for this framework are based on the models from the literature and are relevant to the problems experienced by organisations in the FSI. The design principles are illustrated in Figure 2 [7, 14, 27-30].

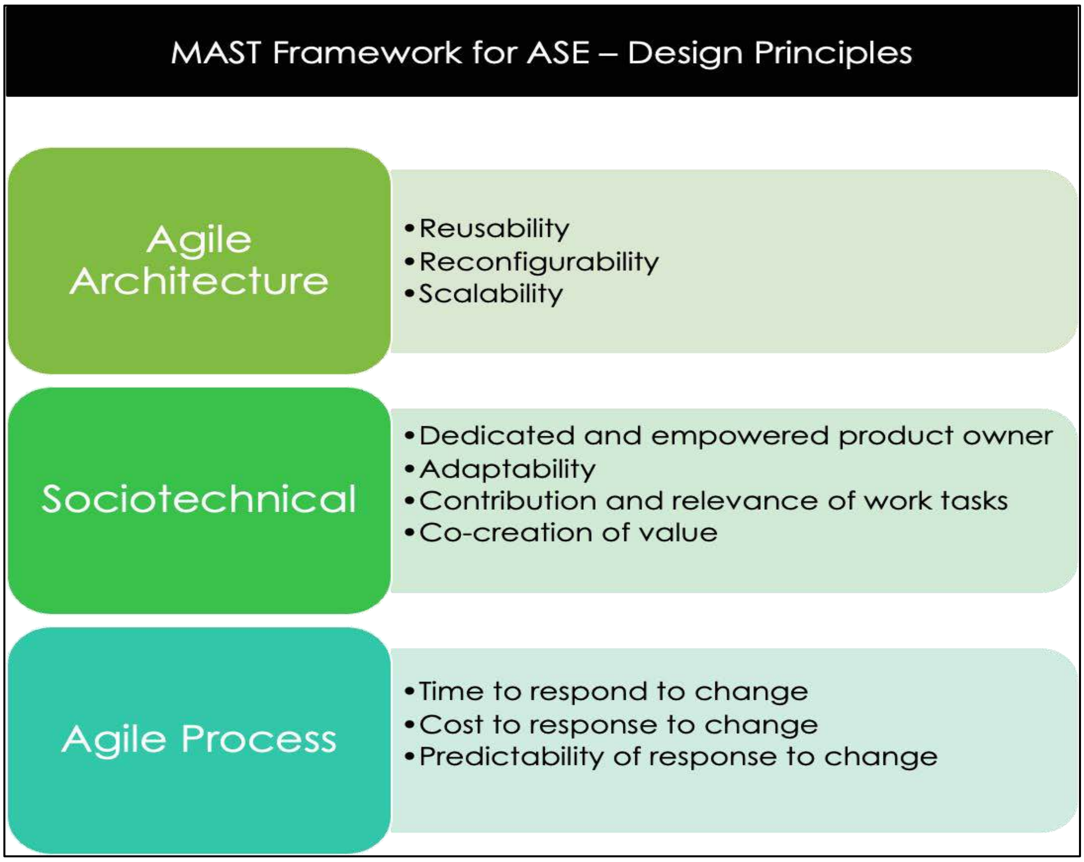


Figure 2: MAST Framework for ASE - Design Principles.

3.1.1 Agile Architecture

The agile architectural design principle defines the system as simplifying how system components (or other systems) can be used in different contexts. The components should be distinct, separable, and independent. The components should further have specified interactions and standards to allow their reuse. Components should be well-defined and easy to find to enable the reusability principle. From the author of this paper's experience in organisations in the FSI, a component fulfilling the same function exists across multiple divisions due to a lack of a central, easily accessible and understandable repository to search for the desired functionality and components. Components must interact directly via peer-to-peer relationships and operate in parallel rather than series. The aim of components should be based on their objective rather than method based on the best information available. Components should be designed with the knowledge that requirements will change as the design/development process continues, and they should be able to adapt to cater to this. To support this level of reusability and reconfigurability, components need passive infrastructure to standardise interactions of components as new requirements evolve or new components are added. This responsibility needs to be dedicated to a member of the change team. The correct duplication of components allows for redundancy. Lastly, components can be combined in responsive assemblies to increase or decrease capacity within the current architectural design [7].

3.1.2 Socio-technical

Socio-technical systems involve the complex interactions between humans, systems (previously machines) and their environment. When designing complex SoS, all these dynamic factors must be considered, along with the five critical elements as described by Baxter and Sommerville [28]:

1. Systems should exhibit interdependence among their constituent parts.
2. Systems must demonstrate their ability to adapt to and actively pursue objectives within their external surroundings.
3. Systems encompass an internal environment consisting of distinct yet interconnected technical and social subsystems.
4. Systems exhibit equifinality, indicating that their objectives can be attained through various pathways, necessitating design decisions during system development.
5. A system's performance relies on optimising technical and social subsystems. Neglecting one in favour of the other will likely result in diminished system performance and efficacy.

Agile methodologies have an excellent approach to involving the end-users and product owners in the case of this research paper to take ownership of requirements, but this should be extended to a broader set of system stakeholders to be genuinely socio-technical [28].

3.1.3 Measurable (Agile Process)

The MAST Framework's Measurable (Agile Process) design principle aims to incorporate agile methodologies to focus not only on software but also on systems, people, processes and the environment. The critical elements of this design principles are [29]:

- Obtain feedback from end users through capability demonstrations to validate assumptions and quantify improvements. Also, measure product-market fit and adapt accordingly.
- Work in small teams to foster frequent feedback and be adaptable to changes.
- Employ metrics and reflection to improve and adapt to changes.
- Empower and enable teams to manage their workflow efficiently and consistently.

3.2 ASE Framework Process Steps

The conceptual ASE framework comprises seven primary process steps, divided into two subprocesses. The first subprocess is considered the “project phase” of the system, and the second subprocess is the “operation phase” of the system. The process steps, as seen in Figure 3, are (1) problem definition, (2) solution design, (3) requirement co-creation, (4) development, (5) operationalisation, (6) support and (7) decommissioning [7, 10, 13, 14, 16].

The proposed process is relatively linear in design but has iterative loops. Once a target design has moved backwards from any step and then forward once more, this increments the requirement evolution by one, thus having a more refined end system. The operational phase succeeds the project phase once all the steps have been completed. The project phase can undergo various requirement evolutions without necessarily reaching the operational phase. ASE processes are based on real-time experimentation and continuous learning throughout the process, and the decision to enter a step in the process for experimental knowledge development is possible without producing an output for the following step [13].

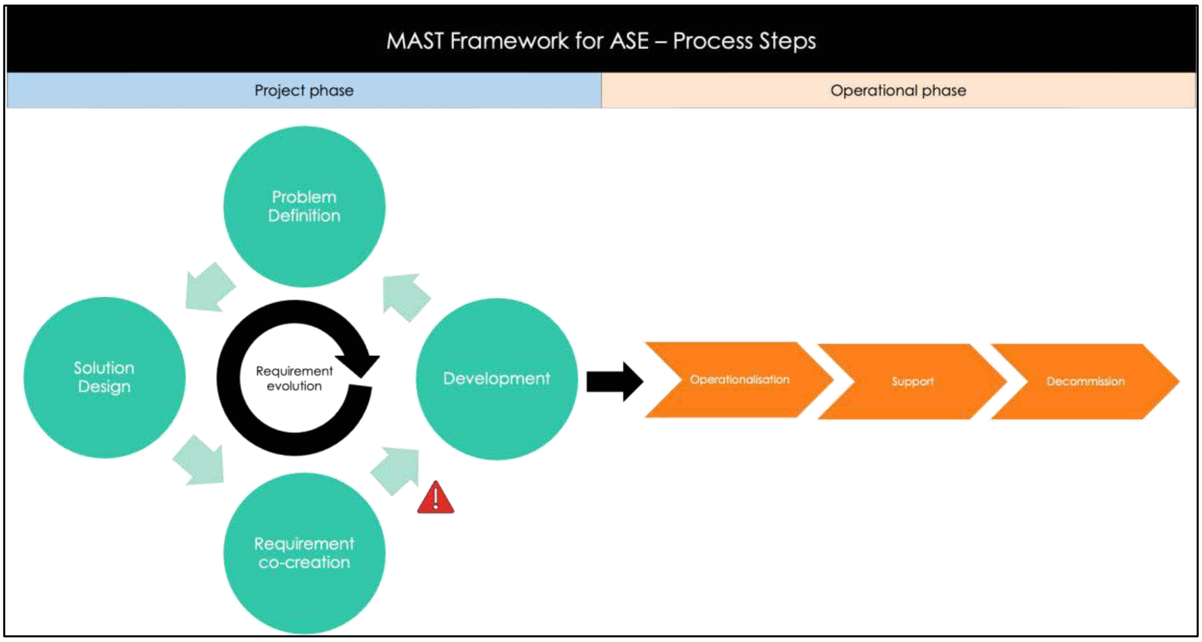


Figure 3: MAST Framework for ASE - Process Steps.

3.2.1 *Problem Definition*

The problem definition is the first step in the ASE Framework process. This is done by analysing system issues or opportunities within the service system [2, 10, 14]. For organisations operating within the FSI, this process step can be precipitated either as a response to external competition or internally as a need to increase efficiency. Based on the type of organisational structure, specifically hierarchically, this usually starts from the executive or senior level, flowing downwards. For this research paper, the organisational structure is assumed to be flat, and leadership is distributed. Anyone in the organisation can identify problems and opportunities, reducing the need to cater for additional organisational complexities.

Design principles: Socio-technical.

3.2.2 *Solution Design*

This process combines other steps from the literature: idea management, service blueprint, service design, and concept [2, 10, 13-15]. Once the problem/opportunity has been well-defined and understood by all parties involved, ideas and potential solutions are brainstormed, and value is co-created. Robust debates are encouraged, and everyone has an equal opportunity to contribute. This can be done via a well-facilitated workshop. During this step, resource combinations/recombinations in different systems, both internal and external, are also discussed.

The high-level overall output of this step is a blueprint that defines the proposed system's functionality and how it interacts with other systems in the broader landscape, as well as defined boundaries [15].

Design principles: Socio-technical, agile architecture, agile process.

3.2.3 *Requirement Co-creation*

Requirement co-creation is the most crucial step in the proposed process as part of the MAST Framework. It is where key actors (resources), information and systems come together to co-create requirements, thus co-creating value in a socio-technical system, enabling the defined problem to be solved and creating a new service system [3]. Another reason for the importance of this step is that it directly inputs into the development step, where rework becomes expensive. This step can also include producing prototypes of the future system to test with the end user to see if it meets their expectations before starting development. Based on the feedback of the prototypes, this step can iterate and requirements further refined (evolved) until the end user is satisfied before moving to development.

Outputs of this step include detailed technical designs of how the future service system can be developed and business requirements agreed upon by the product owner before moving on with the process. This can consist of user interfaces, system requirements, functional requirements, business requirements, resource configurations, marketing and performance requirements [14]. What is crucial to note here is that requirements must be defined to the right level of detail, not over-specified like Waterfall or underspecified, as in some agile implementations [18]. A non-negotiable output is a well-defined and understood architecture framework for the target state of the system. This will guide the technical development and address previous concerns about agile implementations' lack of focus on the architecture [6].

At the end of this step, it is decided whether development begins, the process ends, or whether a design iteration is needed as sufficient detail and knowledge around the problem has been established.

Design principles: Socio-technical, agile architecture, agile process.

3.2.4 Development

The development step receives all the input from the previous requirement co-creation step and has enough information to start the development of the system. The development step follows an Agile SDLC methodology to produce working software that enables the system to achieve its target state. This step also includes various levels of iteration of development, testing, evaluation, and readiness for deployment.

The output of this step is working software that enables a system to achieve its final design state. Software changes can only happen with the next step of operationalisation.

Design principles: Socio-technical, agile architecture, agile process.

3.2.5 Operationalisation

The operationalisation step marks the end of the project phase and the start of the operational phase. This is where the changes that have been made to the system are deployed to the end user. For the change to be successful, depending on the size and complexity of the deployment, various levels of change management will be needed.

3.2.6 Support

Once the change management has been completed, the system enters a state of continuous monitoring and support. If the system operates outside the defined boundaries, intervention is required to ensure the end users are unaffected.

3.2.7 Decommissioning

All systems have a life expectancy as defined during the requirement co-creation step. During this step, the system and its resources are disposed of to meet the disposal requirements [7].

4 RESEARCH DESIGN

4.1 Concept Framework Development

A scoping review was done to determine the extent of research on service systems engineering. From the initial database search, only 96 papers were found under the search term "service systems engineering". This highlights a knowledge gap in SSE regarding the number of research papers available on SSE. Following the scoping review process proposed by Peters et al. [31], 28 papers were selected for analysis based on the inclusion criteria. This consisted of a mixture of journal articles (12), conference papers (14) and editorials (2).

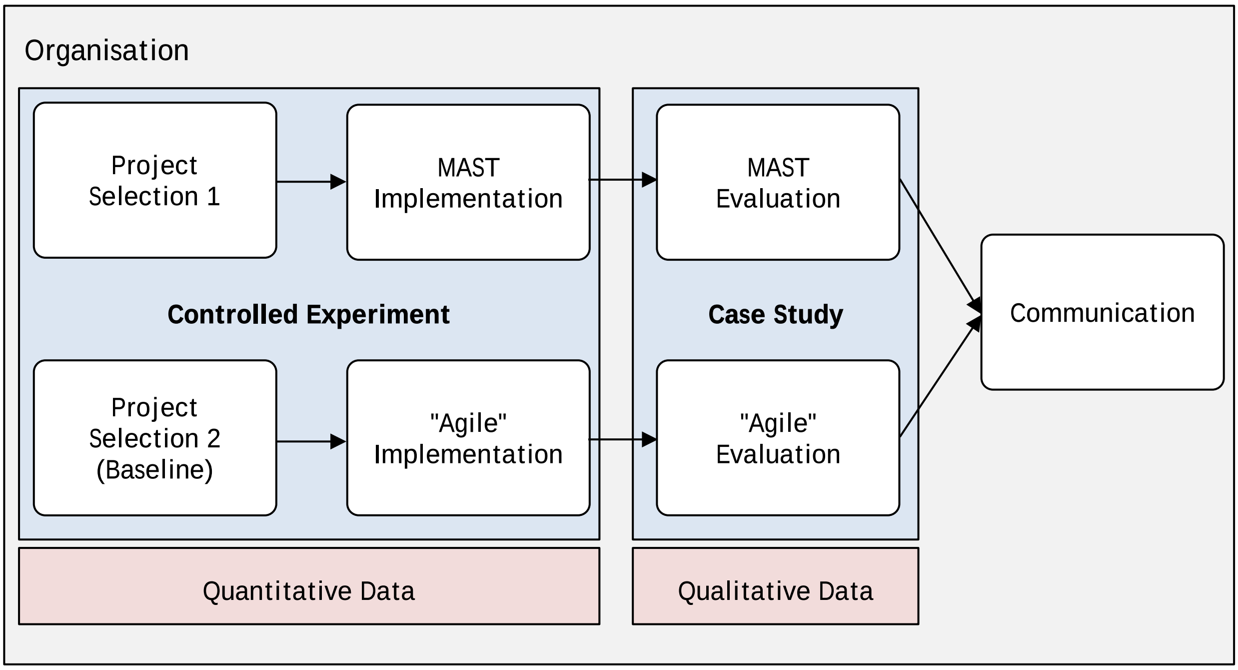
The scoping review included papers on product-service systems (PSS). Product-service systems are an approach manufacturing organisations take to incorporate more service-orientated offerings in their value propositions [32]. The rationale for inclusion in the scoping review was to get a broader view of how SSE methods are being used by other industries that are not purely related to services.

Once the primary frameworks/processes/models for both SSE and software development methodologies were understood and their gaps identified, a grounded analysis approach was then used to develop the conceptual framework based on features of each SSE and SDLC method that would be attractive to FSI and their use cases.

4.2 Concept Framework Validation

Based on the framework presented in this paper, a mixed method of evaluating its efficacy is proposed, see Figure 4. This will include a controlled experiment method for collecting quantitative data and a case study method for collecting qualitative data for ex-post evaluation. The MAST Framework can be assessed in the context of any FSI organisation; hence, it is a naturalistic evaluation typology [33].

Prat et al. [33] proposed 32 criteria for artefact evaluation in IS after studying the extant literature on DSR and the criteria they used. The authors divided the requirements related to the following system dimensions of the artefact: (1) goal, (2) environment, (3) structure, (4) activity and (5) evolution. Based on this, this research study used the following criteria for the MAST artefact evaluation, as seen in Figure 5, based on the organisational issues and addressing the research objective.



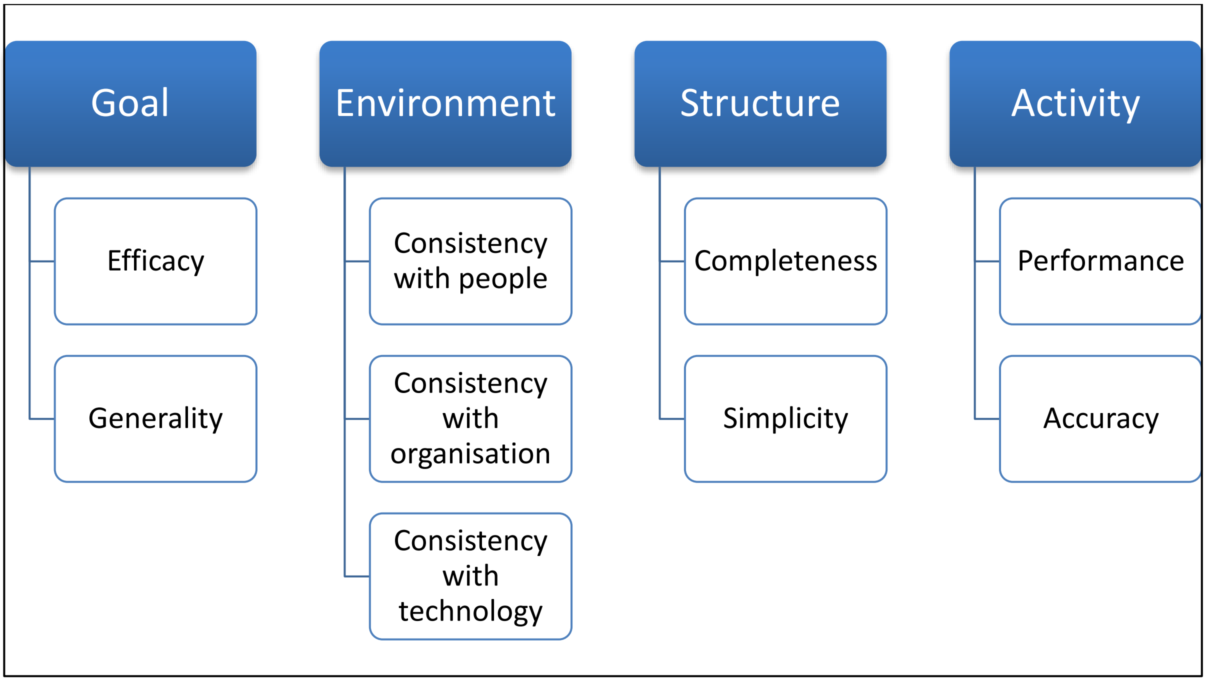


Figure 5: Artefact evaluation criteria, adapted from Prat et al. [33].

5 CONCLUSION

This paper presents a conceptual model framework based on the literature survey, in which various process models and frameworks relating to SE, ASE, and Agile methodologies were compared. The conceptual model framework or MAST Framework for ASE uses the existing literature to develop a framework that can address the problems experienced by banking organisations and create customer value propositions at their own pace. The MAST Framework presented in this paper aims to address this by agile architecture to enable the framework, socio-technical to enable value co-creation across various teams operating across systems and the development process to be agile to allow for rapid responses to change in the internal and external environments.

The main limitation of this paper is that the artefact still needs to be evaluated in an organisation. Secondly, suppose an organisation in the FSI is selected to use this artefact. In that case, certain ethical and competitive-related limiting factors might prevent the results from being published in the public domain due to these organisations' sensitive and highly regulated environment.

Future work is required to test the proposed framework in practice and evaluate its efficacy. In addition, it also needs to be tested in other industries to establish the generalisability of the artefact.

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TOWARDS A COMPREHENSIVE META MODEL FOR ENTERPRISE SYSTEM DYNAMICS

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ABSTRACT

Enterprise engineering (EE) is a discipline that advances the creation of scientific rigour in developing and testing theories, contributing towards a sound body of knowledge for designing, governing and aligning enterprise systems. System Dynamics (SD) also takes a whole-system perspective, focusing on the nonlinear behaviour of complex systems, including enterprise systems. Research indicates that SD has the potential to inform enterprise (re-)design decision-making when used to obtain a shared understanding of existing system behaviour. Bridging the gap between concepts that emerged separately within EE and SD, previous research developed a *meta model for enterprise system dynamics* (MMESD). The main contribution of this article is to further extend the MMESD, discovering new concepts that emerged within SD modelling tools, validating the comprehensiveness of the MMESD. The article includes a demonstration of the additional MMESD concepts, when the MMESD concepts are used to construct a causal-loop-stock-and-flow-diagram.

Keywords: system dynamics, general ontology specification language, causal loop diagram, stock and flow diagram

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1 INTRODUCTION AND PROBLEM DEFINITION

Enterprise engineering (EE) as a discipline, furthers the creation of scientific rigour in developing and testing theories, it contributes towards a sound body of knowledge in EE [1]. System dynamics (SD), with its focus on understanding complex systems over time, complements EE by offering tools to analyse non-linear behaviour through concepts like stocks and feedback loops [2]. Both disciplines focus on complexity and ill-defined problems inherent in enterprises. Recognizing this synergy, De Vries and Dietz [3] proposed using SD to inform decision-making in EE. They further developed a meta model for enterprise system dynamics (MMESD) using the General Ontology Specification Language (GOSL) to enhance clarity and guide users in constructing comprehensive causal loop stock and flow diagrams (CLSFDs).

The initial MMESD was developed, applying the concepts to an existing car industry case [3], using Vensim as the software tool. Yet, the MMESD concepts were not applied, using other SD software tools, where other software tools might include additional concepts that are not reflected in the initial MMESD. Based on [3], Hussain [4] investigated the use of SD concepts in different SD software tools, highlighting the differences in the use of symbolic formalisms, suggesting changes for an extended MMESD, i.e. the eMMESD. The eMMESD was demonstrated using a teacher faculty case [5] to construct a CLSFD in Vensim, providing an additional demonstration of the eMMESD by instantiating some of the eMMESD types. A limitation of the study was that the teacher faculty case was fairly simple, facilitating ease of understanding, but could not demonstrate some of the types, such as QUAL ASPECT, OUTPUT, AUXILIARY, QUANTITY DEPENDENCY LINK, the recursive connections "[quantity] is part of [set of quantity]" and "[stock is part of [set of stock]".

The teacher faculty case highlighted the need for more complex demonstration cases to illustrate and validate eMMESD concepts. According to the system dynamics society [6], other SD software tools exist, that are also common, such as GoldSim and Simile. Yet, the eMMESD was not validated on all the common tools. Therefore, the main objective of this paper is to evaluate and further extend the eMMESD by answering the following research question:

How can an existing meta model for enterprise system dynamics be further extended to be more comprehensive in modelling the dynamics of an enterprise?

Since the initial version of the MMESD and the eMMESD were developed using design science research (DSR) [3, 7], this study continues with a further iteration of developing the artefact, using guidance from Peffers et al. [8, 9]. Answering the research question, this article is structured as follows, also highlighting the main research objectives: Section 2 presents background on the eMMESD and evaluation results on the different symbolisms used in SD modelling tools, addressing one of the main objectives of the study, namely to present extension results, i.e. the e1MMESD. Section 3 addresses a second objective, namely to provide a demonstration of the e1MMESD, using the education for sustainable development (ESD) case. The paper concludes with section 4 with recommendations for future work.

2 BACKGROUND

Conceptual modelling (CM) is a technique used to capture and communicate knowledge about user requirements and facts about an application domain [10, 11]. Conceptual models are used in EE to represent the design and behaviour of enterprises [12, 13]. Recent research [14] indicated an opportunity to use EE and SD in combination, since SD also entails conceptual modelling and the potential to highlight long term dynamic behaviour in enterprises, simulating different decision-making scenarios at an enterprise.

Based on the premise that EE may be informed by SD to support better decision-making on where to focus actions and re-design efforts, De Vries & Dietz [15] suggested the use of GOSL to provide additional clarity on the concepts that are used in SD, developing a MMESD with a summarised set of guidelines to guide the user to design a comprehensive causal-loop-stock-and-flow-diagram (CLSFD).

GOSL is a first order logic language for specifying the state space and transition space of a world [16] and is used within the EE community. GOSL [16] consists of both a *graphical formalism*, used in this article to express the e1MMESD in Figure 9, and *textual formalism*, specified in Peano Russel Notation.

Hussain [4] conducted a survey with 30 participants and evaluated whether the initial MMESD, when expressed in GOSL, supplemented with guidelines, was *easy to understand* and *use*, guiding a practitioner, when constructing a CLSFD. Research by Hussain [4] used DSR to address the limitations identified in the initial MMESD. In this paper, we continue using DSR, since DSR encourages incremental development of an artefact, based on evaluation feedback cycles.

Section 2.1 details the development of an extended version, the eMMESD. This extension was built by comparing how SD concepts are used across five of some common SD software tools, according to the system dynamics society [6], highlighting the discrepancies in their symbolic formalisms. Additionally, the eMMESD was applied to a teacher education faculty (TF) case study in Croatia, drawing on the work of Tomljenović, et al. [5].

2.1 The extended MMESD

The initial MMESD [3] was extended by exploring the symbolic representation of MMESD types within common software tools employed for SD modelling. Five such tools were selected for comparison: Vensim, PowerSim, STELLA, NetLogo, and AnyLogic [6]. The comparative evaluation by Hussain and De Vries [7] revealed two primary areas for improvement within the MMESD. Firstly, the comparison identified the existence of new conceptual elements not previously included in the MMESD. An example of this scenario, is the DECISION LOGIC concept, represented by a diamond symbol in STELLA. Secondly, the comparison revealed discrepancies in the symbolic representations used for existing MMESD elements like QUANTITY, STOCK, and LINK.

To address the identified inconsistencies and enhance the overall comprehensiveness of the MMESD, the research proposed the development of an extended version, referred to as the eMMESD. This extension incorporated several key improvements as shown in Figure 1. We only highlight changes to eMMESD types that required further extension, shown in Table 1 and Table 2 for the e1MMESD.

The extensions, highlighted in red text in Figure 9, aim to promote consistency and improve communication within the SD community by providing a more comprehensive and standardized framework for representing key concepts.

The results of the survey conducted by Hussain [4] also lead to a review of how specializations, subtypes, and attributes are used within the meta model as shown in red text in Figure 9. One change involved replacing the "open system" and "closed system" specializations with a single attribute named "system sort" with values "open" and "closed." This simplifies the model as these categories are mutually exclusive and not directly related to other concepts.

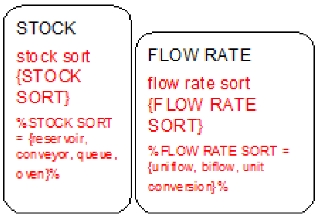
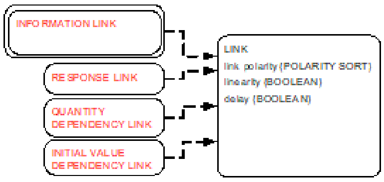
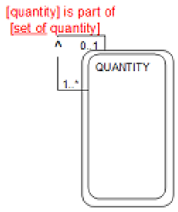
Concept extended	Extension details
	New attributes have been added to both STOCK and FLOW RATE types. The "stock sort" attribute for STOCK allows for the differentiation of various stock types, such as "reservoir," "conveyor," and "queue." Similarly, the "flow rate sort" attribute for FLOW RATE distinguishes between different flow rate types like "uniflow," "biflow," and "unit conversion." These attributes provide additional clarity and precision in representing these concepts within the eMMESD.
	The eMMESD introduces four new subtypes for the LINK entity: "information link," "response link," "quantity dependency link," and "initial value dependency link." These subtypes provide a more granular representation of the different functionalities associated with LINK instances.
	The QUANTITY entity required a recursive relationship '[quantity] is part of [set of quantity]' to indicate that multiple 'quantity' instances may relate to a single 'set of quantity' instance.

Figure 1: Extensions to the MMESD [7], included in eMMESD

The next section introduces additional software tools that were not previously analyzed as part of the work by Hussain and De Vries [7].

2.2 Other software tools used for System Dynamics

To identify concepts from existing SD software tools, and further extend the eMMESD, this section utilizes the tools and categorization developed by the System Dynamics Society [6]. The System Dynamics Society classifies the tools into eight groups: core software, web-based, pedagogical, documentation, group model building, model analysis, open-source, other tools, and other sites [17]. Focusing on the most widely used category, core software tools, the study shortlisted 13 tools for further investigation. Five of these core software tools, iThink/STELLA, Powersim, Vensim, Anylogic and NetLogo, were *excluded* as they have already been compared by Hussain and De Vries [7] and incorporated into the eMMESD.

To identify the most used SD tools in recent publications, a preliminary Google Scholar search was conducted without specifying any tools. Focusing on publications after 2020, Vensim and Stella emerged as the most frequently employed tools for SD applications, confirming the findings of Hussain and De Vries [7].

To further validate the usage of the shortlisted tools, a targeted Google Scholar search was performed using the following search string for publications after 2020: "tool name" AND ("system dynamics" OR "causal loop" OR "stock and flow"). Papers where the software tool was identified as being used for SD diagrams were selected, with a minimum of three publications for each tool.

From the search the following software tools were selected for extending the eMMESD: GoldSim, iMODELER Desktop, Insight Maker, Simile, and Ventity. Ventity, initially considered due to its capabilities in SD modelling, is excluded from the final comparison because it utilizes the same standard MMESD symbols for STOCKs, FLOWs, and other entity types as Vensim [18].

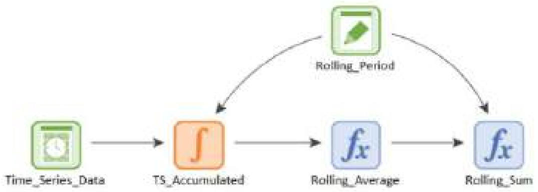
In a previous study, Vensim's compatibility with the MMESD was already established by Hussain and De Vries [7].

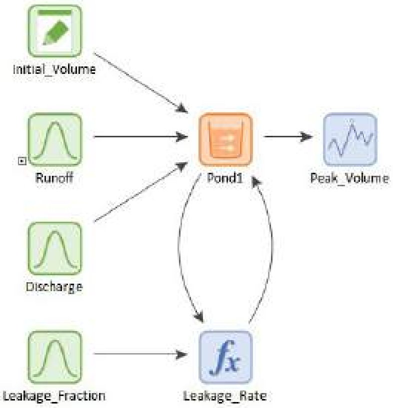
Like *Ventity*, *iMODELER* is excluded from the final comparison, since the concepts used already addressed by the existing eMMESD. As highlighted by Neumann, et al. [19], iMODELER allows for qualitative cause-and-effect modelling using arrows between factors, with "+" or "-" signs to denote influence. This aligns with the established concepts of MMESD for depicting causal relationships. However, iMODELER offers an additional feature, i.e. the ability to assign weights (0% to 100%) to these interconnections, signifying the relative influence of one factor on another.

The symbols used in *Insight Maker* were also considered and no additional concepts were discovered to extend the existing eMMESD. Insight Maker offers two types of STOCKs both represented as blue rectangles [20]. The first type designated simply as "stock" functions as a standard reservoir, analogous to STOCK SORT of “reservoir” within the eMMESD. The second stock type, termed "conveyor stock with delay," incorporates an inherent time lag mechanism. The embedded delay aligns with the concept of "delay" found in the eMMESD's STOCK SORT of "conveyor" and "oven". The software also offers “converter”, “variable”, “flow”, and “link” which directly correspond to the eMMESD's AUXILIARY (AS CONVERTER), FACET (AS VARIABLE), FLOW, and LINK" concepts respectively.

Table 1 indicates additional concepts that emerged from *GoldSim* and *Simile*, indicating how the new version of the eMMESD, now called the e1MMESD as a further extension of the original eMMESD, should be adapted to accommodate the additional concepts. We also highlight changes to the *graphical formalism* of the e1MMESD in Figure 9, using blue color-coding. A representation of the full *textual formalism* of the e1MMESD is outside the scope of this paper due to space limitations.

Table 1: GoldSim MMESD type related to symbol

Type	GoldSim [21]		Explanation
STOCK	Two STOCK types are distinguished within GoldSim: (1) **Integrator**: is designed to integrate information. It computes the moving average of a specified input.	∫	(1) **Integrator**: The integrator requires an *initial value* and a *rate of change*, and at any given point in time it calculates a single value given by: $Value = Initial\ Value + \int (rate\ of\ change)dt$ This can be used to track information such as daily temperature readings over a specified time (e.g., number of days). This gives you a smoother trend over time, like the average weekly or monthly temperature. **Example**: In Figure 2 below, the model accumulates daily data (e.g., sales) from the Time_series_Data input element and calculates rolling averages and sums using an **Integrator element**. The Integrator provides a moving average (TS_Accumulated) of the daily input for a specified period. This is the rolling average. The Rolling_Sum is simply the averaging period (Rolling_Period) multiplied by the current Rolling_Average value.  **Figure 2: Rolling sum example from GoldSim** *[22]* In **e1MMESD**: For improved clarity, the e1MMESD textual formalism should be updated to specify that STOCKS are only used for tangible material (i.e., cash, water, cars, dirt, etc.) that physically accumulate and flow through the system. Information, on the other hand, is intangible and is not conserved.

Type	GoldSim [21]		Explanation
			For **e1MMESD**, further guidance should be provided for the AUXILIARY entity type, indicating that continuous calculations may also be required for simulation purposes, such as using a rolling sum.
	(2) **Pool**: A more complex version of a reservoir. It can model multiple inflows and outflows.		(2) **Pool**: it functions like the reservoir, except it allows the user to specify multiple inflows, and request multiple outflows. At any given time, the quantity in the pool is given by: $Quantity = Initial\ Quantity + \int (inflows - outflows)dt$ This can be used to accumulate and track material flow such as the number of people in a city. Births and immigration (inflow) increase the population, while deaths and emigration (outflow) decrease it. The pool continuously calculates the net effect of these flows to determine the current population size. In **e1MMESD**: The current eMMESD does not accommodate for a STOCK with multiple inflows and outflows. In Figure 9 the attribute STOCK SORT now includes an attribute value "pool" with more than one cardinality for the number of FLOWS allowed to and from STOCK. Sterman [2] refers to aging chains where additional inflows and outflows to intermediate stages should be modelled to represent the delays due to ageing.
QUAN-TITY	There are five input elements in GoldSim: (1) **Data**: A single scalar value, or an array of related values.		(1) **Data** elements are used for constant *inputs to the model*. This function can represent both values and conditions (i.e., True/False). **Example**: In Figure 2, Rolling_Period is a constant input element (e.g., 7 days for a weekly period).
	(2) **Stochastic**: An uncertain value defined as a probability distribution.		(2) **Stochastic** elements are used to carry out probabilistic simulation. They represent the uncertainty in the *input data* for your model. These have four outputs: the sample value, the probability density, the cumulative probability, and the distribution information (i.e., Binomial, discrete, Poisson, etc.). **Example**: In Figure 3 below, the model simulates a pond's water balance. Runoff, mimicking natural inflows, varies daily through a stochastic process. Discharge, another uncertain input, represents controlled releases. The pond also experiences leakage proportional to its volume, with a stochastic Leakage_Fraction introducing variability across simulations. These uncertainties capture the dynamic nature of water flows, providing a realistic representation of the pond's behaviour.  **Figure 3: Stochastic element example from GoldSim [23]**
	(3) **Time Series**: A time series of a value.		Similarly, the **Time Series** and **Lookup Table** elements are functionalities that facilitate the incorporation of external data into the modelling process.

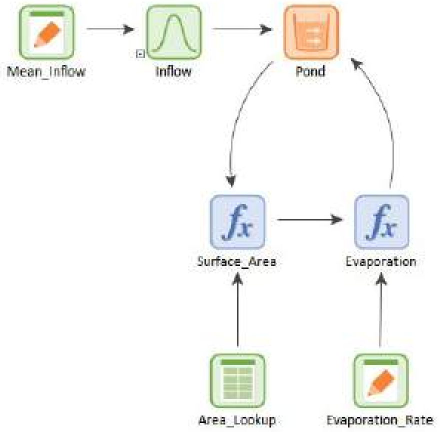
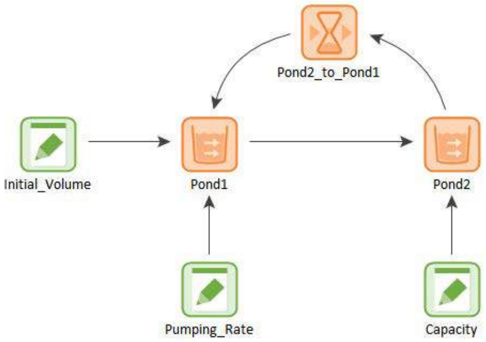
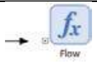
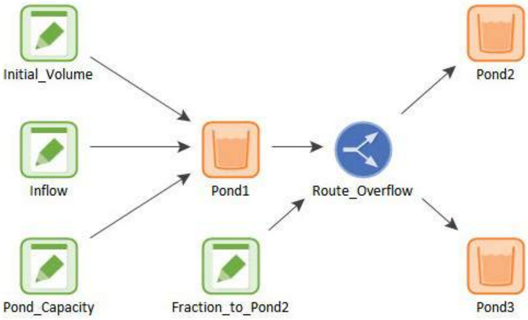
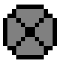
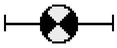
<table>
<tr><th>Type</th><th colspan="2">GoldSim [21]</th><th>Explanation</th></tr>
<tr><td rowspan="2"></td><td>(4) Lookup Table: A response surface specifying how an output varies as a function of up to three inputs.</td><td>▦</td><td rowspan="2">Example: The Time series element is utilized in Figure 2, where Time_Series_Data provides input data for the GoldSim model. It can be defined directly within the Time Series element, imported from an external file (like a CSV), or linked to other elements within the model that generate time-series data. In Figure 2, it provides daily sales figures (time series values) to calculate average daily sales using the integrator.
In Figure 4, the Lookup Table, Area_Lookup, is defined with independent variable pond volume (input) and corresponding surface area values for different volume ranges. In a table like this, the value of the dependent variable for any given value of the independent variables is supplied by GoldSim by interpolating between the data points supplied in the table.


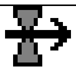
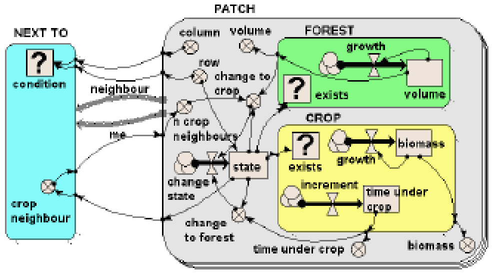
Figure 4: Lookup Table example from GoldSim [24]
Additionally, the History Generator generates random stochastic data for simulation purposes. When modelling a system where a variable isn't constant but fluctuates over time (e.g., customer arrivals, wind speed). The History Generator lets you define the statistical characteristics of these fluctuations, generating a random time series that reflects this uncertainty. For example, for customer arrivals in a store, a time series of random customer arrival times within each hour can be the output. This is different from a Stochastic input element that produces one random value per run, instead of random values for each time step.</td></tr>
<tr><td>(5) History Generator: Generate random (stochastic) time series based on specified statistics.</td><td>📈</td></tr>
<tr><td></td><td colspan="3">In e1MMESD: In Figure 9, an attribute PARAMETER VALUE SORT is added (i.e., %PARAMETER VALUE SORT = |constant, data, stochastic, time series, lookup table, history generator, function|%).</td></tr>
<tr><td rowspan="2">FLOW and FLOW RATE</td><td>GoldSim distinguishes between material and information flow.
(1) The information delay element is used for information FLOW.</td><td>⌛</td><td>Information Delays are intended to represent processes such as delays in measuring or reporting variables (e.g., reporting the inventory in a warehouse, or snowpack levels). Reporting yesterday's rainfall total is an example of an information delay, with a delay time of one day.
In e1MMESD: In Error! Reference source not found., PARAMETER, now includes an attribute “reporting delay” of value type DURATION, to indicate that input values may have a reporting delay.</td></tr>
<tr><td>(2) The material delay element is used for material FLOW. A straight black</td><td>⌛</td><td>Material Delays are intended to represent delays in the physical movement (flow) of material through a system (letters though the mail system, parts on an assembly line, salmon in a river, water moving through a pipe). Material is conserved as it moves through a Material Delay.
Example: As water overflows in Pond2 it does not enter Pond1 immediately [25]. There is a delay while it is transported there as indicated by the material delay element Pond2_to_Pond1.</td></tr>
</table>

Type	GoldSim [21]		Explanation
	arrow represents material flow as shown in Figure 5.		 **Figure 5: Material flow example in GoldSim** *[25]* In **e1MMESD**: The attribute STOCK SORT already incorporates a delay through the values “conveyor” and “oven”. In the textual formalism of the e1MMESD, further explanation should be added to clarify the delaying effect.
Type	**GoldSim [21]**		**Explanation**
LINK	For influences between **containers** (i.e., a grouping of a part of the model elements) a **dot** is placed next to the port.	 	An element that acts like a "box" or a "folder" into which other elements can be placed. It can be used to create hierarchical models. This makes the model visually organized and easier to understand. Each container acts as a sub-model within the larger model, allowing you to focus on specific parts independently. **Example**: The model in Figure 6 can be organised by function to improve organisation and enhance clarity. The model can be separated into two different groups in two different containers (Inputs and Pond_Model).  **Figure 6: Pond model example from GoldSim [26]** Figure 7 shows Inputs which include Initial_Volume, Inflow, Pond_Capacity, and Fraction_to_Pond2. Pond_Model include Pond1, Pond2, Pond3, and Route_Overflow. The use of containers in their simple form does not have any impact on how calculations are done, and is simply used to organise and structure models.  **Figure 7: Container example from GoldSim [26]** In **e1MMESD**: Since the e1MMESD allows for the representations of different enterprise system dynamics models (ESDM) the container concept simply allows for practical management of diagram complexity for human interpretation. In the same way, a real-world instance of ESDM could be represented in different ways, either a causal loop diagram (CLD) or stock and flow diagram (SFD). The following textual formalism should be added, to indicate the possibility of adding containers, where a container can be used to group a sub-set of concepts together, also grouping them together graphically in a diagram. $diagram\_container(x) \Rightarrow diagram(x) \cap container(x)$

Type	GoldSim [21]		Explanation
			As indicated in the graphical formalism in **Error! Reference source not found.**, a container's influence on the modelled scope, is indicated via a CONTAINER LINK, where the CONTAINER LINK is a new sub-type of LINK. Since a CONTAINER LINK instance cannot have the same CONTAINER instance as both destinator and originator at the same time, the following exclusion law should be added in the textual formalism, using Peano-Russel Notation: $\forall x,y$: container destinator $(x,y) \Rightarrow$ container link $(x) \wedge$ container (x) $\forall x,y$: container destinator $(x,y) \Rightarrow \neg$ container originator (x,y) $\forall x,y$: container originator $(x,y) \Rightarrow \neg$ container destinator (x,y)

Table 2: Simile MMESD type related to symbol

Type	Simile [27]		Explanation
STOCK	A rectangle symbol represents a compartment. The rate of change is the net effect of all inflows minus all outflows		In **e1MMESD**: Reservoir is the default for STOCK SORT, already included in eMMESD.
QUANTITY	An octagon with a cross inside is used to symbolise a **variable**. For modelling use, Simile variables are classified further:		
	(1) **Parameter**: a coefficient in an equation (i.e., a constant). LINK(s) cannot point to it but can point from it.		In **e1MMESD**: This refers to PARAMETER (AS INPUT). In Figure 9 an attribute PARAMETER VALUE SORT is added (i.e., %PARAMETER VALUE SORT = %|constant, data, stochastic, time series, lookup table, history generator, function|%).
	(2) **Input lever**: a variable parameter. The slider is used to adjust the value. LINK(s) cannot point to it but can point from it.		
	(3) **Exogenous variable**: its value changes during a simulation run, affecting the value of other variables, but itself remains unchanged. LINK(s) cannot point to it but can point from it.		
	(4) **Intermediate variable**: A derived variable. LINK(s) can point to it and can point from it.		In **e1MMESD**: This refers to AUXILIARY (AS CONVERTER) that already forms part of the eMMESD.
	(5) **Output variable**: report on some aspect of model behaviour. LINK(s) cannot point from it.		Typically used to report on some aspect of the model behaviour (i.e., ratio of two compartments). In **e1MMESD**: This refers to OUTPUT, already included in the eMMESD.
	(6) **Attribute of an object**: variable is inside a multiple-instance sub-model. LINK(s) cannot point to it and cannot point from it.		For example, a sub-model representing a "Tree" may define an attribute called "Species" to differentiate between Pine, Oak, etc. Each instance of the "Tree" sub-model (individual trees) can then have a different value for "Species" to reflect the forest's diversity. In **e1MMESD**: The eMMESD currently does not accommodate for attributes and will not be included in the e1MMESD, as explained further in section 2.3.

Type	Simile [27]		Explanation
FLOW and FLOW RATE	FlOWs, represented as arrows, depict the movement of substance between compartments (i.e., STOCKS). May be one of several flows between two or more compartments, in either direction		In **e1MMESD**: This refers to FLOW RATE, already included in the eMMESD.
LINK	**Influence arrows** are represented by a curved arrow. To draw an influence arrow from A to B, suggests that A is used to calculate B.		In **e1MMESD**: This refers to LINK and its specialisation in the eMMESD i.e., QUANTITY DEPENDENCY LINK and INITIAL VALUE DEPENDENCY LINK.
	A **role arrow** is another type of LINK that is used to connect between sub-models (i.e., a grouping of a part of the model elements).		Simile submodels represent collections of objects or entities within a system. The submodels communicate through role arrows, which can be one way (influence) or two-way (exchange) for data flow. **Example**: Figure 8 shows a Simile model that simulates land use changes between forests and crops across multiple patches on a grid. The following sub-models are observed: (1) PATCH (Multiple-Instance): Represents individual land-use patches with unique row and column attributes defining their grid location. (2) and (3) FOREST & CROP (Conditional): Contained within PATCH, representing the potential forest or crop land use for each patch (only one per patch). (4) NEXT TO (Association): Defines relationships between patches, indicating which patches are neighbours based on row and column proximity.  **Figure 8: Land-use change example in Simile [28]** In **e1MMESD**: The eMMESD currently does not accommodate for sub-models and will not be included in the e1MMESD, as explained further in section 2.3.

2.3 The e1 extension of the meta model of enterprise system dynamics (MMESD)

Table 1 and Table 2 compare the functionalities and symbols used for representing elements in two SD software tools: GoldSim and Simile. The focus was on elements used to represent STOCKS, FLOWS, LINKS, and QUANTITIES.

The comparison validated the additions made to the MMESD by Hussain and De Vries [7]. Notably, both Insight Maker and GoldSim offer functionalities that align with the MMESD's "STOCK" type concept. These functionalities, such as "material delay" in GoldSim and "conveyor stock with delay" in Insight Maker, introduce time delays into material flows, validating the inclusion of the STOCK entity type’s “stock sort” attribute value “conveyor”, within the eMMESD. Furthermore, the "information delay" element observed in GoldSim lead to the addition of a “reporting delay” attribute for PARAMETER.

The comparison also identified gaps in the current eMMESD. Unlike Sterman's guidance, GoldSim distinguishes between "information flow STOCK", called “integrator”, and "material flow STOCK", called “reservoir”. Sterman [2] discusses that information delay should be modelled differently to material delay, since material is conserved, unlike information. GoldSim further offers an additional "pool" STOCK type allowing for multiple inflows and outflows. This capability aligns with the concept of "ageing chains" discussed by Sterman [2]. Ageing chains represent system where entities progress through various stages or age groups, with inflows occurring at different points and outflows happening from various stages.

A key differentiator identified when comparing these SD modelling tools, is the incorporation of object-oriented (OO) modelling in software like GoldSim and Simile. As Tignor and Myrtveit [29] discuss, OO concepts help bridge the gap between SD modelling and software engineering, offering advantages to modelers to facilitate understanding. While traditional SD focuses on STOCKs, FLOWs, and their relationships, some software programs introduce OO elements like "attributes," "sub-models," and "containers." The e1MMESD could benefit from incorporating functionalities for managing complexity and readability of the models, by creating and utilizing sub-models. Both Simile's "sub-models" and GoldSim's "containers" enable modular model building, as a result these software tools also introduce various "LINK" types to define relationships between these sub-models.

Myrtveit (2000) further emphasizes the value of a hierarchical view in models, as observed in Figure 8. This approach allows for presenting the model's structure at different levels of detail, aligning well with how we naturally organize systems into subsystems. However, a potential limitation of hierarchical views is that they might not always be ideal for illustrating feedback relationships. Feedback often involves influences that cross-subsystem boundaries. When examining a sub-model in isolation, the portions of feedback loops extending beyond its scope get excluded. This disrupts the loop's integrity and can obscure the feedback mechanism within the overall system. The current iteration of the e1MMESD prioritizes the concepts of SD modelling. While OO modelling offers potential benefits, its inclusion is limited to the “container”. However, future development of the e1MMESD might explore the integration of OO concepts to enhance model structure and reusability.

Another key observation is the diverse terminology and types used for representing QUANTITIES across the three tools. For instance, GoldSim offers a "stochastic element" for introducing randomness, while Simile uses an "input level" concept. This highlights the need for potential standardization in quantity representation within SD software tooling and the e1MMESD. Figure 9 presents the e1MMESD with the extensions indicated in blue.

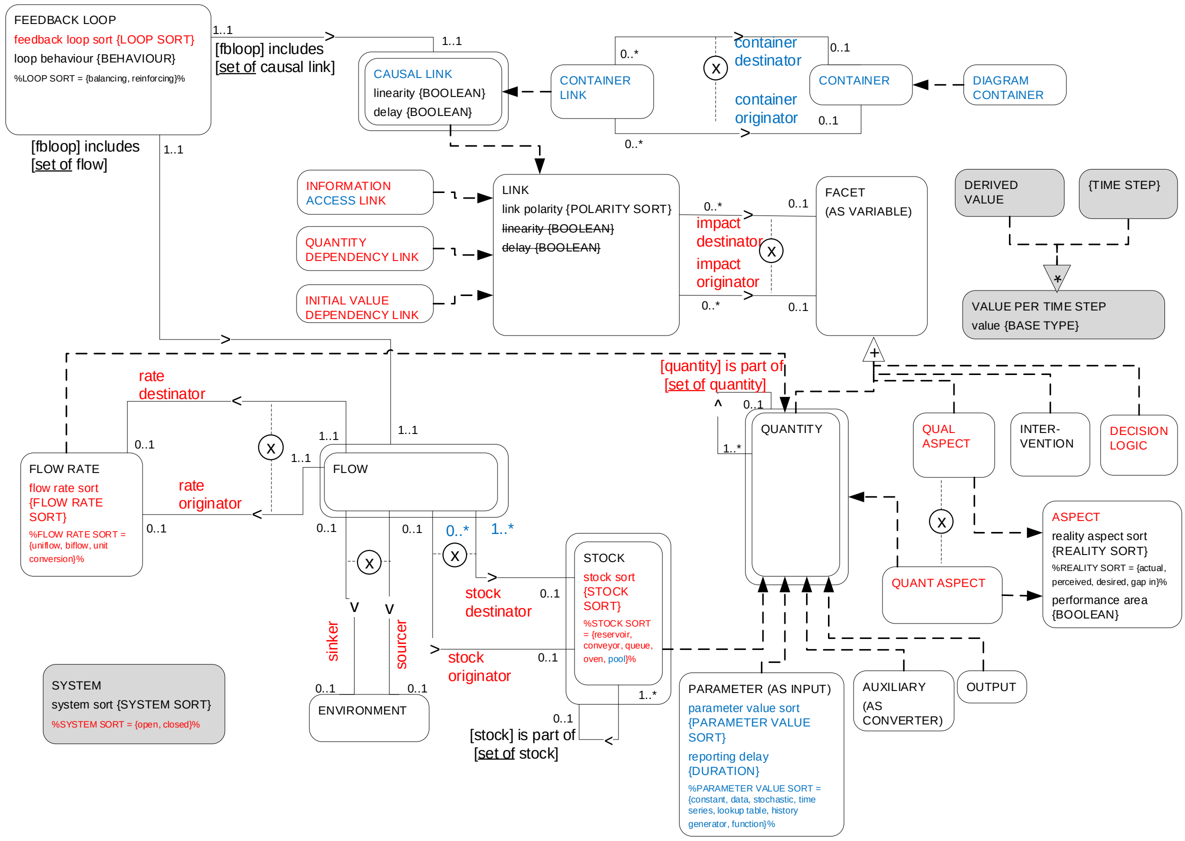


Figure 9: The e1MMESD, where extensions are indicated in blue

3 FURTHER VALIDATION OF THE META MODEL FOR SYSTEM DYNAMICS

To validate the e1MMESD in a real-world context, section 3.1 introduces a case study focused on the integration of education for sustainable development within a higher education institution in Iran, and section 3.2 applies the e1MMESD to the case study. Previous work already validated the MMESD, applying the MMESD concepts to existing cases [3, 7]. This study follows a similar validation approach, applying the e1MMESD to another, more complex case, within the higher education context.

3.1 The education for sustainable development case

The international call for a sustainable future necessitates solutions to address sustainability challenges [30]. Higher education institutions (HEIs) play a critical role in this endeavour by educating and empowering future generations to address societal issues. Effectively integrating Education for Sustainable Development (ESD) within universities requires a holistic approach encompassing curriculum, teaching methods, financial resources, and assessment strategies [31].

Faham, et al. [30] present a case study demonstrating the integration of ESD in Iranian higher education, focusing on the University College of Agriculture and Natural Resources (UCAN) at the University of Tehran. While the importance of ESD is acknowledged in Iran, as in many countries, a deeper commitment and appropriate educational policies are needed for successful implementation.

To identify the mechanisms necessary to cultivate ESD at UCAN and enhance students' sustainability competencies, Faham, et al. [30] utilized a five-step SD approach outlined by Sterman [2]. This approach involves constructing a CLD and an SFD over a 40-year timeframe (1991-2031). Vensim software was employed for model simulation.

The education for sustainable development case was used to understand the influencing factors and obstacles to ESD in higher education at UCAN in Iran. The authors [30] used SD techniques, creating a CLD and a CLSFD to run simulations. Using Vensim, they developed a dynamic model to develop education for sustainable development in HE with an emphasis on the sustainability competencies of students and staff. The model's objective is to evaluate eleven different mechanisms by finding their impacts on improving the problem.

3.2 Applying the e1MMESD to the education for sustainable development case

Using Vensim, the e1MMESD concepts and their extensions, as shown in blue in Figure 9, were applied to the UCAN case, re-modelled in Figure 10.

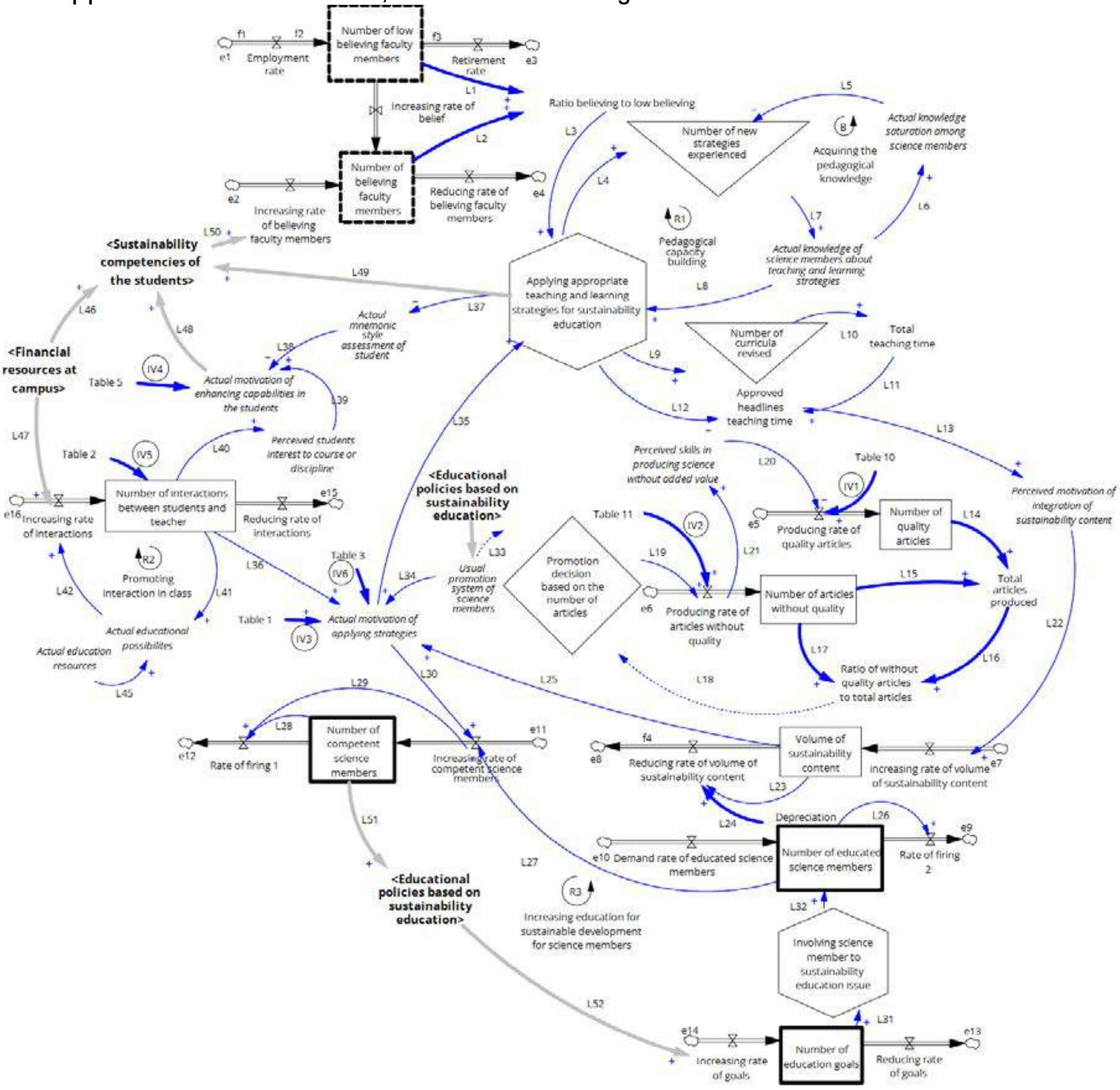


Figure 10: The ESDM, represented as a CLSFD

In Table 3 (in the Appendix), we present the new extensions of the e1MMESD entity types in the *first column*, where concepts are also graphically depicted in Figure 9 using GOSL's graphical formalism. For each concept in Table 3, the *second column* provides an example of an instantiation of the e1MMESD type from the education for sustainable development case. The modelling software, Vensim, allowed us to visually distinguish between some types, further explained in the *third column* of Table 3.

The e1MMESD extensions are shown in blue in Table 3, based on the new concepts extracted from GoldSim and Simile as discussed in Table 1 and Table 2. Extensions regard multiple existing entity types, including the “reporting delay” attribute of PARAMETER (AS INPUT), the CONTAINER LINK, the addition of PARAMETER VALUE SORT, and the addition of new STOCK SORT attribute value “pool”. Furthermore, new entity types, CONTAINER and DIAGRAM CONTAINER were added.

Due to the addition of a “pool” attribute value for attribute “stocks sort”, the cardinality of “stock destinator” was also changed from “0..1” to “1..*” as the case study demonstrated that a STOCK may be linked to one or multiple FLOW instances for in-flows. The “1” cardinality also acknowledges that every STOCK instance should at least have one in-flow but may also have multiple in-flows. Due to the “pool” attribute, the cardinality of “stock originator” was also changed from “0..1” to “0..*, acknowledging that every STOCK instance may not necessarily have any FLOW instances as out-flow, but may also have multiple out-flows.

Since some of the e1MMESD types are only instantiated during simulation, not all the e1MMESD types are included as graphical constructs on the CLSFD, such as VALUE PER TIME STEP (shaded in grey in Figure 9), aggregating DERIVED VALUE and TIME STEP. The demonstration example could therefore not elaborate on these.

Faham, et al. [30] did not include a DECISION LOGIC instance in their model. To address this gap, Figure 10 incorporates the DECISION LOGIC “promotion decision based on the number of articles”, replacing the auxiliary instance "speed of promotion based on the number of articles." This addition necessitates the inclusion of a RESPONSE LINK and INFORMATIONLINKs. Since the example deviates from the pattern discussed in [7], it suggests a need for more specific guidance within the e1MMESD regarding the use of the DECISION LOGIC.

The INFORMATION LINK and RESPONSE LINK previously used in the DECISION LOGIC in [7] were reclassified as a INFORMATION ACCESS LINK (accessing information) and a CAUSAL LINK in Figure 10 and the e1MMESD. Aligning with Dietz and Mulder [16], an *access link* signifies an *actor* having reading access to the *facts* in some *transaction bank* of a *transaction kind*, visualised in the CLSFD as a dotted arrow towards the DECISION LOGIC. Sterman’s [2] definition of a CAUSAL LINK as an arrow with polarity indicating how a dependent variable changes when the independent variable changes, led to reclassifying the “response” LINK from the DECISION LOGIC as a CAUSAL LINK. Consequently, the CONTAINER LINK was also categorised as a subtype of CAUSAL LINK.

The ESD case application found that INFORMATION ACCESS LINKs are excluded from FEEDBACK LOOPs as defined by Sterman [2]. To maintain consistency, the e1MMESD was updated to include only FLOWs and CAUSAL LINKs within FEEDBACK LOOPs. Additionally, “linearity” and “delay” attributes were found to be inconsistent across LINK types and were moved to CAUSAL LINK.

4 CONCLUSION AND WAY FORWARD

We demonstrated how the new extension, e1MMESD, was further developed, using existing SD modelling tools as a means of extracting new concepts. Previous authors already started a DSR project, designing and evaluating different versions of the MMESD [3, 7]. This study presents another iteration of DSR to answer the main research question. We also validated the e1MMESD, using a more complex ESD case from literature, i.e. secondary data, building our own model. Due to the complexity of the case, all the e1MMESD types, except OUTPUT, were instantiated in the UCAN case. This case study also demonstrates the instantiations of eMMESD types not shown in previous work [4, 7] such as the DECISION LOGIC (a diamond shape), and the INFORMATION ACCESS LINK (a dotted line).

Further validation of the e1MMESD is necessary through practical application. While we have only presented its application to literature-derived cases [3, 7], the next step is to experiment with a real-life case. This new case should involve multiple stakeholders who will identify problematic aspects within the enterprise that are considered performance areas, and pinpoint system facets that impact these problematic aspects.

An SD and EE practitioner would then facilitate an interactive modelling session using the e1MMESD as a guide. This session would assess the practitioner's experience with the e1MMESD's *usefulness*. Building on the participative modelling concept supported by Sterman [2], this approach leverages stakeholder input collaboratively. As shown by Valcourt, et al. [32], group identification of facets, causal links, and feedback loops can improve their alignment.

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6 APPENDIX

Table 3 provides some validation results, indicating how the new e1MMESD concepts are instantiated for the ESD case. Although Figure 10 provides multiple instantiations of a particular e1MMESD concept, related to the graphical formalization in Figure 9, Table 3 simply demonstrates a single instantiation per concept.

Table 3: New e1MMESD concepts instantiated in Figure 10

e1MMESD concept	**Instantiation in Figure 10**	**Explanation (if necessary) and graphical representation**
PARAMETER (AS INPUT) SORT	**the** *parameter value sort* **of** *parameter* table 10 **is** time series	The time series facilitates the incorporation of external data into the modelling process. Table 10 refers to a table in an external file that is linked to the CLSFD.
reporting delay	**the** *reporting delay* **of** *parameter* table 10 **is** 1 year	A one-year reporting delay is assumed, reflecting the standard timeframe for scientific article publication and subsequent consideration within the science member promotion process.
stock sort	**the** *stock sort* **of** *stock* number of competent science members **is** conveyor	For the [stock] instance “number of competent science members” any teaching faculty member is employed for some period before leaving the faculty. The “number of competent science members” is represented as a conveyor, represented by a thick black borderline.
	the *stock sort* **of** *stock* number of believing faculty members **is** pool	The [stock] instance “number of believing faculty members” accumulates and tracks the faculty members that believe in incorporating sustainability in HE. The [stock] increases due to graduates from UCAN eventually becoming employees (via [flow rate] instance “increasing rate of believing faculty members”) and current science members gaining knowledge on ESD (via [flow rate] instance “increasing rate of belief”). Sterman [2] refers to aging chains where additional inflows and outflows to intermediate stages should be modelled to represent the delays due to ageing. Therefore, “number of believing faculty members” is represented as a pool, represented by a thick dashed black borderline.
CONTAINER	*container* financial resources at campus **exists**	A container allows model elements to be grouped together based on the similarity and cohesiveness of the contained concepts. For example, [container] instance “financial resources at campus” contain related [facet] instances such as “income”, “number of applied researches”, “sovereign income”, and “student association credit”. Faham, et al. [30] have also identified investment for education at the university as one of five key variables in understanding the system. The [container] instances are indicated graphically with bold text, larger text, and angled brackets (< >).

e1MMESD concept	**Instantiation in Figure 10**	**Explanation (if necessary) and graphical representation**
CONTAINER LINK	*container link* L46 **exists** *container link* L49 **exists** *container link* L50 **exists**	The [container link] instances that are connected to a container are indicated graphically with a thick grey arrow.
container destinator	**the** *container destinator* **of** *container link* L46 **is** *container* sustainability competencies of the students	The [container link] instance "L46" points to the [container] instance "sustainability competencies of the students". Therefore, "L46" has a container destinator "sustainability competencies of the students".
container originator	**the** *container originator* **of** *container link* L46 **is** *container* financial resources at campus	The [container link] instance "L46" points away from [container] instance "financial resources at campus". Therefore, "L46" has a container originator "financial resources at campus".
impact destinator	**the** *impact destinator* **of** *link* L50 **is** *facet* increasing rate of believing faculty members.	Since CONTAINER LINK is a subtype of CAUSAL LINK, and CAUSAL LINK is a subtype of LINK, the implication is that L50 is an instance of [container link], but also an instance of [link].
impact originator	**the** impact originator **of** *link* L49 **is** *facet* applying appropriate teaching and learning strategies for sustainability education	Since CONTAINER LINK is a subtype of CAUSAL LINK, and CAUSAL LINK is a subtype of LINK, the implication is that L49 is an instance of [container link], but also an instance of [link].
link polarity	**the** *link polarity* **of** *link* L50 is positive	-
delay	**the** *delay* **of** *link* L50 **is** true	
linearity	**the** *linearity* **of** *link* L50 **is** true <not shown explicitly>.	As indicated by De Vries and Dietz [5], a link automatically implies a delay and no additional visual cues are required.
INFORMATION ACCESS LINK	*information access link* L18 **exists**	All [information link] instances, also "L18", are graphically indicated with a dotted arrow-line.

IDENTIFYING IMPROVEMENT STRATEGIES FOR THE DIESEL REBATE PROCESS IN SOUTH AFRICAN MINES

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ABSTRACT

Diesel is an influential variable that is strenuous on both the environment and mining operational expenses. The Customs and Excise Act provides a diesel rebate process to help reduce the tax burden incorporated into the diesel fuel price. One of the system’s primary prerequisites is the submission of complete, representative, and legally compliant logbooks. The logbook compilation process is executed in four stages: data collection, verification, traceability, and reporting; leading to a time intensive and multifaceted process. This paper analyses existing improvement strategies that can help alleviate the time intensity of the process. Various strategies were evaluated against each step in the diesel rebate process for applicability and relevance. Lean, Six Sigma, Time Studies, and the PDCA cycle were selected as the most applicable and pertinent strategies based on their demonstrated effectiveness in identifying process wastefulness and reducing process time - with potential time-saving benefits ranging from 1.81% to 60%.

Keywords: diesel rebate, time studies, lean, Six Sigma, PDCA, mining

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1 INTRODUCTION: DIESEL REBATES IN MINING

The South African economy is heavily dominated by mineral extraction and processing (mining), which by its nature is very energy intensive [1]. This energy-intensive economy relies on indigenous coal resources for electricity production and fossil fuels, namely diesel and natural gas [2], [3]. Electricity constitutes 58% of the overall energy resources allocated to the sector, followed by petroleum products and coal at 38% and 4%, respectively [4].

In underground mining, the predominant energy carrier is grid electricity serving not only production and ore transportation purposes, but also critical safety functions such as cooling, water pumping, personnel hoisting, and ventilation [5], [6]. Conversely, open-cast mining relies heavily on diesel as the primary energy carrier, which accounts for 46% of operational expenses, to power heavy-duty vehicles for ore loading and haulage [5], [6], [7], [8]. Although electricity is the main energy carrier in underground mining, it is still highly dependent on diesel to operate heavy-duty vehicles such as excavators, dump trucks, dozers, and graders [9].

Over the years, diesel prices in South Africa have increased and are expected to rise further. Diesel prices rose by 40% in 2021, 28% in 2022, and 8% in 2023 [10], [11]. With further anticipated rises in diesel prices, sectors reliant on diesel will be significantly affected specifically primary producers like the mining industry. Considering this, the South African government introduced a fuel incentive to alleviate the impact of diesel price variability [12]. This fuel incentive is referred to as a diesel rebate.

The diesel rebate scheme was introduced in 2001 and is governed by the Customs and Excise Act 91 of 1964 (‘The Act’), which authorises the refund of 40% of the general fuel levy and 100% of the Road Accident Fund levy [13]. The general fuel levy refund aims to encourage international competitiveness of on-land primary producers mainly farming, forestry, and mining, while the Road Accident Fund levy refund is intended to minimise the overall burden of fuel tax for certain non-road users [12], [13].

The Minister of Finance proposed the general fuel levy, Road Accident Fund levy, and the customs and excise levy remain unchanged for the fiscal year 2024/2025 [14]. Consequently, the diesel rebate levy for land-based primary producers remains at R3.66 per litre of eligible purchases [15]. To qualify for the diesel rebate, specific requirements as prescribed in Schedule 6 Part 3 of The Act are to be met [13], [16]. These are:

- Conduct eligible activities: eligible activities in mining are those conducted for primary production purposes.
- VAT registration: applicants are required to be registered for VAT.
- Record keeping: to demonstrate conformity, the claimant is expected to provide purchase invoices, sales invoices, and logbooks.
- Contractual agreement: should a contractor conduct eligible activities; the applicant must provide proof that the employed contractor does not purchase their diesel.

The diesel rebate system is based on the self-assessment principle and applicants must adhere to the abovementioned requirements [17]. One of the primary prerequisites of the diesel rebate system is the submission of complete, representative, and legally compliant logbooks [13]. Ngwaku *et al.* [18] conducted a study on improving logbook compliance. The authors utilised the data quality concept to alleviate issues that may lead to a non-compliant logbook. The steps to carry out the diesel rebate process were outlined in the study as follows: data collection, data verification, data reporting, and data traceability. Within the study context, these translate to data capturing, cross-reference verification, pump balances, running hours verification, logbook compilation, and internal auditing. Quantifying the total amount of eligible litres is challenging, time-consuming, and may lead to fallacious values. Such complexity is due to the sheer volume of data, the multitude of variables required, and the intricacies of the calculation procedures. Thus, yielding a multifaceted and time intensive process [18].

This study aims to determine potential strategies that can help alleviate time intensive aspects of the diesel rebate process. This will be achieved by examining existing quantitative and qualitative improvement strategies. These strategies will be evaluated against each other for applicability and suitability to each step of the diesel rebate process.

2 CURRENT DIESEL REBATE PROCESS

The diesel rebate process utilises the data quality concept [18], [19]. Consequently, the process is performed in four steps, namely (1) data collection, (2) verification, (3) traceability, and (4) reporting. An adapted overview of the diesel rebate process flow is illustrated in Figure 1 [18].

2.1 Data collection

Data is collected using a mobile application and handwritten manual logs. The mobile application allows for photos of the machine's engine running hours and the quantity of diesel the machine received to be captured. The data captured using the mobile application is added to a centralised database from which it can be extracted as an Excel file. The mobile application relies on the operator to manually input the data. As a precautionary measure, diesel operators additionally manually collect and handwrite all issues. The handwritten manual logs are later transcribed into Excel files by an administrator. The available data is then verified for accuracy and completeness.

2.2 Data verification

The data verification process is divided into three processes namely cross-reference verification, pump balances, and running hours verification. This ensures that all aspects of the data are verified and can be used.

2.2.1 Cross-reference verification

The proofreading technique ensures data accuracy by verifying the data in the mobile application's database against corresponding photos. This process is carried out daily, and any discrepancies found are updated in the mobile application. When photos are unavailable, handwritten manual logs are used to verify the entries.

2.2.2 Pump balances

Pump balances use the concept of mass balances to ensure data completeness [18], [20]. Data completeness is an important requirement for the diesel rebate process. This signifies that the amount of diesel that left the tank should equate to the sum of all the individual transactions that were received by equipment and machinery [18], [20].

To ensure completeness, the mobile application data is extracted from the database into an Excel spreadsheet and then cleaned to remove duplicates. Handwritten manual logs are added to account for missing entries and the data undergoes further cleaning to remove any duplicates from the added data. Pump balances are applied to the cleaned data, and any pump meter reading discrepancies missed during the first verification stage are corrected on the mobile application.

2.2.3 Running hours verification

Data is extracted from the database to incorporate updated information from the mobile application. Manual logs from pump balances are combined with the mobile application data. A data cleaning process is carried out to account for any delayed new data.

Thereafter, the Excel FILTER function is used to filter a range of data based on the vehicle registration criteria. This enables the analysis of individual vehicle engine running hours for any outliers. Ideally, engine running hours should be in ascending order. Instances of unusually high or low engine hours are reviewed and matched with the correct vehicle registration. Consequently, the vehicle registration details are corrected in both the Excel file and the mobile application, ensuring accurate data entry.

2.3 Data traceability

Record-keeping is one of the prescribed prerequisites as previously mentioned. This ensures easy accessibility and traceability in case of an audit, as the South African Revenue Service (SARS) requires specific records to support the compiled logbooks.

2.4 Data reporting

In this process, the logbook is compiled with the available data. Once completed, internal auditing is conducted on the logbooks.

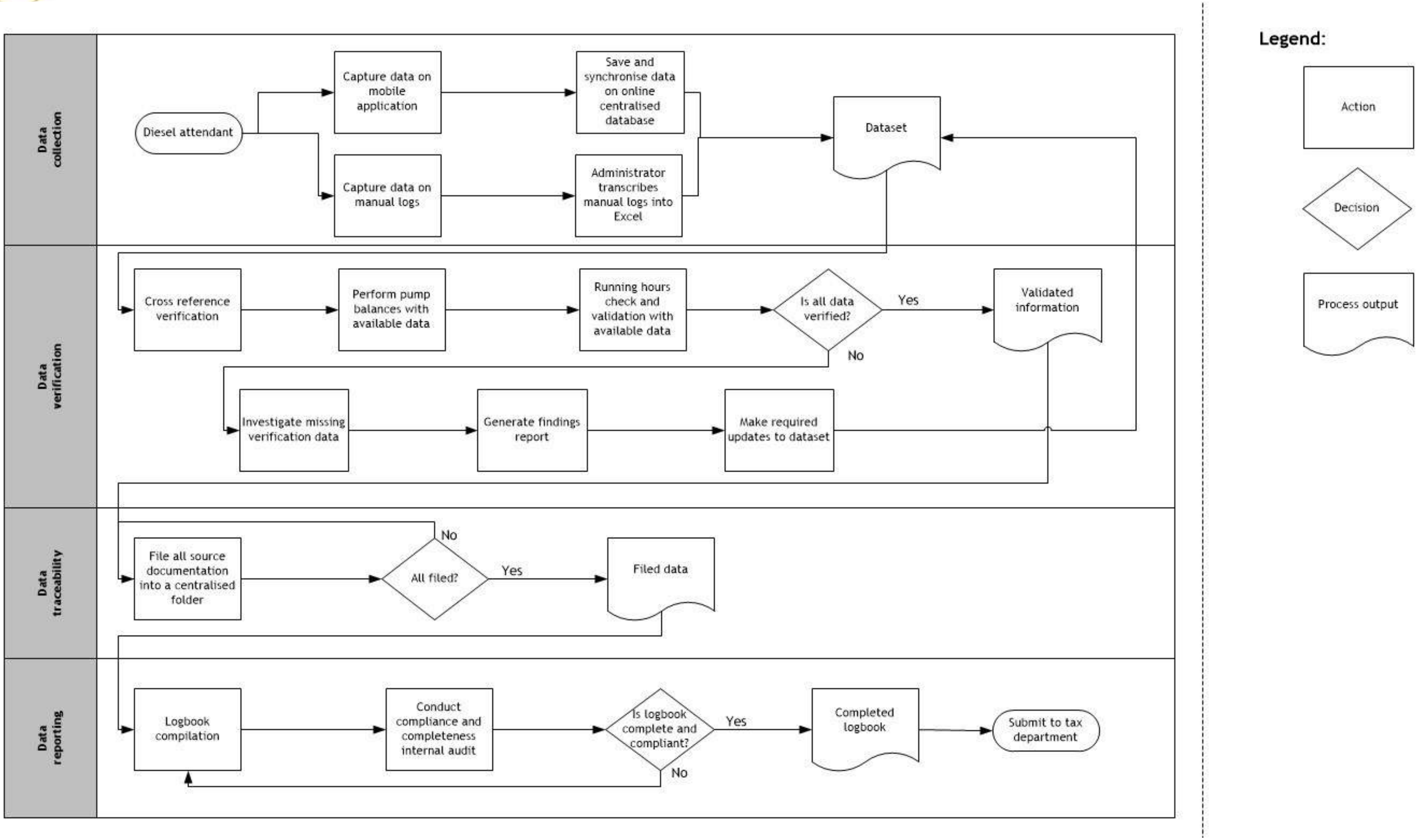

Figure 1: Diesel rebate process flow

3 METHODOLOGY

The previous sections identified and delineated the problem and need for the study. The study's methodology entails identifying, systematically searching and selecting relevant improvement strategies in the literature using established databases and criteria. The attained articles will undergo rigorous analysis to narrow down the research findings further and exclude articles beyond the research scope. Pertinent improvement strategies, that reduce process time, will be analysed, assessed, and compared against each step of the diesel rebate process for applicability and relevance. The most applicable improvement strategies will be outlined and recommended for each diesel rebate process step.

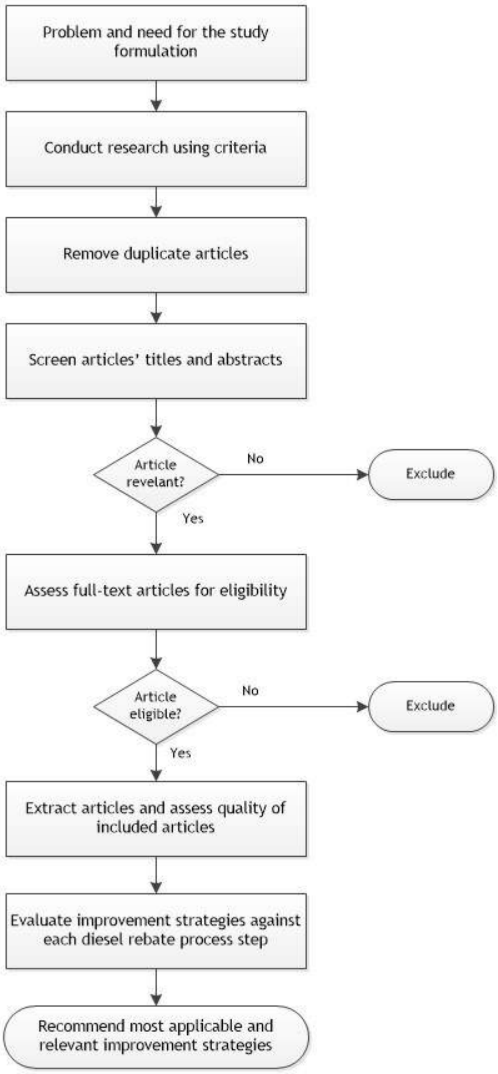

Figure 2: Research methodology

4 RESEARCH DESIGN: IDENTIFYING IMPROVEMENT STRATEGIES

Based primarily on the process outlined in Figure 1, it is evident that it has several steps that can add to the time intensive nature of the process. Thus, there is a need to improve it using existing process improvement strategies. The study will investigate potential improvement strategies that can help alleviate the process' time intensity. The improvement strategies will be explored and assessed against each other for relevance to each diesel rebate process step. The most suitable strategies will be selected for each step.

To achieve the study's aim, various electronic databases were utilised to sample improvement strategies namely, Google Scholar, Elsevier, ResearchGate, Science Direct, Scopus, IEEE Xplore, and other publications. In the initial stage, keywords such as “process improvement methodologies” OR “process improvement strategies” OR “process improvement” were used to find relevant strategies that can be used to improve processes. The search criteria were limited to articles between the years 2019 to 2024, the literature search was limited to English publications, which yielded 7320 results. The most common theme was the application of the following strategies: lean, Six Sigma, lean Six Sigma, PDCA cycle, Total Quality Management, Agile, and Kaizen.

To narrow down the research findings, the keywords “process time reduction” OR “cycle time reduction” OR “reduce process time” OR “reduce cycle time” were added to the search for relevant publications and this yielded 103 results. During the screening stage, the titles, and abstracts of the 103 papers were further analysed. Abstracts that appeared to be outside the review's scope due to vagueness, lack of detail, and duplication were excluded. This led to a further reduction in the number of papers to 54, with some of the articles sourced from relevant publications’ references.

These papers were identified as being suitable for the study and an analysis was conducted on them, where the following improvement strategies were prevalent: lean, Six Sigma, PDCA cycle, and time studies. The selected strategies will be evaluated against each other within the diesel rebate process steps context. Following evaluation, strategies applicable to a particular diesel rebate step will be delineated and recommended.

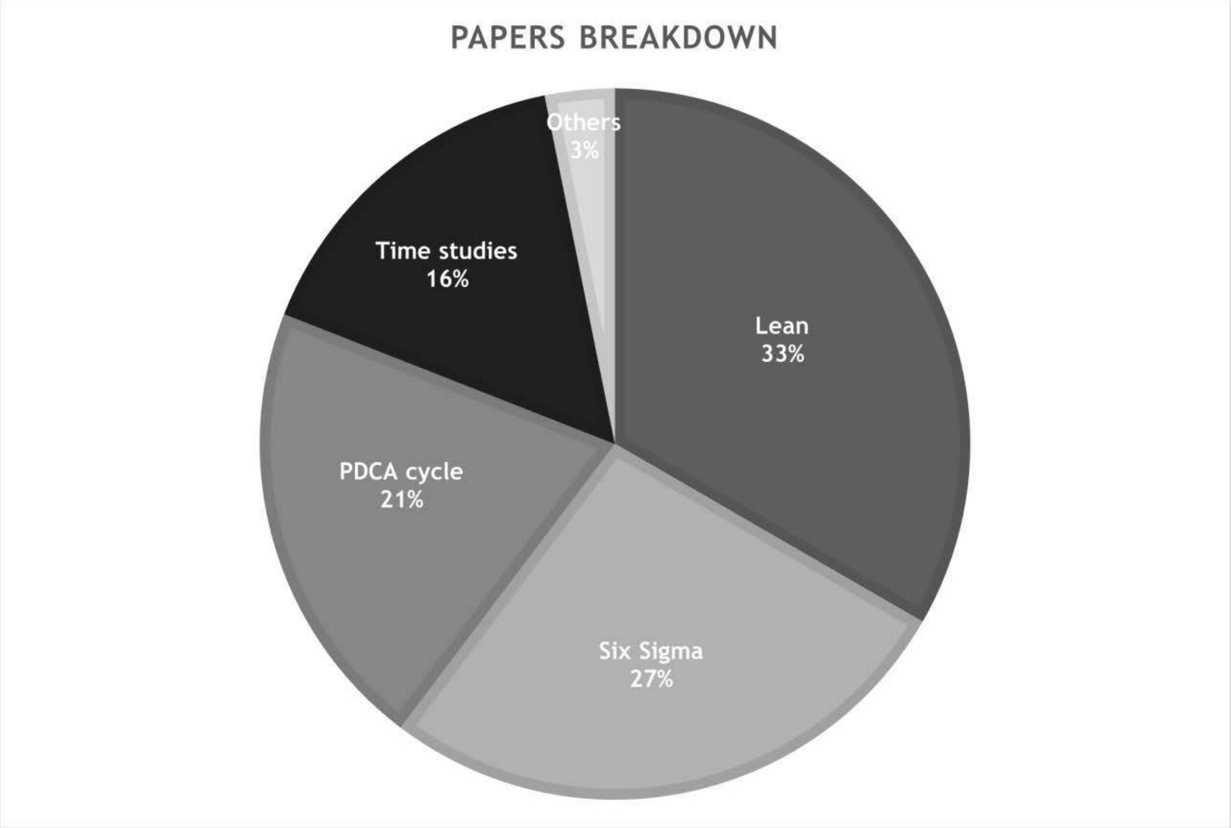

Figure 3: Breakdown of improvement strategies papers

5 IDENTIFIED IMPROVEMENT STRATEGIES FOR DIESEL REBATE PROCESSES

5.1 Lean

The concept of lean focuses on waste elimination and value creation [21], [22], [23]. Lean encourages supplying what is needed, when needed and in the quantity required; and any excess inventory is eliminated from the process [24]. Within the context of lean, waste is anything that does not add value to the product from the customer's perspective [25].

Womack *et al*. [26] delineated the application of lean through five principles grounded on the assumption that all organisations comprise processes. The principles outline that an organisation must ascertain the customer's perception of value before implementing lean principles. This involves identifying customer value, eliminating waste, creating a smooth customer flow, instituting pull systems, and striving for continuous improvement.

Nahmias [27] and Monden [28] identified some of the most common lean tools. These tools mainly focus on standardising work processes and the organisation of workplaces. Such tools are kanban, just-in-time, setup time reduction, total quality maintenance, and 5S. Value Stream Mapping was identified as another important lean tool by Rother and Shook [29]. Value Stream is utilised to analyse, design, and manage the flow of information and materials from raw materials to the customer. It helps identify and eliminate waste in the value stream [29].

Ohno [30] identified and defined seven wastes that can occur in a value stream: waiting, overproduction, overprocessing, inventory, defects, transportation, and motion. Researchers have employed their knowledge of these seven wastes to help eliminate wastefulness in processes and improve process efficiency. Johnson *et al.* [22] implemented lean methods in a radiology operation. A value stream diagram was used to illustrate employee movements in the work area and readily showed workflow inefficiencies. Pareto analysis and fishbone diagram were subsequently applied to find the root causes. Following analysis and workflow redesigning, the waste of motion was eliminated which essentially reduced the amount of walking and time to perform patient imaging.

Saleeshya *et al.* [31] employed lean practices in a machinery manufacturing industry with part shortages because of delays in the process. Such delays were due to quality rejections, machine downtime, and rework. The scholars used lean tools to identify and eliminate wastefulness that led to delays and reduced the flow time by 82%.

Upadhye *et al.* [32] examined challenges experienced in various enterprises and demonstrated how lean can be implemented to illuminate wastefulness in processes and improve efficiency and effectiveness. Lean tools such as kaizen, just-in-time, value stream mapping, and 5S were used to identify and eliminate wastes which improved the cycle time by 15%. Similar lean methods including poka-yoke, kanban, and visual controls were applied in the textile industry and yielded results of increased machine efficiency [33].

Sahoo *et al.* [34] utilised Lean's value stream mapping to identify waste in radical forging production flow lines. Present and future value stream maps were constructed to pinpoint and eliminate waste sources and improve the production process. The setup time and the work-in-process were reduced. Value stream mapping together with kaizen and single-minute exchange of die was also implemented to improve the productivity of the air conditioning coil manufacturing company [35]. The productivity increased by 77% while the setup time reduced by 67%.

5.2 Time Studies

Generally, time study is a work measurement technique used to quantify/gauge the time it takes to perform a specific task [36]. According to Harrison *et al.* [37], implementing time studies to processes has significant benefits; with one of the main advantages being productivity improvement through the identification and elimination of non-value-added activities in a process.

Several time study techniques can be used to measure work, namely: the stopwatch technique, work sampling, predetermined motion time standards, and analytical estimating [38]. The stopwatch technique and work sampling are based solely on direct and continuous observation of a task while the rest of the techniques are data and analytical-focused [38]. The technique's applicability is dependent on whether the task is repetitive or nonrepetitive.

The stopwatch technique also referred to as time study, is widely implemented for short, repetitive, direct tasks. Conversely, work sampling applies to long-cycled heterogenous operations that require multiple observations [38]. Synthetic data technique is performed on shot-cycled repetitive tasks while analytical estimation is done on nonrepetitive tasks [38]. The predetermined motion time standards technique is executed for manual operations confined to one work centre [38].

Puvanasvaran *et al.* [39] implemented the stopwatch time study technique to improve the Overall Equipment Efficiency (OEE) of the autoclave process in the aerospace industry and verify the current OEE standard. Maynard's Operation Sequencing Technique time study revealed non-value-added activities, which were eliminated increasing the OEE percentage by 4.62%. Yusoff *et al.* [40] used time study techniques to establish a benchmark time to produce car seats. The stopwatch technique effectively quantified actual working time, with working times of 13.42 minutes and 14.09 minutes per cycle for 100% and 95% production efficiency, respectively. Al-Saleh [41] investigated how time study techniques can be used to reduce inspection time which increased throughput by 174.8%.

Systematic observation, workflow process and stopwatch time study were exploited to improve the productivity of a small-scale industry [42]. The work in process was improved through the elimination of waste which reduced the manufacturing time of one stay vane from 28:15:5 to 26:00:57. [43] developed and applied a time study model to assist in achieving production targets. To monitor the production line in a bearing manufacturing company, Patel [44] employed the stopwatch time study technique. The method helped identify and eliminate wastefulness, reducing cycle time and increasing productivity. Vidyut *et al.* [45] integrated modern soft skills with work-study techniques i.e., method study and time study to improve productivity. Work sampling was utilised to identify and remove waste in the process, improving the process time by 15%.

5.3 PDCA cycle

The PDCA cycle, also called the Deming cycle, is a total quality management control system to facilitate continuous improvement [46]. It is usually applied in the manufacturing industry to remove waste such as waiting time, idle, failure, and defects [46]. The cycle is defined by four steps namely Plan, Do, Check, and Action [46], [47]. In the *Plan* phase, improvement opportunities are identified and prioritised. The process' current state is outlined and analysed to determine the root causes of the identified problem and possible solutions [48]. The developed action plan is implemented during the *Do* phase and the results are examined in the *Check* phase to ensure the established objectives were achieved [49]. The achieved results are standardised during the *Action* phase [50].

Jagusiak-Kocik [50] asserted the versatility of the PDCA cycle and its successful application in different sectors. Ab Rahim *et al.* [51] exemplified the use of the PDCA cycle in the automotive industry to minimise operational expenditure and lead time. The most common defects were pinpointed, and several work processes were shortened leading to a 42% decrease in direct man-hours. In a comparative study conducted by Nabiilah [52], the application of the PDCA cycle reduced the sanding man-hour by 34%.

Although the PDCA cycle is typically implemented in manufacturing to minimise defects and errors [53], literature has proven its applicability across other industries as well. Júnior *et al.* [54], for example, deployed the methodology to analyse and solve the problem of excessive sauce losses during frozen meal production leading to an 86.75% reduction in sauce losses. Jagusiak-Kocik [50] practically applied the PDCA cycle to solve prominent quality problems during photo frame production, reducing nonconforming material by over 60%.

Literature has demonstrated that the PDCA cycle can be utilised to increase the process capability index which in turn improves the process efficiency and effectiveness. Kholif *et al.* [55] showcased a reduction in the number of contaminated UHT milk samples after capability index improvement through the PDCA cycle implementation. The capability index was increased by 0.55. A comparative study used statistical process control through the PDCA cycle to improve the capability index for aluminium beverage cans that did not meet customer specifications [56]. The study resulted in a significant improvement for the company by raising the process capability index from 0.48 to 1.79, meeting the required specification of at least 1.33.

In literature, the PDCA cycle is widely acknowledged as a potent tool for quality control and continuous improvement [57]; however, the methodology also serves as a foundation for incorporating other strategies like Lean and Six Sigma. To substantiate this assertion, Realyvásquez, *et al.* [48] integrated the PDCA cycle with quality control tools like Pareto analysis and flowcharts to reduce defects in a manufacturing process by at least 20%. Comparably, [56] used the Ishikawa diagram, 5WH1H method, and nominal techniques to improve beverage cans packaging. Garza-Reyes *et al.* [58] proposed a method for systematically conducting Environmental-Value Stream Mapping studies utilising the PDCA cycle which improved the green performance of operations. Likewise, Nguyen *et al.* [59] incorporated 5Whys, Ishikawa diagram, 5W2H, Computer-Aided Design, and prototypes with the PDCA cycle to produce user-friendly packaging designs.

5.4 Six Sigma

A considerable amount of literature has been published on Six Sigma and various researchers have similarly defined the concept. In essence, Six Sigma is a statistical approach that aims to improve the efficiency of processes through defect reduction [60], [61]. The approach strives for perfection by attaining a quality level of 99.99996% [62]. This can be accomplished by employing Six Sigma's sub-methodologies namely DMAIC and DMADV [62]. The DMAIC methodology (Define, Measure, Analyse, Improve, Control) seeks incremental improvements of existing processes; conversely, the DMADV methodology (Define, Measure, Analyse, Design, Verify) is utilised during the development of new processes or products [62].

Six Sigma adoption has expanded beyond manufacturing [63], [64]. The DMAIC methodology was implemented to reduce defective units in the single-pin insertion process [65]. The methodology was coupled with quality tools such as cause-and-effect diagrams, flowcharts, and control charts. The results were significant product quality improvements. Likewise, a tire manufacturing company adopted the DMAIC methodology and decreased nonconforming material by 0.89% [66].

A company in the automotive industry applied the Six Sigma methodology to enhance its organisational innovation processes [67]. The DMAIC technique was implemented and led to work productivity, efficiency, and effectiveness improvements of 89%, 50%, and 50% respectively. [68] used the DMAIC methodology to investigate the root causes of rubber glove defects and provide solutions to eliminate them, resulting in a 50% reduction in defects.

Lemke *et al.* [69] highlighted the use of Six Sigma to aid in assessing the level of customer satisfaction. Several studies in the literature have supported this claim; Pereira *et al.* [70], for example, applied Six Sigma to analyse customer satisfaction at the product design and development stage. Customer satisfaction key performance indicator was analysed to ensure optimum results were achieved. The DMADV was used to obtain desired quality control and time-to-market results. Lemke *et al.* [69] applied DMAIC to improve efficiency and customer satisfaction in urban logistics.

Similar to the PDCA cycle, Six Sigma can be integrated with complementary strategies like Lean [71]. When Lean and Six Sigma are coupled together, they form what is known as Lean Six Sigma. Lean Six Sigma as defined by Jirasukprasert *et al.* [68] is a collaborative approach to improve performance through waste elimination. Extensive research has been undertaken on the Lean Six Sigma concept and numerous researchers have implemented this methodology to eliminate waste and reduce process times [72], [73], [74].

6 ANALYSIS OF THE STRATEGIES AND RELATION TO THE DIESEL REBATE PROCESS

6.1 Data collection

Data collection is executed through automatic and manual means.

Table 1: Evaluation of the improvement strategies in comparison to data collection.

Data collection	Time study	Lean	PDCA cycle	Six Sigma
Positives for step	The time to collect data using dual data collection techniques can be quantified. Inefficiencies in the redundant data collection techniques can be highlighted. Eliminating one data collection method will aid in standardising the process to ensure consistency and quality in the captured data. Pizziferri *et al.* [75] eliminated one data collection method, leading to a 1.81%-time reduction.	Implementing lean can reduce the time required to capture data. The waste of task duplication, such as using multiple data collection methods, can be eliminated. This can be achieved by utilising the mobile application thereby eliminating duplication of data capture methods. Lean reduced the cycle time by 41% in outpatient blood collection [76].	The PDCA cycle will ensure continuous improvement and incremental adjustment of the process step based on results and acquired personnel feedback.	Inefficiencies in the process step can be identified using Six Sigma's DMAIC. This methodology will allow the problem to be quantified and analysed for root causes. After which applicable tools will be applied to solve the root causes. Six Sigma integrated with Lean improved process time by 1.81% [77].
Negatives for step	Human factors such as fatigue, interruptions, and personal breaks affect performance; thus, the time study may not	Personnel may resist change introduced through lean application. Personnel will require training on how to utilise	Implementation of the cycle on the step will be time and resource-intensive due to its iterative nature.	Personnel may resist change introduced through Six Sigma implementation. The implementation process will be time-consuming.

Data collection	Time study	Lean	PDCA cycle	Six Sigma
	accurately represent the process step.	the mobile application correctly and consistently.		
Applicability to step	Applicable	Applicable	Not Applicable	Applicable

Capturing the same data on two platforms increases duplication and tedium. A time study will be conducted to quantify the amount of time it takes to complete the step. Implementation of Lean and Six Sigma will aid in the reduction and elimination of waste such as duplication of the data collection methods. According to prior research, it is expected that the use of time study, lean, and Six Sigma techniques will result in time reductions of between 1.81% to 41%.

6.2 Data verification

Data verification is carried out in three steps namely cross-reference verification, pump balances, and running hours verification.

Table 2: Evaluation of the improvement strategies in comparison to data verification.

Data verification	Time study	Lean	PDCA cycle	Six Sigma
Positives for step	The overall time required can be measured and where most of the time is allocated can be illuminated. Additionally, duplication of tasks will be highlighted through time study.	Wastefulness such as task duplication can be pinpointed and resolved. Tasks duplicated during data verification include manual transcription of handwritten manual logs into Excel, data cleaning, and downloading mobile application data. A verification process time through lean implementation improved by 60% [78].	The cycle can be implemented in collaboration with Lean to prioritise, identify and highlight deficiencies such as the time taken to move from one verification step to the next. The PDCA cycle helped to reduce errors and failures in the product verification process, making it more efficient [79].	The current verification process performance can be measured, and the root causes of prolonged time can be identified. The identified root causes will be eliminated, and this will ensure a more standardised and structured approach which will increase efficiency, accuracy, and reliability. DMAIC coupled with lean reduced the verification process time by 60% [78].
Negatives for step	The step encompasses three sub-steps and conducting a time study for	Eliminating some process steps will change the overall verification	The iterative cycle is resource and time intensive and may	It might take time for personnel to adjust to the new enhanced process.

Data verification	Time study	Lean	PDCA cycle	Six Sigma
	each subtask will be time-consuming.	process and personnel will need to adjust to the new improved process.	result in change resistance.	
Applicability to step	Applicable	Applicable	Applicable	Applicable

This process step has a significant number of duplicated tasks, intensifying the timeliness of the process. Such duplicated tasks include transcription of handwritten logs into Excel, data cleaning, and redownloading mobile applications data in all the verification steps. Conducting a time study will quantify these durations, and the most time-consuming steps can be prominent. By integrating Lean principles with the PDCA cycle, wastefulness can be illuminated. Employing the Six Sigma methodology will highlight the root causes of waste and propose measures to eliminate wastefulness. Drawing from earlier research, it is expected that the adoption of lean and Six Sigma techniques could result in a 60% reduction in time, whereas the implementation of the PDCA cycle will enhance the efficiency of the verification process.

6.3 Data traceability

Record-keeping is one of the main requirements of the diesel rebate process. The required records include purchase invoices, diesel logbooks, handwritten manual logs, and all available source documentation. Storing supporting documentation in their respective folders takes minimal time and does not require improvement. However, this process step will impact the inverse process during a SARS audit. Whereas, if the information was not sufficiently stored, the process of gathering information would be very timeously. It is thus important to ensure that all information is stored during the execution of the process.

6.4 Data reporting

This step encompasses logbook compilation and internal auditing.

Table 3: Evaluation of the improvement strategies in comparison to data reporting.

Data reporting	Time study	Lean	PDCA cycle	Six Sigma
Positives for step	Performing a time study will aid in the identification of bottlenecks in the process of logbook compilation and internal auditing. The time to complete these tasks will be quantified and tasks causing	Duplicative tasks such as copying and pasting manual logs to account for missing entries on the mobile application, will be eliminated for a smoother process flow. The number of internal reaudits will significantly decrease. Lean	Repetitive tasks can be pinpointed using this reiterative cycle. The tasks can be streamlined and improved by removing bottlenecks allowing for a smooth process flow.	Possible defects and variations in the step can be identified and eliminated. Such variations may include inconsistencies and missing source data information. Elimination of such variations will reduce the timeliness of the

Data reporting	Time study	Lean	PDCA cycle	Six Sigma
	delays can be pinpointed.	reduced same-day cytology reporting time by 43.90% [80].		process. Six Sigma reduced financial reporting process time by 50% [81].
Negatives for step	Individual work styles and fatigue factors may not be considered, and important performance contributors like motivation might be overlooked.	Employees may have a hard time adjusting and embracing the new process.	The PDCA cycle is an iterative process that needs to be repeated multiple times to achieve the desired results.	Employees may have a hard time adjusting and embracing the new process.
Applicability to step	Applicable	Applicable	Not Applicable	Applicable

Eliminating duplicative tasks such as reauditing due to inconsistency, missing information, and transcription of handwritten logs into Excel to account for missing data in this step will improve workflow efficiency. Performing a time study will assist in pinpointing where most of the time is spent in this process. Implementing Lean and Six Sigma methodologies will aid in highlighting and addressing bottlenecks, ultimately reducing both monotony and process time. In a comparable scenario from past studies, lean implementation is anticipated to lead to a time reduction of 43.9%, while Six Sigma is expected to result in a 50% decrease.

7 DISCUSSION

The table below summarises the results obtained from section 5.

Table 4: Recommended improvement strategies.

Diesel rebate step	Recommended improvement strategies
Data collection	Time study, lean, Six Sigma
Data verification	Time study, lean, PDCA cycle, Six Sigma
Data traceability	None
Data reporting	Time study, lean, Six Sigma

Time study will likely apply to data collection, verification, and reporting. This is mainly because these process steps encompass multiple quantifiable subtasks, unlike data traceability, which entails securely storing the required supporting documentation. This process is often indirect and intermittent and occurs sporadically throughout the workflow. Data traceability takes minimal time and doesn’t require improvement although important for the SARS audit.

Implementation of Lean and Six Sigma in data collection, verification, and reporting will aid in the identification of waste, and variations in the process steps. Non-value-added activities, such as task duplication, can be identified and eliminated. However, some non-value-added activities, like data cleaning, will not be eliminated from the process as they are necessary to ensure data quality. Six Sigma will illuminate the root causes of the delays in each of the process steps, enabling appropriate measures to be taken to prevent the recurrence of such delays. The PDCA cycle is particularly relevant to data verification due to its iterative nature and significance in ensuring high accuracy, completeness, consistency, and quality of data. Implementing the PDCA cycle to the data verification step will facilitate continuous improvement of the data quality assurance process and cultivate confidence in data reliability and integrity.

8 CONCLUSION

The South African mining industry uses a significant amount of diesel. With diesel prices constantly rising, a financial strain is placed on diesel-reliant sectors including the mining sector. For this reason, the South African government introduced a diesel rebate process to lessen the tax burden incorporated into the fuel prices. A diesel rebate process prerequisite is submitting complete, representative, and legally compliant logbooks. However, compiling the logbooks is time intensive. To address this, the study investigated potential qualitative and quantitative strategies that can help reduce the time intensity of the process.

The improvement strategies analysed in the study include lean management, the PDCA cycle, time studies, and Six Sigma. These strategies were examined against the four diesel rebate steps namely data collection, verification, traceability, and reporting. Time study, lean, and Six Sigma are applicable in data collection, verification, and reporting; with potential combined time savings varying between 1.81% to 60%.

These strategies aim to identify and eliminate non-value-added activities and the root causes of the process' timeliness. However, the PDCA cycle is suitable for data verification due to its iterative nature. The PDCA cycle will ensure continuous improvement in the data quality assurance process for data reliability and integrity. Data traceability does not directly benefit from these methodologies as it is an indirect and intermittent process that takes minimal time. These strategies can now be implemented on the respective steps and alleviate the overall time burden of the process while maintaining high-quality outputs.

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ARTIFICIAL INTELLIGENCE INTEGRATION IN SYSTEMS ENGINEERING: NAVIGATING OPPORTUNITIES AND RISKS ACROSS THE SYSTEM LIFECYCLE

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ABSTRACT

The pervasive integration of publicly accessible Large Language Models (LLMs), epitomised by tools such as ChatGPT, has underscored the profound implications of Artificial Intelligence (AI) across diverse domains. In Systems Engineering (SE), activities such as requirements elicitation and functional analysis intricately hinge on language-based processes. The deployment of AI in this context presents a nuanced interplay of opportunities and inherent risks. This paper investigates the potentialities of leveraging AI tools within the SE framework throughout the system lifecycle. Through meticulous adherence to established guidelines and the strategic utilisation of available tools, the exploration posits the feasibility of augmenting the quality of outputs while concurrently improving efficiency within the overarching SE process. This is a scoping study to identify the current state of integration of AI in SE. Issues such as bias, data privacy, and ethics are key to this area, and risks may negatively affect successful implementation. This research proposes a systemigram conceptual framework that details the steps for incorporating AI technologies into SE.

Keywords: Systems Engineering, Artificial Intelligence, Large Language Models, Requirements Elicitation.

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1 INTRODUCTION

This is a scoping study to establish the current state of the art regarding using Artificial Intelligence for Systems Engineering (AI4SE). There is a separate field of applying Systems Engineering to AI systems (SE4AI). This study only considers AI4SE. AI has been used widely as a technical solution, with many applications such as self-driving cars, chatbots, etc. This aspect of AI is not included in this study. This study intends to determine what has been done in AI4SE from published academic literature. How can AI be used to assist in the application of System Engineering?

The research methodology in this paper follows a pragmatic constructivist approach to emphasise practical solutions and the application of Artificial Intelligence (AI) tools to real-world Systems Engineering (SE) problems [1]. Constructivism focuses on how people construct meaning through their experiences and interactions, which can be relevant for understanding how SE professionals and stakeholders perceive and utilise AI tools. Constructivism holds that reality is subjective and constructed through social processes and interactions. This approach can help explore the diverse perspectives of SE professionals on AI's role and impact [2].

A comprehensive scoping literature review is conducted to identify the current challenges in SE and the potential opportunities and associated risks presented by AI technologies. The study utilises existing literature, case studies, and documented examples of AI applications in SE to gather relevant data. The research method implemented in this paper was more informal and flexible than the guidelines provided in the PRISMA-SCR framework [3] due to the limited research available on the topic. Therefore, this paper implements a snowballing approach. The snowballing approach is helpful in research fields with emerging literature or scattered examples across various disciplines, making it challenging to develop a comprehensive list of search terms. It is an effective method for uncovering relevant studies that may not be indexed or easily accessible through conventional database searches [4].

First, a small set of relevant key papers was identified as a starting point for further exploration. An iterative backward and forward snowballing process examined references cited by these papers to identify prior and subsequent relevant works. Papers were selected based on their relevance to the context of AI implementation in systems engineering, considering factors such as the scope of AI applications discussed, the challenges and solutions proposed, and the particular focus on systems engineering methodologies [4]. The analysis used a narrative approach to capture the opportunities and risks for implementing AI in SE in a conceptual framework. The extracted information was synthesised using systems thinking to map the drivers and their interactions into a Systemigram. This framework outlines the steps for integrating AI technologies, addressing key challenges, and leveraging AI capabilities to enhance SE practices.

2 BACKGROUND

2.1 Systems Engineering

SE is defined as a multidisciplinary approach that aims to enable the successful realisation of complex systems. It integrates various engineering disciplines and specialities into a structured development process from concept to production to operation. SE focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and proceeding with design synthesis and system validation while considering the complete problem [5].

SE has become a well-established discipline. It has been demonstrated as a useful set of interdisciplinary methodologies that provide systematic guidance for developing systems and addressing problems in various industries, including aerospace, automotive, defence, healthcare, energy, and manufacturing. SE focuses on designing, integrating, and managing systems throughout their life cycles. These methods aim to improve efficiency, quality, and performance while reducing costs and risks. Another vital role of SE is managing modern systems' complexity. Some of the SE elements include the following [6]:

- Requirements Engineering to identify and document customer needs and system requirements.
- System Design that creates a system architecture and design specifications.
- Integration and Testing of combined components to ensure they work as intended in the system.
- Validation and Verification of the system to confirm that it meets the specified requirements and works as expected.

2.2 Increased Complexity

However, there is an ever-increasing level of complexity and pressing problems [7]. This places new demands on the Systems Engineer to apply the methodologies. As technologies develop, there are opportunities to harness these within the SE context for more efficiency. Systems Engineers need to understand the context and stakeholders and develop requirements that represent the problem that must be addressed. As the world becomes more interconnected, achieving this level of understanding is becoming near impossible as the amount of information and data available grows exponentially [5], [8].

2.3 Potential technologies and solutions looking for a problem to address

In strict SE practice, we first frame the requirements prior to looking for solutions. At times, new technologies and solutions become available that may solve problems that have not been specifically identified. Many new ideologies, technologies, and approaches are being advocated to address the difficulty of SE in handling complex problems and systems. Many are clamouring for our attention. Vendors advertise various tools and techniques that will solve our problems. Navigating the minefield of potential benefits is in itself a challenge. One such technology is AI. There is much hype about how AI is one of the critical aspects powering the current Fourth Industrial Revolution (4IR). AI is an extensive category with many methods and application areas. Especially in the last decade, many accessible AI-based tools and methodologies have become available to Systems Engineers [9].

2.4 Artificial Intelligence

AI is a branch of computer science focused on creating systems capable of performing tasks that typically require human intelligence, such as learning, reasoning, problem-solving, perception, and language understanding. Over recent years, AI has seen significant advancements and has been increasingly integrated into various domains, including healthcare, finance, transportation, and education. In healthcare, AI aids in diagnostics and personalised treatment plans; in finance, it enhances fraud detection and algorithmic trading. Autonomous vehicles and smart cities benefit from AI-driven technologies, improving safety and efficiency. The education sector employs AI for personalised learning experiences, making education more accessible and effective. This growing integration is transforming industries, driving innovation, and reshaping the future of human-computer interaction [10]. How can AI be used in the SE process itself, and not only in the technical solution of a system?

The launch of ChatGPT has dramatically increased the awareness of the potential of using Large Language Models (LLM). There has been a proliferation of using ChatGPT and other similar LLMs in the areas of assistance in formulating written content by prompting the LLM to provide the information and the writing style required. Within the standard systems engineering process, some sections require significant language usage. Eliciting, documenting and validating requirements from a potential user is one such area.

This paper investigates the integration of AI into SE, as it seems essential for managing the increasing complexity of modern systems, enhancing decision-making, and enabling predictive maintenance. AI automates repetitive tasks, improves efficiency, and fosters innovation by enabling adaptive, resilient systems that respond to real-time changes. This leads to significant cost reductions, optimised resource allocation, and improved user experiences. AI-driven systems provide a competitive advantage by offering new capabilities and functionalities, making them indispensable in today's technological landscape [11].

3 RECENT TRENDS AND CHALLENGES FACING SYSTEM ENGINEERING

As the introduction mentions, SE is an interdisciplinary field that designs, integrates, and manages complex systems over their life cycles [5]. The key processes in SE can be broadly categorised into the following stages [5], [12]:

- <u>Requirements Analysis</u>. This process identifies and documents the stakeholder needs and constraints. The activities to achieve this include analysing stakeholder needs to develop refined requirements, defining system requirements, and establishing performance parameters.
- <u>System Design</u>. The output of this process is an architecture that meets the requirements. Typical activities include developing a system architecture, defining subsystems, and creating detailed design specifications.
- <u>Implementation</u>. According to the design specifications, the system is now implemented into physical or software components.
- <u>Integration</u>. The implemented system elements are now combined into subsystems and a complete system.
- <u>Verification and Validation (V&V)</u>. Testing is performed at various stages to ensure the system meets requirements and performs as intended. Typical activities include testing, simulation, and formal reviews.
- <u>Deployment</u>. Deliver the system to the end-users through installation, user training, and initial operation.
- <u>Operations and Maintenance</u>. In this phase, SE ensures the system continues functioning over its intended lifespan through routine maintenance, updates, and troubleshooting.
- <u>Disposal</u>. Finally, SE assists in safely decommissioning the system at the end of its lifecycle.

However, executing these processes occurs in the real world, which is increasingly complex. This is called VUCA, the acronym for volatility, uncertainty, complexity, and ambiguity. Although the concept originated in the early 1990s in the United States military, it was adopted by the business community and management consultants to describe the chaotic and rapidly changing business environment in the 2000s [13], [14]. Nowadays, it is a widely recognised framework for understanding and navigating the complex and unpredictable nature of the modern world. As discussed in the sections below, SE faces difficulties or limitations in delivering effective solution systems within this environment.

3.1 Requirements Engineering

Good quality requirements are a cornerstone of sound SE. Each requirement set must be complete, consistent, feasible, comprehensible, and validatable [15]. Requirements are developed by humans and subjectively reviewed by humans. When written in an unconstrained natural language, objectively assessing that a written requirement is complete is impossible. Natural language is by far the dominant choice for framing requirements [16]. A high portion of system development cost is often budgeted for requirements capturing and analysis. However, cost overruns of large system development have often identified poor requirements as one of the significant contributors. This is applicable across all implementation domains [17].

The acquirers of systems and suppliers of systems must fully understand user requirements. This covers many perspectives, from end users, funders, marketers, suppliers, development engineers, integrators, verifiers and others. System stakeholders are from multiple countries with different language preferences, cultures, and backgrounds. Providing clear, consistent requirements that are entirely understandable by all stakeholders is complex. Stakeholder requirements often evolve during the system development lifecycle, necessitating continuous updates and adjustments. This volatility can lead to scope creep and resource allocation issues [18].

3.2 System Complexity Management

Modern systems are becoming increasingly complex, involving numerous interconnected components and stakeholders. This places increasing demands on the SE effort required to manage such complexity. Systems engineering is a discipline that provides the structure, processes and principles to manage complexity, which can be complex in itself. Managing this complexity while ensuring all elements function cohesively is a significant challenge. Therefore, effective SE requires collaboration across various disciplines with its terminologies and methodologies. Ensuring smooth communication and coordination among diverse teams can also be difficult [19], [20], [21].

Another confounding factor is the integration of legacy systems. Even during digital transformation, many organisations still rely on legacy systems that must be integrated with new technologies. Ensuring compatibility and functionality across old and new systems presents many technical and operational challenges [22].

3.3 Project Complexity Management

Managing the complexity in system development projects, from an SE in support of a project management perspective, is also increasing due to rapid technological changes, resource constraints, regulatory and compliance issues, and sustainability demands. The fast pace of technology development may render existing systems obsolete quickly. Integrating new technologies into existing systems to keep up with these changes is challenging. Also, limited budgets and constraints on time and human resources hamper project execution and the SE process. Achieving system development's required quality and completeness is now more difficult. Systems must comply with various industry standards, regulations, and legal requirements. Navigating these regulations can be complex and time-consuming. Modern systems need to be designed with sustainability in mind, considering environmental impact, energy efficiency, and long-term viability [23], [24], [25].

3.4 Risk Management

Identifying, assessing, and mitigating risks in complex systems is crucial but challenging. Unforeseen risks can have significant impacts on project timelines and costs.

4 THE NEED FOR ARTIFICIAL INTELLIGENCE IN SYSTEMS ENGINEERING

As seen in the discussion above, navigating the complexities of the modern and integrated world is one of the main concerns for SE. The INCOSE Vision 2035 document highlights several aspects related to the use of AI technologies in SE [26]:

- Enhancing SE Processes. AI technologies can automate routine tasks for more efficient and accurate analysis and improve decision-making. Model-Based Systems Engineering (MBSE) may benefit from AI-generated models, optimised designs and automated assessments to detect inconsistencies.

- Data-Driven Decision Making. Big data analytics with Machine Learning (ML) can process large volumes of data to extract meaningful insights. It may enhance system performance monitoring, system diagnostics, and predictive maintenance.
- Human-AI Collaboration. AI-based tools will provide systems engineers with advanced tools for problem-solving, scenario analysis, and risk assessment, enhancing their ability to make informed decisions.

The future of SE is envisioned as one that fully utilises aspects such as agile methods, MBSE, Product Line Engineering (PLE), Digital Engineering (DE), AI, Internet of Things (IoT), cloud computing and Blockchain, all of which can provide powerful capabilities to assist in many areas that are currently inefficient or error-prone. However, optimised use of AI technologies to support SE requires transparency, explainability, and trustworthiness. Ethical considerations and V&V processes for AI-driven systems must also be considered [26]. Some key problems in SE that AI can potentially help to solve are discussed below.

4.1 Requirements Analysis

Analysing and managing complex and evolving requirements is time-consuming and prone to errors. The extent of large and interconnected system requirements now exceeds the human brain's capacity. Possible AI solutions include Natural Language Processing (NLP), which automates the extraction and analysis of requirements from documents, reducing ambiguity and improving consistency. LLMs can be implemented to trace the impact of a change throughout a requirement specification. It may be possible to have all requirements objectively checked for completeness. All information is fully digitalised [20] with accurate cross-referencing of all other relevant information according to standard, ubiquitous taxonomies. An authoritative source of truth provides consistent, accurate, up-to-date information.

4.2 Design Optimisation

Optimising design parameters for complex systems involves navigating a vast solution space that is too difficult for traditional trade-off tools. ML algorithms can perform multi-objective optimisation, helping engineers find optimal design solutions more efficiently [27].

4.3 Decision Support

Making informed decisions in systems engineering involves processing large amounts of data and considering numerous variables. AI-based tools can provide decision support by analysing data, identifying patterns, and suggesting optimal courses of action based on predictive analytics.

4.4 Risk Management

Assessing and mitigating risks in complex projects is challenging due to the uncertainty and interdependencies involved. AI can assess risks by analysing historical data and simulating potential future scenarios, helping engineers develop more effective risk mitigation strategies [28].

4.5 Lifecycle Management

Managing the entire lifecycle of a system, from conception to decommissioning, has a long duration, is complex and involves multiple stakeholders. AI can assist in lifecycle management by automating documentation, tracking changes, and ensuring compliance with standards throughout the system's lifecycle. Fully Implemented automated digital twins are operational, providing real-time evaluation and prediction. Full life cycle support is made efficient with automated change management and scenario simulations and continuously updated with real-world data [29].

5 ARTIFICIAL INTELLIGENCE TECHNIQUES TO ADDRESS SYSTEMS ENGINEERING PROBLEMS

5.1 Machine Learning for Optimisation

ML can significantly enhance design optimisation in SE by improving efficiency, accuracy, and innovation in the design process [30]. Specific examples are discussed in the subsections below.

5.1.1 Automated Design Exploration

ML algorithms can automatically explore a vast design space, identifying optimal or near-optimal design configurations. Algorithms like genetic algorithms (GAs) and neural networks can quickly generate and evaluate numerous design alternatives, uncovering innovative solutions that may not be apparent through traditional methods. For example, Deep Neural Networks (DNNs) have been used on a range of Arm Cortex-A CPU platforms, achieving up to four times improvement in performance and over two times reduction in memory with negligible loss in accuracy [31].

5.1.2 Surrogate Modelling

Surrogate models (also known as meta-models or approximation models) that approximate complex simulation models can be used to speed up the optimisation process. Surrogate models, such as Gaussian processes or polynomial regression, can predict system performance without requiring extensive simulations, significantly reducing computational time and resources. For example, surrogate models can offer an efficient and reliable alternative and facilitate evaluating the performance of multiple structures under different hazard scenarios [29], [32].

5.1.3 Multi-Objective Optimisation

Multi-objective optimisation techniques can be used to balance trade-offs between competing design objectives. Multi-objective evolutionary algorithms (MOEAs) can optimise multiple objectives simultaneously, such as minimising weight while maximising strength in structural design. For example, factors such as energy consumption, memory demand, and latency can be optimised for wearable IOT devices. The inherent trade-offs in these metrics are used to find the optimal configuration for given conditions [33].

5.1.4 Constraint Handling

ML can be used to handle complex constraints in design problems, ensuring that generated solutions adhere to requirements and limitations. Constraint handling techniques, such as constraint satisfaction problems (CSPs) and constrained optimisation algorithms, can manage various physical, regulatory, and operational constraints. For example, in manufacturing, ML can optimise the energy consumption of machines in production under the throughput constraint of the plant [34].

5.1.5 Real-Time Optimisation

Real-time optimisation using online learning and adaptive algorithms that continuously update design solutions based on new data and changing conditions can be used in dynamic environments where design parameters may change over time, such as in adaptive control systems and smart grids. For example, in smart grid design, ML can optimise energy distribution in real-time, adjusting to fluctuations in demand and supply to maintain system stability and efficiency [35].

5.1.6 Predictive Analytics and Insight Generation

Predictive analytics can be utilised to forecast the performance of different design options based on historical data and trends. Predictive models can provide insights into potential design outcomes, enabling informed decision-making and reducing the risk of design failures. In urban planning, for example, predictive models can forecast the impact of various infrastructure designs on traffic flow and pollution levels, guiding sustainable development.

5.1.7 Generative Design

ML algorithms can create design options based on specified goals and constraints, iteratively refining designs to meet desired outcomes. Generative design leverages ML to produce various viable design solutions, which can be further analysed and refined to achieve optimal performance. In product design, generative algorithms can create various component shapes that optimise strength while minimising material use, leading to innovative and efficient product designs.

5.1.8 Sensitivity Analysis and Robust Design

Sensitivity analysis can be conducted to understand the impact of varying design parameters on system performance and develop robust designs that perform well under uncertainty. ML can identify which parameters influence system performance, guiding designers to focus on critical aspects and create robust designs that can withstand variations. Sensitivity analysis can help optimise water treatment processes in environmental engineering by identifying key factors affecting treatment efficiency and ensuring robust operation under different environmental conditions.

5.2 Natural Language Processing

NLP is a field that employs computational techniques for learning, understanding and producing natural language content. NLP has been applied to Requirements Engineering for linguistic analysis tasks on requirements. This has been termed NLP4RE (Natural Language Processing for Requirements Engineering). NLP4RE is a very active area in the research domain, but it still appears to have a low penetration in the industry. At least 130 NLP tools have been developed, and studies have been done to evaluate their effectiveness as an aid in Requirements Engineering. Not many of the tools are accessible [36].

Various guidelines are available to system engineers on structuring requirements in English. For a functional requirement, the following structure is a good guideline: “The AGENT shall FUNCTION in accordance with INTERFACE-OUTPUT with PERFORMANCE [and TIMING upon EVENT TRIGGER in accordance with INTERFACE-INPUT] while in CONDITION. “. Similar guidelines are available for different types of requirements. [31] The terms in upper case are the elements that the system engineer needs to populate for their specific needs. Similar sentence structures are available as guidelines for systems engineers to use when writing requirements for different requirement types. Such structures lend themselves well to the NLP requirements analysis according to structure and content.

NLP4RE tasks can be categorised as follows: detection, extraction, classification, modelling, tracing and relating, as well as search and retrieval. Various terms are considered inappropriate for requirements. Terms such as “approximately”, “if possible”, “if appropriate”, “potentially”, shortcomings, etc. are indications of lack of clarity for a requirement. Identifying such potential shortcomings in requirements statements would fall into the “detection.”

NLP has been used successfully to improve requirements quality by identifying statements that use words or phrases that are typically not recommended when striving for reasonable quality requirements. The requirement statements can then be re-drafted to remove ambiguities or other deficiencies [37]. NLP can be easily implemented in Python. Therefore, companies can develop their tools for specific tasks to help with the assessment of requirements.

5.3 Large Language Models

5.3.1 Background

LLMs represent a significant advancement in the field of NLP. These models are neural networks trained on vast amounts of text data to understand and generate human language with a high degree of fluency and accuracy. LLMs, such as OpenAI's GPT-3 and GPT-4, Google's BERT, Gemini and others, leverage deep learning techniques and architectures, particularly transformers, to perform state-of-the-art NLP tasks. LLMs represent a transformative extension of NLP, offering unprecedented capabilities in understanding and generating human language. Their ability to handle various tasks accurately makes them invaluable across various industries. However, their deployment must be approached with careful consideration of ethical, resource, and interpretability challenges. [44]

When prompted, ChatGPT gives some useful guidelines for writing requirements. It can easily give examples of a set of bad requirements and examples of reasonable requirements. From a training perspective, such examples can be helpful for people wanting to know how to write reasonable requirements. A drafted requirements statement can be given, and an evaluation can be requested. ChatGPT will typically respond with an assessment of specificity, measurability, achievability, relevance and clarity. As research and development continue, LLMs are poised to advance the field of NLP further and broaden the horizons of human-computer interaction. [44]

5.3.2 Limitations of LLMs

LLMs are still a new and developing technology that is known to produce hallucinations. Hallucinations are when the model generates seemingly plausible but factually incorrect or nonsensical outputs. Guidelines to reduce hallucinations can be used, and models can be improved to reduce the frequency of hallucinations. However, hallucinations are inevitable [38]. This limits how such models can be used for critical decision-making. Guardrails and fences are needed to ensure that LLMs operate within expectations. Where critical safety decision-making is concerned, human control is required. The use of LLMs will not provide a way of definitively providing high-quality requirements, but it can be helpful as an aid in writing good requirements.

Concerns about the security of a company's confidential data limit how LLMs can be used. Various methods are being pursued to deal with this for different LLM applications. Currently, this limits the use of LLMs where data is confidential [45].

5.3.3 Uses of LLMs

Leveraging LLMs like GPT-4 for system dynamic modelling can be useful. Its ability to respond to and generate human-like text could streamline the iterative process of model development, making it more efficient and less prone to human error. Additionally, its capacity to identify errors and generate expansion ideas could lead to more robust and comprehensive models. The ability to convert models into Python code could make them more accessible for implementation and further analysis [39].

5.4 Symbolic Artificial Intelligence

The use of models, as part of MBSE, if done according to a mathematically sound ontological systems framework, could conceivably remove the need for humans to write requirements but for the requirements to be auto-populated in CNL (Controlled Natural Language) statement syntax as the IPM (Integrated Project model) is defined. First, Order Logic definitions for SE can be established to enable AI-supported machine readability. If symbolic AI (as opposed to sub-symbolic AI) is used, such AI can make explainable decisions if built upon an ontological knowledge base written using First Order Logic. This can be used to prepare the bridge between computation and human utility [29].

5.5 AI Used within System Engineering Tools

In the SE landscape, there are many areas where tools are used. Recently, many tools have AI capabilities. Where safety critical systems are developed, compliance with regulatory requirements such as DO-178C and DO-330 is required. The Tool Qualification Level (TQL) guidelines from DO-330 must be considered. It is essential to categorise the various tools correctly and use techniques to minimise the potential negative impacts of tools. For software where DO-178C compliance is required, the Design Assurance Level needs to be considered, together with the TQL level of tools used in the system engineering activities [40].

6 GENERAL FRAMEWORK FOR IMPLEMENTING AI IN SYSTEMS ENGINEERING

This section proposes a general framework for integrating AI into SE processes. This framework is suitable for all domains where Systems Engineering is applied. With this structured framework, organisations can effectively integrate AI into their SE processes, enhancing system performance, reliability, and innovation while ensuring alignment with existing workflows and compliance requirements.

This framework is based on a standard lifecycle that can be used for most AI endeavours [41]. The application of such a lifecycle approach, considering the current SE challenges and the identified AI approaches, can assist in applying AI to SE processes.

Figure 1 shows the core components and related aspects. Each of these components has relationships with other factors, as indicated. The main goal is to manage complexity in SE. To support SE processes with AI, start with data acquisition and pre-processing. Key issues are security of the environment for the data, ethics, privacy and interpretability of the data. Then, model selection and training taking into account the nature of the data and applications. At the centre of the framework, the actual integration of the AI with the existing SE processes takes place. Verification and Validation are required to ensure that correct and required outputs are achieved. Maintenance and continuous improvement for issues identified by the verification and validation continue throughout the lifecycle.

6.1 Data Acquisition and Pre-processing

Data needs to be collected, cleaned, transformed and stored. Data identified for a particular task must be accessible and in a format of the required quality for processing. For instance, if text-based natural language requirements statements are going to be processed, the data must be available and cleaned of issues such as removing informal content or content not in the language used. Where the data is quantitative, it may be helpful to transform it by normalising, scaling and encoding it. It may be necessary to perform feature extraction and highlighting so that the most relevant information gets the required attention [10].

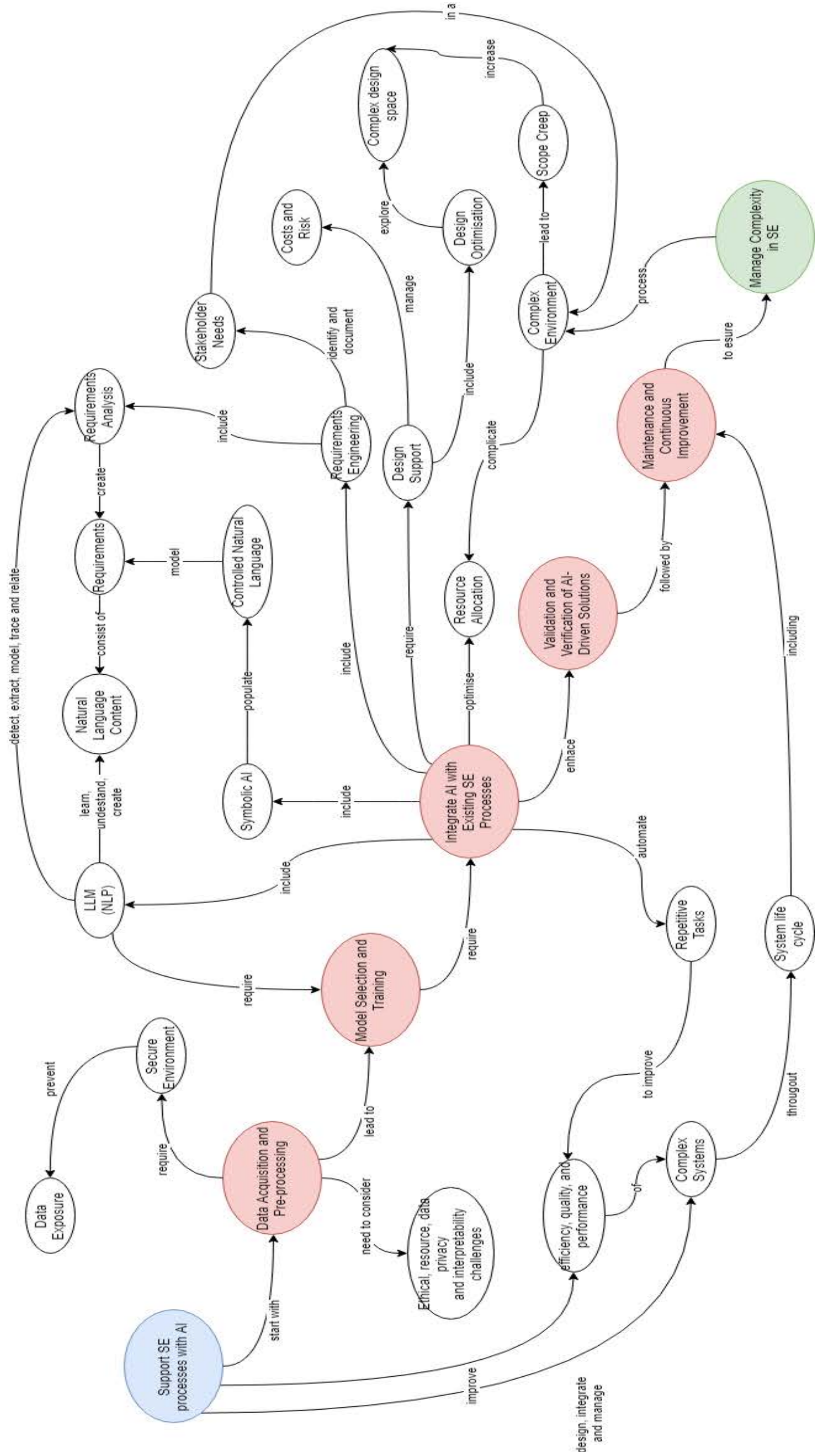

Figure 1. Systemigram of framework

6.2 Model Selection and Training

Algorithm selection is an essential step in the framework. The best type of algorithm must be selected depending on the task required for suitable AI algorithms. Typical categories are regression, classification, clustering and reinforcement learning. The selected model needs to be trained with pre-processed data. This involves splitting the data into training, validation, and test sets to evaluate the model's performance. Using recall and grid search techniques, model parameters must be optimised to enhance accuracy and performance.

6.3 Integration with Existing SE Processes

Collaboration between AI experts and SE professionals needs to be fostered to achieve alignment between the AI solutions and the system requirements and constraints. The workflow integration needs to be carried out to embed AI models into the existing SE workflows and systems. Change management practices need to be implemented to address the impact of AI integration on existing processes. The people involved must be trained on the new tools and integrated workflows [42].

6.4 Validation and Verification of AI-Driven Solutions

Validation of AI-driven solutions needs to confirm that the stakeholders fulfil the intended purposes of the solutions. User acceptance testing and performance testing need to be carried out. Verify that the AI model outputs meet specified requirements and perform as intended. This may include code reviews, unit testing and integration testing. Compliance with relevant regulations, standards and ethical guidelines needs to be ensured.

6.5 Maintenance and Continuous Improvement

As the models are used, monitoring the systems for performance, accuracy, and reliability is essential. Key metrics can be established and tracked. When new data becomes available, models can be retrained to maintain relevance. Feedback from users and other stakeholders needs to be solicited to identify areas for improvement. Documentation needs to be comprehensive, well-configured and maintained.

7 CHALLENGES AND RISKS OF AI INTEGRATION IN SYSTEMS ENGINEERING

7.1 Ethics, bias and transparency

The general area of AI has prompted some debate on the ethical issues for different AI applications. When AI is applied, issues such as transparency, justice, fairness, equity, responsibility and accountability are essential considerations. The data that the model is trained on can easily, without explicit intention, represent a bias due to the nature of the environment where the data is collected and curated. Intentional bias can also play a role. In order to remove bias, care must be taken to gather as broad a sample of training data as possible. Other review measures can also be applied in the data analysis to check for bias. Ensure diverse data representation and conduct regular audits to identify and correct biases.

7.2 Transparency, explainability and trust

Lack of transparency in how AI algorithms operate can lead to distrust and non-compliance with regulations. Ensuring algorithms are transparent and regulated is crucial. Follow best practices for algorithmic transparency, including documenting model choices, data sources, and decision-making processes. Stay informed about and comply with relevant regulatory frameworks. AI models, especially complex ones like neural networks, can act as “black boxes,” making it difficult for users to understand their decision-making processes. Use interpretable models where possible and invest in explainable AI techniques to provide insights into how models make decisions. Ensure that explanations are accessible to all stakeholders [43].

7.3 Data privacy

Due to data privacy concerns, not all users want to share or expose their data using AI tools. Secure access to protect their data from becoming visible to other users will need to be assured. Companies can deploy AI tools within their secure environment to prevent data exposure. Any general learning that could be gained for the broader user community would be lost in such a setup. Users, vendors, and regulatory authorities must carefully consider the risks and benefits to provide protection and benefits. Implement robust data governance practices, including encryption, anonymisation, and secure data handling protocols. Adhere to relevant regulations [11].

7.4 Accountability

8 AREAS OF OPPORTUNITY FOR AI INTEGRATION INTO SE

The future of AI integration in SE is poised for significant advancements and transformative changes. As both fields evolve, their convergence will likely lead to more sophisticated, efficient, and resilient systems.

8.1 Enhanced Human-AI Collaboration

The integration of AI will shift towards augmenting human capabilities rather than replacing them, fostering collaborative intelligence. AI-driven tools will provide real-time insights and recommendations, enhancing human decision-making in systems engineering. AI will also assist in creative processes, such as design generation and problem-solving, by offering innovative solutions and alternatives.

8.2 Explainable and Ethical AI

There is a growing emphasis on making AI systems more transparent, explainable, and aligned with ethical standards. Future AI integration will prioritise explainability, enabling engineers to understand and trust AI decisions. Ethical frameworks will guide the development and deployment of AI in SE, ensuring fairness, accountability, and transparency [11], [43].

8.3 Digital Twins and Simulation

Digital twins—virtual replicas of physical systems—are becoming more prevalent in SE. AI-driven digital twins will enable continuous real-time monitoring, simulation, and systems optimisation. They will facilitate predictive maintenance, scenario analysis, and system validation, leading to more accurate and efficient system management [44].

8.4 AI-Enhanced Systems Lifecycle Management

AI will play a crucial role throughout the entire system lifecycle, from design to decommissioning. AI tools will automate and enhance various lifecycle stages, including requirements engineering, design synthesis, validation, and testing. Continuous integration and continuous deployment (CI/CD) pipelines will incorporate AI for seamless system updates and improvements [45].

8.5 AI-Driven Optimization and Efficiency

Optimisation of complex systems will increasingly rely on AI techniques. AI algorithms will optimise resource allocation, energy consumption, and process efficiency, leading to more sustainable and cost-effective systems. AI will also enhance multi-objective optimisation, balancing trade-offs between competing performance metrics.

8.6 Resilience and Adaptability

Systems must be more resilient and adaptable to changing conditions and uncertainties. AI will enable systems to dynamically adapt to new information and unexpected changes, enhancing their resilience. ML models will continuously learn from operational data to adjust system parameters and configurations in real time.

8.7 Integration with Emerging Technologies

AI integration will increasingly intersect with other emerging technologies, such as quantum computing, blockchain, and 5G. Quantum computing will enhance AI's ability to solve complex optimisation problems at unprecedented speeds. Blockchain will provide secure and transparent data management for AI systems. 5G will support high-speed, low-latency communication essential for real-time AI applications [46], [47].

8.8 Regulation and Standardisation

As AI integration in SE grows, so will the need for regulation and standardisation. Developing industry standards and regulatory frameworks will guide AI's ethical and safe deployment for SE, ensuring compliance and interoperability across different systems and industries [29].

9 CONCLUSION

Integrating AI into SE processes and supporting tools is set to revolutionise how systems are designed, managed, and optimised. Future advancements will focus on increasing autonomy, enhancing human-AI collaboration, and integrating AI with emerging technologies. The use of LLMs for requirements engineering is one of the areas with the highest potential. Emphasis on ethical AI, explainability, and regulatory compliance will guide responsible AI deployment. As AI continues to evolve, it will unlock new possibilities and drive significant innovations in SE, leading to smarter, more efficient, and adaptable systems.

In the academic domain, much evidence exists of adapting and using AI to directly benefit SE activities. Minimal evidence in academic publications could be found of the successful use of AI in SE by practicing System Engineers. Anecdotal evidence displays how some SE practitioners have used AI for SE successfully.

Further research in the area is recommended in the following:

- Identifying the reasons for the low level of practical use of AI in SE.
- Overcoming the risks associated with the use of AI in SE.
- Identifying the opportunity areas for the best use of AI in SE.
- Identifying and monitoring areas of advancement of AI to be more widely used and accepted by SE practitioners.

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IMPACT OF FOUNDRY PROCESS VARIABLES ON THE FINANCIAL FEASIBILITY OF THE BINDER JETTING PROCESS

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ABSTRACT

Applications of binder-jetting process to metal casting have grown prominently over the years. However, the process is still expensive, thus preventing its complete adoption as mainstream casting process by local foundry industry. A financial model process was previously established, which was based on manufacturing cost model through the net present value and used Voxeljet VX1000 printer available at Vaal University of Technology. Foundry process variables related to the types of refractory sand and binder content were not factored in the feasibility assessment. This paper uses scenario-based analysis to assess the impact of metallurgical factors on the economic feasibility of rapid sand casting determined by the discounted payback period (DPBP) and the net present value (NPV). This study builds on previous scientific efforts to understand the financial feasibility of rapid sand casting by considering foundry variables and aims to make this process viable for the local South African foundry industry.

Keywords: Binder jetting process, Foundry variables, Financial feasibility, Cost model, Silica sand, Furan binder, Voxeljet VX1000

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1 INTRODUCTION

Additive manufacturing (AM), also known as three-dimensional printing (3DP), has gained international attention in various countries for its ability to transform traditional manufacturing processes. As per the ISO/ASTM 52900:2021(E), this technology is defined as the method of joining material successively layer by layer to produce physical objects as determined by computer-aided design (CAD) data [1]. This innovative technology offers numerous advantages, including increased design flexibility, shorter production time and enhanced customisation capabilities [2]. Due to its transformative role in driving advanced digital integration of technologies across various industries worldwide, AM has become a crucial element of the fourth industrial revolution (4IR) [3].

AM methodology is more economically relevant as it effectively conserves energy by producing consolidated lightweight components, with material deposited only as needed during the manufacturing process. Figure 1 summarises the three generic processes of AM [4]. Firstly, the development of product data using the CAD model where a design is digitally constructed using the solid modelling software. Secondly, the preprocessing of the data model where the CAD model is translated into a standard triangle language (STL) file format. The STL file is then transferred to slicing software. Lastly, printing and post-processing which involves printing the part using the AM machine, and cleaning and heat treating the part to meet the required mechanical properties.

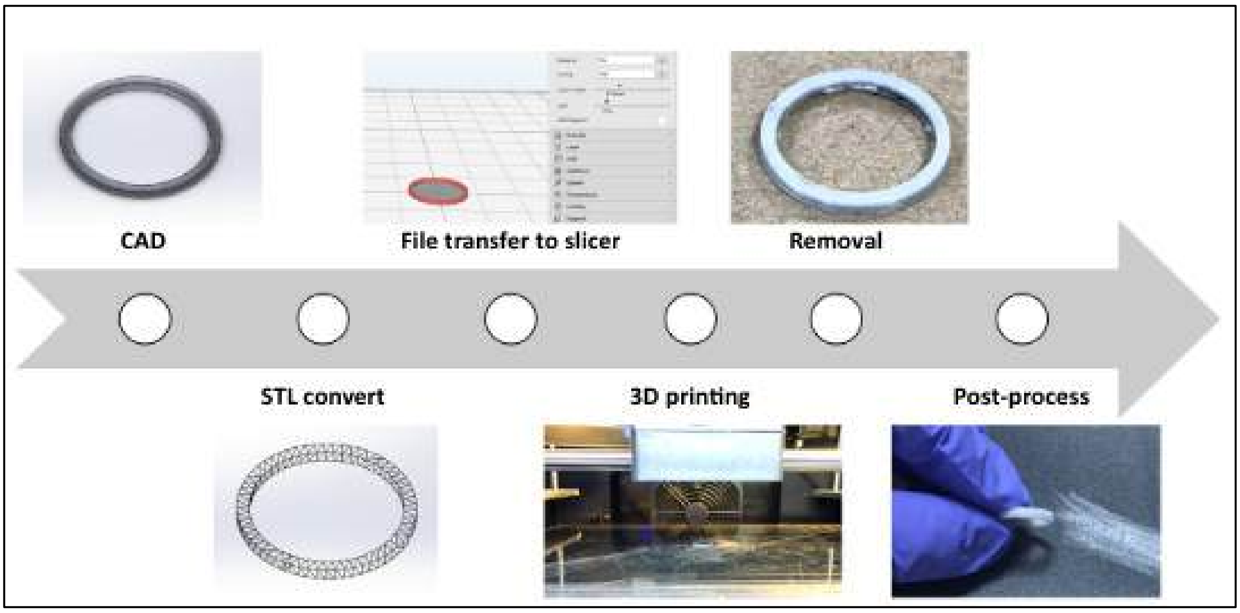

Figure 1: General steps in the AM process [4]

As AM is classified as Industry 4.0 and part of the 4IR, it can also enhance efficiency while simultaneously reducing waste across the complex production lines of the manufacturing industry [5]. This technology has enhanced productive and innovative strategies globally, while also stabilising environmental and social impacts. The AM industry continues to advance and expand at an exceptional pace with new processes and products being continually introduced to improve its production processes [6]. Figure 2 shows the predicted compound annual growth rate (CAGR) of 21.6% between 2023 and 2030 of the global AM market. In 2022 it was valued at USD14.5 billion and it is expected to reach USD69.3 billion by 2030 [7]. Due to its steady growth towards efficient printing methods, future trends are likely to include the production of complex multifunctional parts in a single print and the use of recyclable materials with moderate environmental impact [8].

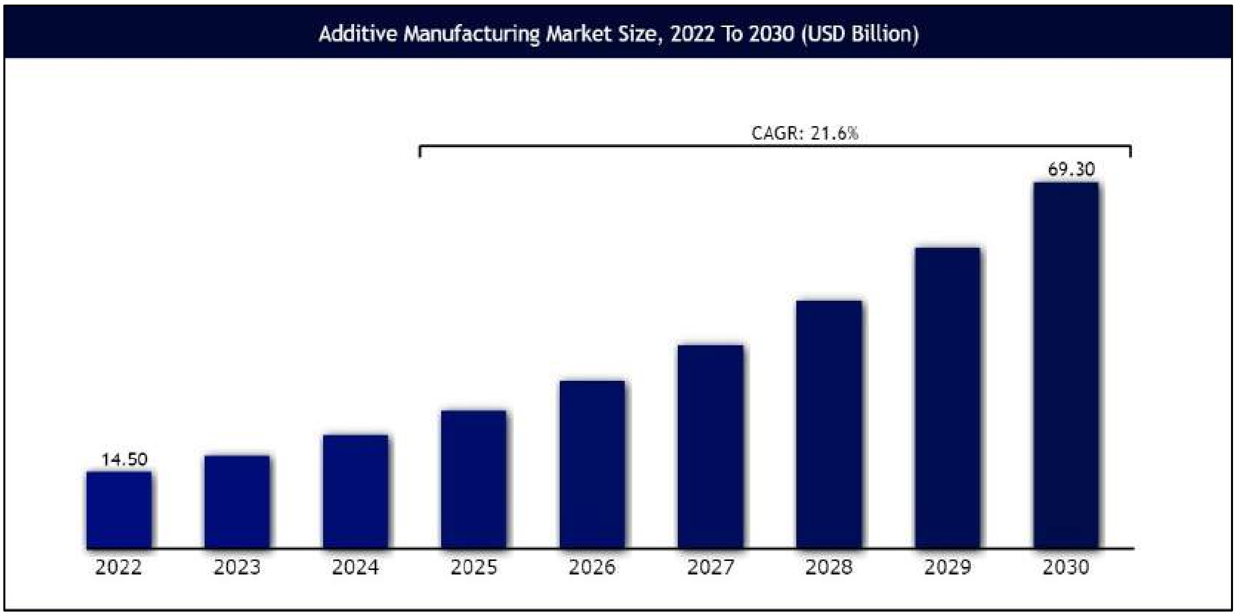

Figure 2: Predicted AM global market by 2030 [7]

AM has been classified into seven different categories by the ISO/ASTM 52900:2021 based on the different mechanisms and feedstock used during printing [1]. These seven categories include binder jetting, sheet lamination, material jetting, material extrusion, directed-energy deposition and powdered fusion. Binder jetting is one of the methods used for manufacturing sand moulds and cores for the foundry casting process. This process of manufacturing sand moulds and cores using AM technology is also termed rapid sand casting [9]. There are various machines available in SA for rapid sand casting. These include the Voxeljet VX1000 and VX500, the EOSINT S 750, and the Z Corporation Spectrum 550, which are housed at the Vaal University of Technology (VUT), the Central University of Technology (CUT), and the University of Johannesburg (UJ), respectively [10]. Locally there are also over 300 AM systems that has been established as a result of programs put in place by the SA government, industry role players and other academic institutions [11]. These academic institutions provide services to industries, including local foundries, by helping them address existing challenges and enhance global competitiveness [12], while supporting their students' research. Additive manufacturing has numerous applications in various fields, including in the following industries: automotive, aerospace, construction, health care, manufacturing and metal casting; as well as in academic institutions. In the metal casting process, AM technology, namely binder jetting, can be used to create sand moulds. This application of AM technology to the printing of sand moulds is known as rapid sand casting, which is discussed in the next section.

2 BINDER JETTING AND RAPID SAND CASTING

Binder jetting technology is one of the AM technologies that uses a binding agent to bond sand material or powdered material together during the printing process, this process is similar to the furfuryl alcohol resin-bonded sand used in the foundries to produce moulds. The process involves the printhead selectively depositing a liquid-based binding agent onto thin layers of the precoated powder. This powder can be the silica sand used in foundries for mould making, ceramics, etc. [13] Once a layer has been selectively bonded and printed, the powder bed is lowered and a new layer of powder is deposited, typically through a counter-rotating rolling mechanism as shown in Figure 3 [14]. This process is repeated until the part or mould is completely printed. On completion, the mould is sometimes left for a period on the build platform to allow the binder to set fully, which also helps to improve the strength of the mould. The sand mould is then removed from the build platform and any unbound sand is removed using pressured air and infiltration. The infiltration process involves placing the cured part in the furnace which enhances the strength of the mould and potentially imparts additional mechanical properties. Of the various commercial 3D printing machines available on the market for binder jetting, ExOne and Voxeljet (VX) are the most popular. Voxeljet produces some of the leading binder jetting machines on the market as they offer a very high volumetric output rate due to both the large build box and the print speed. In addition, due to Voxeljet printhead technology, these machines lead the way in 3D printing scalability [15]. ExOne is also one of the leading 3D printers that offers a variety of sand and binder combinations for both ferrous and non-ferrous processes [16]. Voxeljet printers can employ various materials for printing, including the furfuryl binder, silica foundry sand, ceramics and plastics. ExOne uses foundry-grade silica sand and binders for its printing processes. The choice of binder for the printed sand mould in ExOne machines depends on the alloy to be cast.

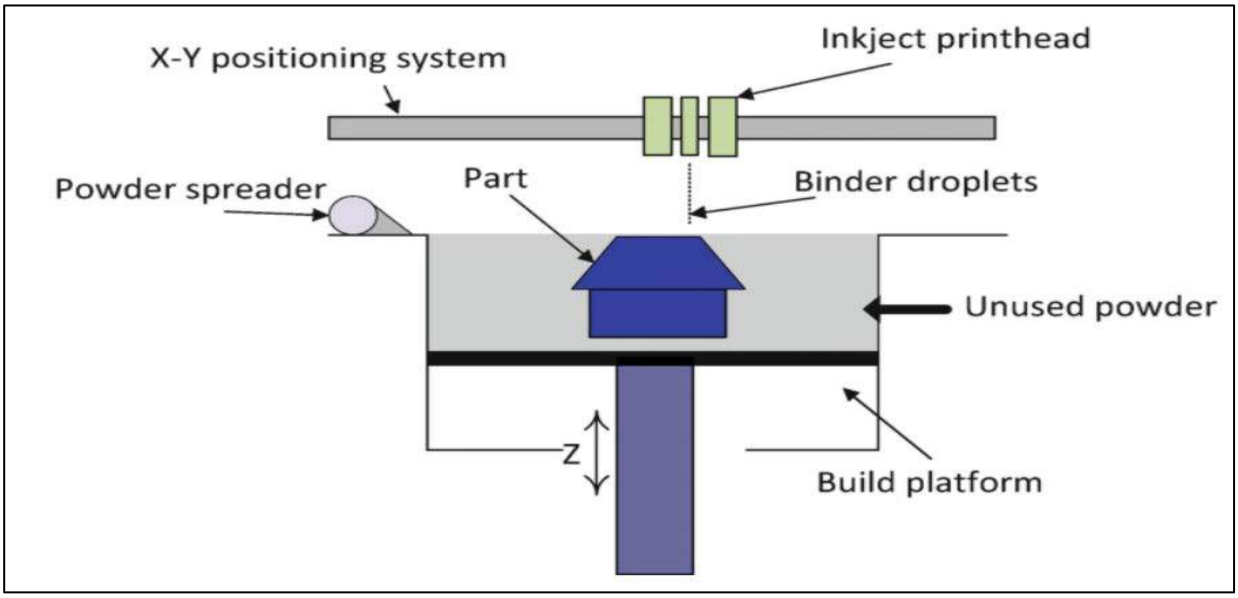

Figure 3: The schematic of the binder jetting process [14]

Rapid sand casting

Rapid sand casting is categorised as a binder jetting process used for printing sand moulds for the foundry industry. This method has the potential to accelerate the generation of mould making by eliminating some stages in the traditional manufacturing process. These steps are shown in Figure 4 [17]. The eliminated stages include the manufacturing of the patterns, the production and assembly of the cores, and the production of the cope and drag model. This process also allows for technical improvements in casting practices, including part consolidation, the reduction of hazardous chemical usage and the elimination of hard tooling, which is the main cost contributor in traditional sand manufacturing [18]. The rapid sand casting process is locally available for adoption by South African foundries.

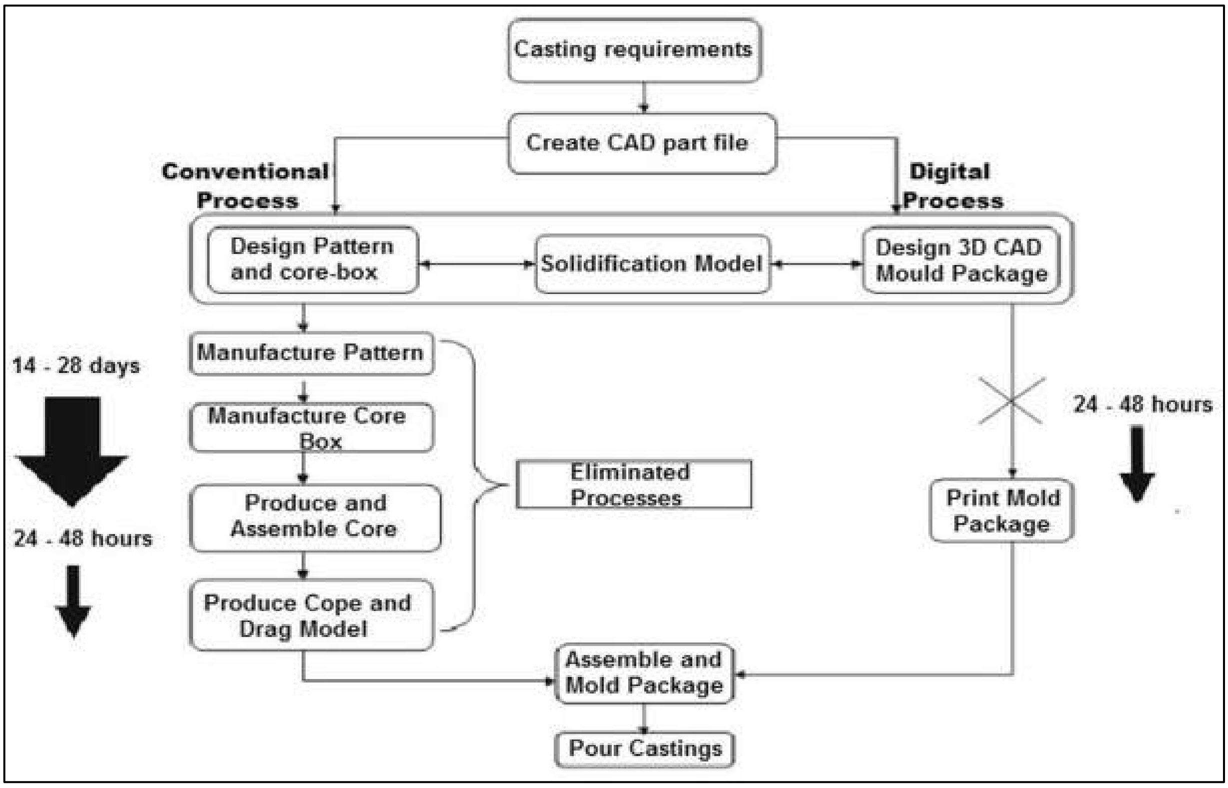

Figure 4: Comparison between the traditional and rapid sand casting processes [17]

3 FOUNDRY PROCESS VARIABLES

The two primary raw materials used in the foundry moulding process are sand and furan resin binder. The quantities of these materials depend on the composition and properties of the sand, as well as the specific moulding process employed. The sand layer thickness and the ratio of binder used in sand-mould production, significantly influences the quality of the sand mould and, consequently, the casting outcomes. These factors impact dimensional accuracy, printing resolution, surface roughness and the overall strength of the mould. Control of these variables is crucial as it can affect both the mechanical and the physical properties of the printed sand moulds and, ultimately, the final casting. These two foundry variables which are discussed in detail in the following section.

3.1 The refractory sand - silica sand

Silica sand is the most widely used refractory material for making moulds for foundry metal casting due to its abundant availability, reasonable cost and favourable thermal and chemical properties compared to other refractory materials. Generally, the key foundry properties of silica sand encompass grain-size distribution, grain shape, chemical purity, refractoriness and thermal expansion. These properties contribute to minimising resin consumption, optimising mould strength, and ensuring the soundness and defect-free quality of the final castings [19]. Several studies have been undertaken in the South African context to explore the effectiveness of using local silica sand for rapid sand applications and to optimise this process. The suitability of local silica sand was assessed according to its mechanical properties, physical properties, quality of the final cast, dimensional accuracy, the possibility of reclaiming or reusing the sand after the reclamation process, and the financial feasibility of investing in the rapid sand casting process. These studies have shown that the use of local silica sand is suitable for the rapid sand casting process. However, the local sand has not yet been widely adopted by the local foundry industry.

3.2 The binder - furan resin

Furan resin is used as a bonding material that binds the sand particles together. The amount used varies depending on the quality and type of sand particles. The binder content might affect the strength and the permeability of the sand moulds printed, i.e., higher binder content improves mechanical strength, but it can cause harmful gas defects in the cast product [17]. Rapid sand casting employs the same chemical process used in the traditional manufacturing of mould, but the method of mixing furan resin and sulphonic acid differs [12]. With rapid sand casting, the furan binder is selectively deposited onto precoated sulphonic acid sand layers, as explained in the section above on binder jetting (Section 2). The sulphonic acid catalyses the reaction between the sand and the binder. This initiates the acid hardening reaction of condensation and cohesion, thus adding strength to the sand particles to maintain the shape of the 3D-printed sand mould [19].

4 STUDY’S OBJECTIVES AND RESEARCH GAP

The local South African foundry industry has not yet adopted the rapid sand casting process. One reason is that the financial feasibility of this process remains uncertain, and the impact of foundry variables on its viability has not been established. Understanding these factors can help the foundry industry assess the financial implications of adopting this technology and determine how the raw materials used influence the process's economic feasibility. The study’s objectives included examining the impact of silica sand and furan resin content on the financial feasibility of the rapid sand casting process, as these are major factors contributing to the quality of sand moulds and, ultimately, the quality of the castings produced. The feasibility analysis was conducted using the discounted payback period (DPBP) and net present value (NPV) methods to understand the economic benefits and of implementing the rapid sand casting process. The assessment utilized data collected from the Voxeljet VX1000 machine at the Vaal University of Technology (VUT), a leading and unique additive manufacturing specialist that supports the foundry industry in producing sand moulds for casting processes. The methodology of the assessment is outlined in detail in the next section.

5 METHODOLOGY

This section outlines the methodology used to evaluate the impact of foundry variables on the financial feasibility of the binder jetting process. Figure 5 illustrates the four sections of this methodology, which include the case study on which the study was based on, the cost modelling, the capital budgeting techniques, and scenario analysis based on the foundry variables, namely, the sand and binder. The first section outlines the case study that forms the foundation of this research, detailing the data collection and its basis for the study, focusing on the impeller sand mould printed through the binder jetting process using the VX1000 machine. The second section explores the cost modelling of rapid sand-cast printing, highlighting the four primary cost components associated with the direct costs of rapid sand casting. The third section discusses how the financial feasibility was analysed using capital budgeting techniques, specifically the discounted payback period (DPBP) and net present value (NPV). The DPBP is also compared to the traditional payback period (PBP) to see the difference in recovery of the initial investment. The final section examines the impact of process variables on the above mentioned capital budgeting techniques and how their variations affect these methods. The analysis of this study was conducted using the results from a prior study, which assessed the financial feasibility of manufacturing an impeller with the VX1000 machine.

This method of approach differs from others on the same topic because the study was specifically based on the VX1000 machine which maybe unique compared to other studies which might use models or different types of AM machines. The study also focuses on the emphases of the use of the local SA silica sand evaluating its suitability for rapid sand casting process and other studies might focus on different types of sand or materials. The use of both the DPBP and the NPV methods for financial feasibility analysis is a more detailed approach that provides a comprehensive view of the economic viability, and other studies might use different financial methods of evaluating a process using different AM processes or machines.

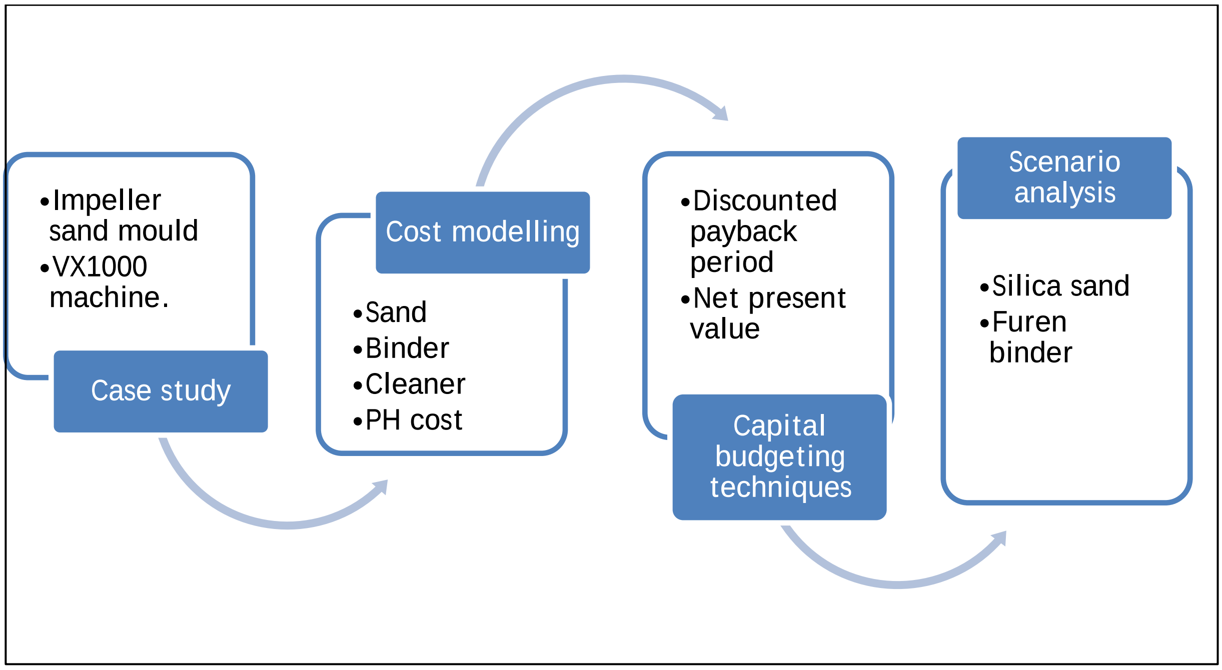

Figure 5: The methodology of assessing the financial feasibility of the rapid sand casting process

5.1 The case study

The focus of the case study was on two main components: the impeller sand mould and the VX1000 printer. The focus was specifically on the dimensions of the impeller to be printed and the specifications of the VX1000 machine used. The impeller sand mould was of particular interest due to its complexity, especially the veins which demand high dimensional accuracy to optimise performance, and to ensure efficient production cycles for impellers across various industries. In SA, impellers are widely used across various sectors, including mining. Traditionally, SA foundries employ conventional manufacturing methods, but binder-jet technology, such as that provided by the VX1000 machine, offers an effective alternative for manufacturing these components. This study used the Vaal University of Technology’s (VUT) VX1000 machine to print the impeller. Table 1 displays the dimensions of the two primary components in the case study: the impeller sand mould suitable for printing and the VX1000 machine.

Table 1: The dimensions of the case study components.

Impeller sand mould	**Dimensions**
Height (H_p)	310 mm
Total volume (V_t)	141 087 929.136 mm^3
Total number of layers (N_l)	1 050
Printing time of the sand mould (T_p)	10.21 h

VX1000 machine	**Dimensions and printing properties**
Length (L*m*)	1 100 mm
Width (W*m*)	637 mm
Height (H*m*)	500 mm
Printing time per layer (T*l*)	35 s
Layer thickness (L*t*)	0.3 mm

5.2 Cost modelling

A cost model is a tool that is used to representatively identify all the costs incurred during a production process and whether this cost is related to the direct, indirect, variable or fixed costs. As reviewed by Thompson et al. [20], AM cost is still regarded as a barrier to adoption by other industries, like the foundry industry, but the value that is added by AM outweighs the cost. The literature relating to the cost modelling of rapid sand casting in SA is insufficient and there is not much research on this aspect. But a cost model relating to the rapid sand casting process in the context of SA relating to the VX1000, has been developed. This model proposes four types of costs contributing to the direct total cost of printing a sand mould using the VX1000 machine, and these were calculated from the sand cost, the binder cost, the cleaner cost, and the printhead operational cost. These were considered to be the four main components of the binder jetting process when printing a sand mould using a VX1000 machine. The section below briefly discusses these four cost components.

- The cost of the sand was determined using the volume of the sand mould to be printed, the sand density, the mixing ratio of the new and the reused sand, and the per kilogram price of purchasing the sand.
- The binder cost was determined using the volume of the binder used per mm^3, the safety factor, the volume of the sand mould to be printed, and the price of the binder per litre.
- The cleaner cost was determined using the total number of layers needed to print the sand mould and the amount of cleaner used after each layer.
- The cost of the printhead was determined using the time taken to print the sand mould, and the operational cost of the printer per hour calculated from the replacement cost of the printhead and its expected lifetime.

From the above four cost components, the total cost of printing a sand mould was determined. Then, factoring in VAT and the markup calculated from benchmarking ratios, the price of the sand mould was established. From the price of the impeller sand mould, the revenues were calculated based on the total number of impeller moulds that could be printed per year. After the total cost was calculated, the cost of goods sold (COGS) was calculated; and from the revenues and the COGS, the gross profit cash flows (GPCF) were obtained. These were the three sections that were used to generate an income statement of the rapid sand casting process. The GPCF were calculated from the direct cost of printing since they are related directly to expenses associated with the printing of the impeller sand mould and are generally considered a good indicator of operating efficiency and good financial profitability analysis. Therefore, the study's analysis focused on the foundry variables, namely the sand and binder, as they are the primary consumables in determining the total cost of printing the impeller sand mould. These variables impact the GPCF and ultimately the financial feasibility of the rapid sand casting process.

The GPCF analysis was examined as annual cash flows over a five-year period to obtain the most accurate results for the payback period. This was based on the general assumption that investments in machinery have a long lifespan, typically exceeding five years. This analysis is shown in the income statement in Appendix A. Using the GPCF generated, as reflected in the income statement, capital budgeting techniques were employed to analyse the financial feasibility of the rapid sand casting process in the foundry. The techniques used for this assessment were the DPBP and the NPV, both of which are elaborated in the following sections.

5.3 Capital budgeting techniques

Capital budgeting techniques, also known as financial models, refer to the methodologies used to evaluate the financial feasibility of a process or project prior to investing in it. These techniques enable investors to assess the estimated value and profitability of the project or process, providing predictions that aid in investment decision-making. The study only employed two methods, namely the DPBP and the NPV, to assess the financial feasibility of rapid sand casting based on the significant foundry variables that need to be considered when printing a sand mould. These methods were specifically chosen because they include the time value of money (TVM), making them more accurate for assessing the profitability of the rapid sand casting process. The traditional PBP does not consider the TVM, it only increases the yearly cash flows based on the inflation rate. The TVM is a concept that states that money available today is worth more than the same amount in the future. TVM emphasises the importance of considering the timing of cash flows in investment decisions by discounting future cash flows to their present value. This approach allows for a more accurate evaluation of an investment's worth and profitability. Basing investment decisions only on the PBP may not yield accurate results. However, using the DPBP and the NPV allows foundrymen to predict more accurately the profitability of adopting rapid sand casting for producing sand moulds.

5.3.1 Discounted payback period

Just like the PBP, the DPBP is defined as the time taken to recover the initial investment of a project or a process but considers the TVM. Because of this consideration, the financial analysis tends to give the most accurate prediction of the investment's profitability [21]. Four components are considered when calculating the DPBP, namely, the initial investment, which is the price of purchasing the machine, the annual cash flows, the discounting rate (r), and the number of years (n) over which the process will be studied. The annual cash flows are defined as the money generated by a process or a project over a period of one year (12 consecutive months), while the initial investment is defined as the upfront cost of purchasing a machine. Lastly, the discount rate is defined as the interest rate that is used to represent the value of money, including its potential future growth. The formula for calculating the DPBP is shown in Equation 1 below. Two steps were followed in calculating the DPBP, firstly, the annual future cash flows were calculated to the present values by discounting them with the discounting rate; secondly, the accumulative discounted cash flows were calculated each year until the initial investment had been covered, which will indicate the number of years needed to recover the initial investment.

$$DPBP = \frac{Annual\ cash\ flows}{(1+r)^n} \qquad \textbf{Equation}\ (1)$$

5.3.2 Net present value

Like the DPBP, the NPV is determined by discounting future cash flows to their present value for each consecutive year. The sum of these present values is then subtracted from the initial investment to obtain the NPV. The equation for calculating the NPV is shown below in Equation 2. Essentially, the same discounted cash flows used in calculating the DPBP were used to calculate the NPV.

$$NPV = \sum_{t=1}^{n} \frac{Annual\ cash\ flows}{(1+r)^n} - Initial\ investment \qquad \textit{Equation (2)}$$

5.4 Scenario analysis

Due to process and quality optimisation, the foundry variables can change based on the required output of the sand mould and the final casting. These foundry variables include the sand and the binder used during the rapid sand casting process. The scenario analysis was then performed to study the effect and the impact of these metallurgical factors on the economic feasibility, i.e., the DPBP and the NPV, as shown in Figure 6. The standard printing layer thickness for the VX1000 machine is 0.3mm [22] but layer thickness ranging from 0.15 mm to 0.3 mm can also be used [23]. The study then used 0.3mm, the 0.2mm and the 0.15mm for its analysis and based on the VX1000 used at the VUT the binder used for 0.3mm was 2,52E-08. The variation in layer thickness will affect the amount of binder used per layer and ultimately the entire object or sand mould printed.

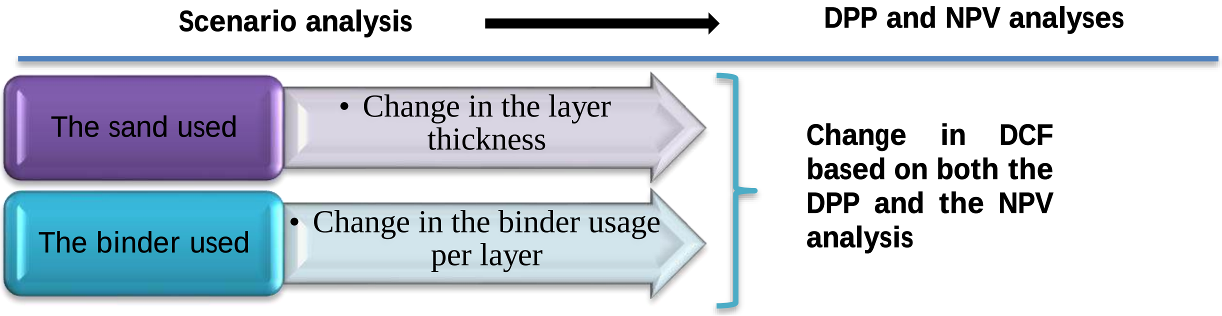

Figure 6: Scenario analysis based on the metallurgical factors

6 RESULTS AND DISCUSSIONS

This section presents the results of the methodology discussed in Section 4, which include the results of the cost modelling, the capital budgeting and the scenario analysis.

6.1 Cost modelling

Table 2 gives the total cost of printing the impeller sand mould based on the sand cost, binder cost, cleaner cost and the printhead operational cost (as discussed in Section 4.2). Table 3 displays the outcomes of the three income statements, which computed the GPCF from both revenues and the COGS (as per Appendix A).

Table 2: The cost modelling results

The total cost and the price of the impeller sand mould	
Sand cost	R5 560.76
Binder cost	R7 511.76
Cleaner cost	R72.38
Printhead operational cost	R1 276.04
Total print cost	**R14 420.93**
Total price + Markup (39.9%)	**R20 174.89**

Total price of the mould (incl. VAT 15%)	**R23 201.12**

Table 3: Income statement results

Year	Revenues	COGS	GPCF
0	R0.00	R0.00	-R15 200 000.00
1	R12 064 581.94	R5 041 031.71	R7 023 550.24
2	R12 667 811.04	R5 293 083.29	R7 374 727.75
3	R13 301 201.59	R5 557 737.45	R7 743 464.14
4	R13 966 261.67	R5 835 624.33	R8 130 637.34
5	R14 664 574.75	R6 127 405.54	R8 537 169.21

6.2 The discounted payback period

Table 4 shows the present value cash flows and the discounted GPCF from which the PBP and the DPBP were calculated, respectively. Year 0 represents the initial investment, while year 1 to year 5 represent the direct cash flows generated when printing a sand mould. These cash flows were escalated based on a 5% inflation rate per year, as shown in the income statement given in Appendix A.

Table 4: The cash flow outlay used to calculate the PBP and the DPBP

Year	Present value cash flows (PBP)	Discounted cash flows (DCF)
0	-R15 200 000.00	-R15 200 000.00
1	R7 023 550.24	R6 564 065.64
2	R7 374 727.75	R6 441 372.83
3	R7 743 464.14	R6 320 973.33
4	R8 130 637.34	R6 202 824.30
5	R8 537 169.21	R6 086 883.66

- In year 1, R6 564 065.64 of the initial investment of R15 200 000.00 would have been recovered.
- In year 2, R13 005 438.47 would have been recovered (R6 564 065.64 from year 1 and R6 441 372.83 from year 2).
- By the end of year 3, R2 194 561.53 would have been recovered, with only 34.7% (R2 194 561.53/R6 320 973.33 = 0.3472) of the year 3 cash flow of R6 320 973.33 needed to complete the payback of the initial R15 200 000.00
- Therefore, the discounted payback period of the discounted cash flow = 2.35 years, as demonstrated in Figure 7.
- In calculating the traditional PBP, in year 1, R7 023 550.24 would have been recovered from the R15 200 000.00 initial investment.

- In year 2, R14 398 277.99 would have been recovered (R7 023 550.24 from year 1 and R7 374 727.75 from year 2).
- By the end of year 3, R801 722.01 would have been recovered, which means that only 10.35% (R801 722.01/ R7 743 464.14 = 0.1035) of the year 3 cash flow of R7 743 464.14 will be needed to complete the payback of the initial R15 200 000.00 investment.
- Therefore, the traditional PBP of the normal present cash flow = 2.10 years, as demonstrated in Figure 8.

When comparing the traditional PBP with the DPBP, it can be observed that, although the initial investment is recovered in the same year (year 3), the PBP is recovered earlier in that year compared to the DPBP. This can be attributed to the fact that with the DPBP it takes slightly longer for the initial investment to be recovered because TVM is considered by discounting the GPCF. In contrast, the PBP focuses solely on the direct cash flows without applying any discounting.

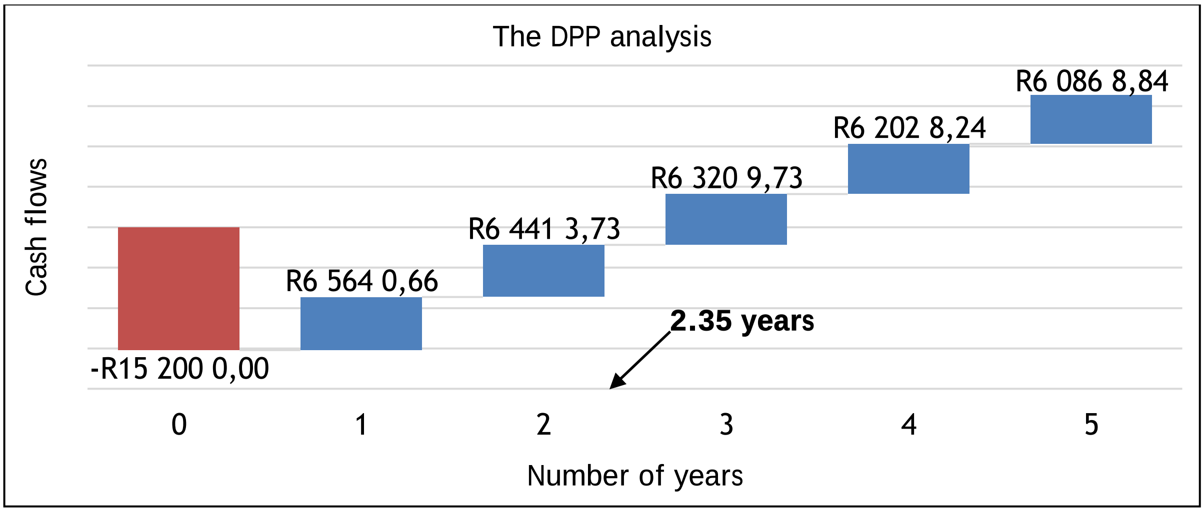

Figure 7: Discounted payback period analysis for the rapid sand casting process

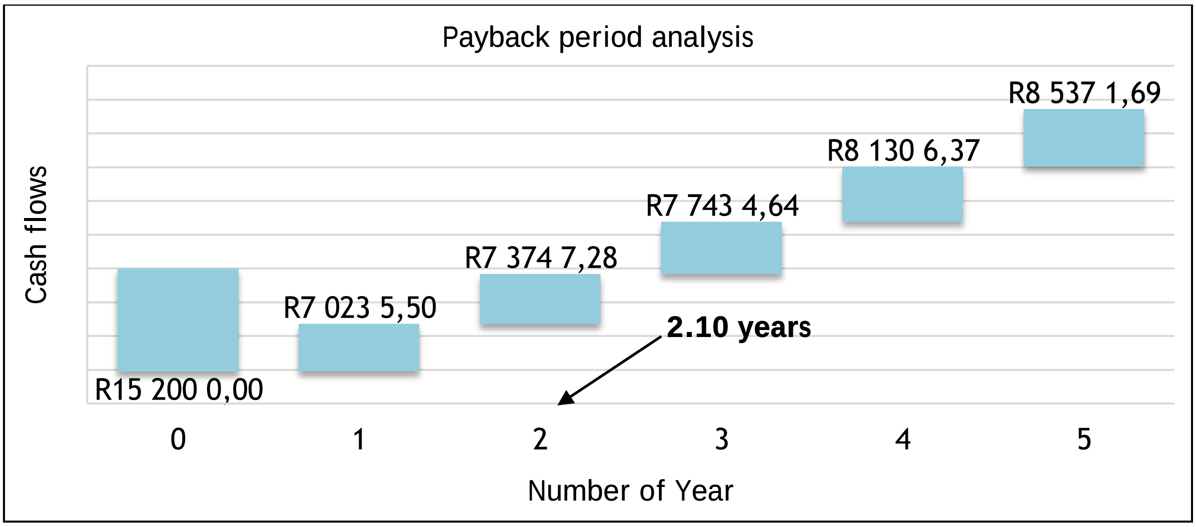

Figure 8: Payback period analysis for the rapid sand casting process

Investment in a process is generally approved if the DPBP falls within the 5-year duration of the cash flow analysis. Since the DPBP for recovering the initial investment of R15 200 000.00

is within this 5-year period, the process is deemed feasible and can be adopted for printing the sand moulds.

6.3 The net present value

This section discusses the results of the NPV method. Table 5 shows the present value cash flows and the discounted cash flows from year 1 to year 5.

Table 5: The cash flow outlay and the NPV

Year	Present value cash flows	Discounted cash flows
0	-R15 200 000.00	-R15 200 000.000
1	R7 023 550.24	R6 564 065.64
2	R7 374 727.75	R6 441 372.83
3	R7 743 464.14	R6 320 973.33
4	R8 130 637.34	R6 202 824.30
5	R8 537 169.21	R6 086 883.66
Total (Y1 to Y2)		R31 616 119.76
NPV		R16 416 119.73

- The sum of the discounted cash flows (DCF) from year 1 to year 5 is R31 616 119.76. Subtracting the initial investment in year 0 from this total gives the net present value (NPV) of R16 416 119.76, as shown in Equation 2.
- Since the NPV is greater than R0, this process shows the feasibility of printing the sand mould using the binder jetting technology.
- Since the cash flows were based on the direct cost of printing the sand mould, the NPV value demonstrates the good operating efficiency of the direct consumables cost involved in printing the impeller sand mould using the VX1000 printer.

6.4 The net scenario analysis

The section below presents the results of the scenario analysis when varying the layer thickness of the sand and the amount of binder per layer.

6.4.1 The sand used per layer

Table 6 shows the effect of changing the sand layer thickness on both the DPBP and the NPV value. Figure 9 shows that, as the thickness of the sand layer increases, the number of years required to recover the initial investment decreases. In other words, a greater sand layer thickness leads to a shorter DPBP. This occurs because increasing the layer thickness reduces the total number of layers that need to be printed, which in turn decreases the printhead operation cost. The printhead operation cost is based on the total number of layers to be printed, and the time required to print each layer of the sand mould. Figure 10 shows that increasing the sand layer thickness also increases the NPV of the rapid sand casting process. This is because when the sand layer thickness increases, the total number of layers to be printed decreases. This reduction in layers lowers the printhead costs due to the decreased total cost of printing the sand, which ultimately increases the direct DCF of the rapid sand casting process, resulting in a higher NPV.

Table 6: Effect on DPBP and NPV of changing the sand layer thickness

Layer thickness (mm)	DPBP (years)	NPV (rands)
0.15	2.61	R13 259 809.24
0.20	2.47	R14 837 964.50
0.30	2.35	R16 416 119.76

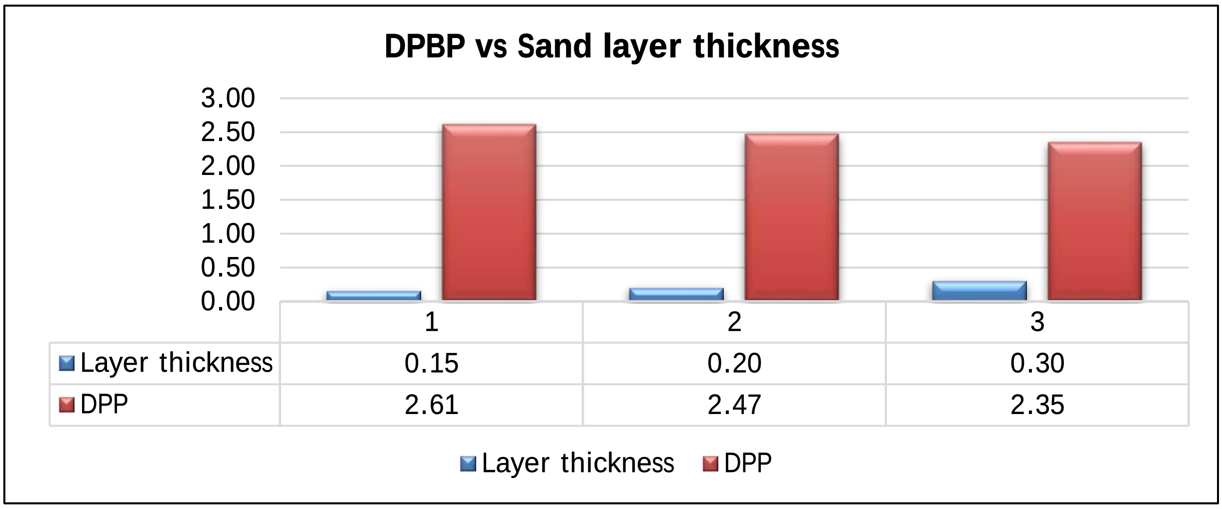

Figure 9: DPBP vs the change in layer thickness

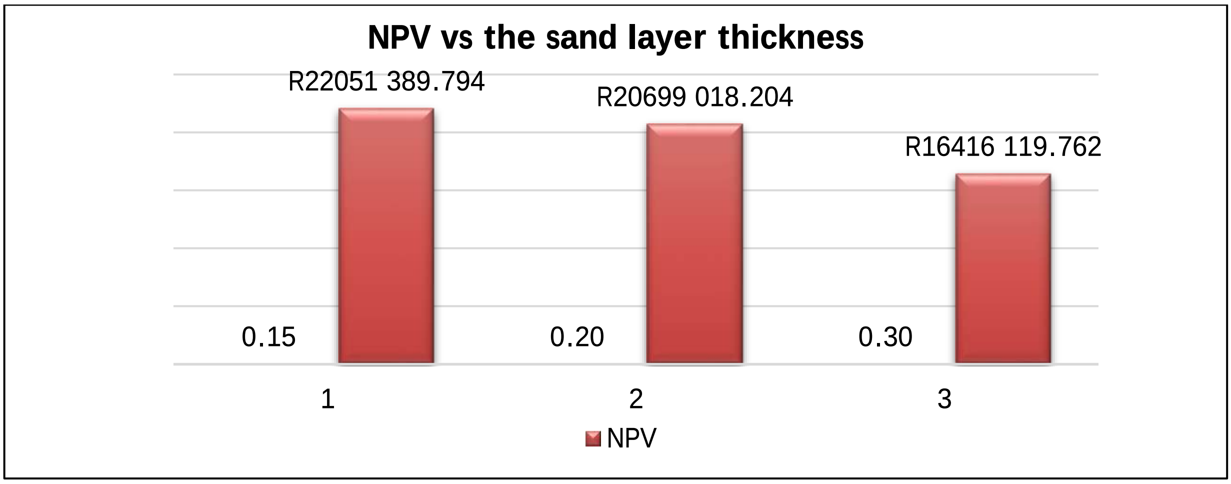

Figure 10: NPV vs the change in layer thickness

6.4.2 The binder used per layer

Table 7 shows the change in volume of the binder used per layer with varying layer thickness. The binder used per layer increase as the layer thickness increases, increasing the layer thickness decreases the total number of layers that should be printed while simultaneously increasing the total binder used due to the thicker layer. Figure 11 illustrates the effect on the DPBP of changing the amount of binder used per layer. As the binder amount per layer increases, the DPBP also increases. This is due to the higher cost of printing the sand mould, which decreases the annual cash flow. Consequently, it takes more time to recover the initial investment. Figure 12 shows the effect of changing binder use on the NPV. The more binder used per layer, the less the NPV value. This is due to the decreased DCFs per year, which reduces the NPV.

Table 7: Effect on DPBP and NPV of changing the binder use per layer

Layer thickness	Binder volume per layer (mm^3)(l)	DPBP	NPV
0.15 mm	1.26E-08	1.97	R22 051 389.79
0.2 mm	1.68E-08	2.06	R20 699 018.20
0.3 mm	2.52E-08	2.35	R16 416 119.76

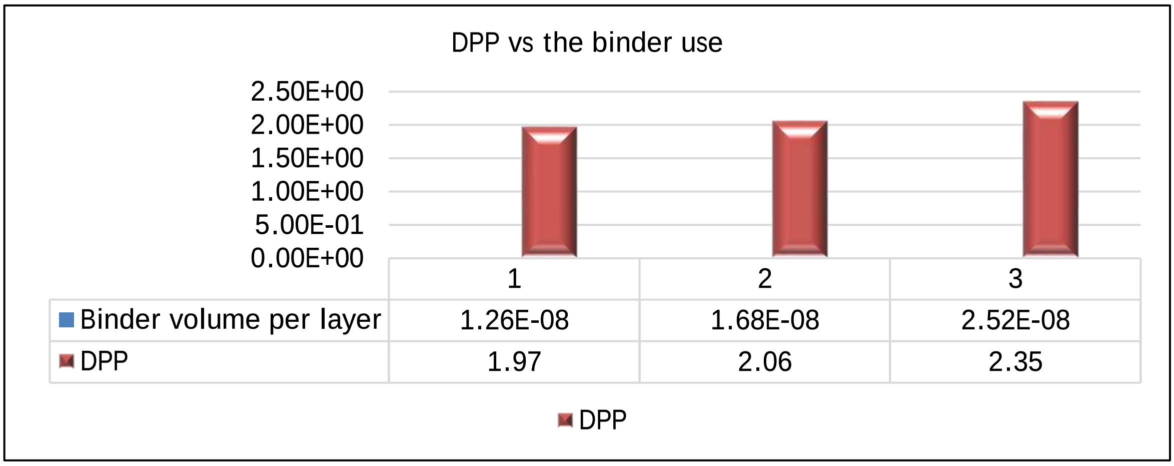

Figure 11: DPBP vs the binder used

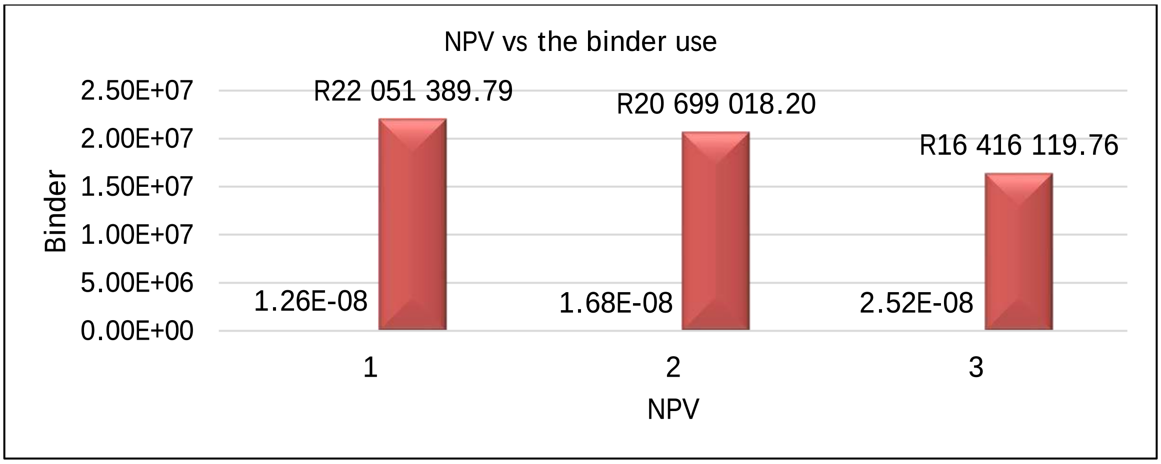

Figure 12: NPV vs the binder used

7 CONCLUSION

The DPBP and the NPV methods were applied to assess the financial feasibility of the rapid sand casting under various operational scenarios. These included the cost modelling results which led to the calculation of the gross profit cash flows. These cash flows then ultimately determined the DPBP and the NPV as 2.35 years and R16 416 119.73, respectively. The study showed that increasing the layer thickness and the binder used per layer, increases the DPBP while decreasing the NPV value. This means more time is required to recover the initial investment, but the recovery is within the 5-year period of this study, which makes the process feasible. Even though the NPV decreases with increasing layer thickness and binder usage, its value is still positive and greater than zero; and this confirms the feasibility of the rapid sand casting process. This is particularly notable due to the generally higher cost of purchasing binder compared to that of silica sand. The study also demonstrated that because the PBP does not discount cash flows, its drawback lies in not accounting for the TVM. Consequently, its recovery duration tends to be shorter compared to that of the DPBP. The investigation shows how to apply the DPBP and the NPV to assess additive manufacturing for foundry applications. Being a favourite method for financial feasibility assessment in the foundry industry, applying the DPBP to the rapid casting process also adds to its understanding in a language easily understood by local foundrymen.

8 FUTURE WORK

Future work could consider the implementation of mass production and other process variables in the foundry industry, which can impact the feasibility of producing a sand mould using binder jetting.

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Appendix A: Printing properties of the sand mould and the income statement with DCF based on local silica sand

Volume of the impeller sand mould	141 087 929.14 mm^3
Total cost of producing sand mould	R9 694.29
Price of the sand mould	R23 201.12
Sand moulds printed per day	2 per print
Layer thickness	0.3 mm
Binder per mm^3 (l) per layer	2.52E-08

	0	**1**	**2**	**3**	**4**	**5**
Year	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Revenues		**R12 064 581.942**	**R12 667 811.041**	**R13 301 201.591**	**R13 966 261.671**	**R14 664 574.754**
Cost of goods sold		**R5 041 031.705**	**R5 293 083.290**	**R5 557 737.455**	**R5 835 624.328**	**R6 127 405.544**
Gross profit cash flows		**R7 023 550.237**	**R7 374 727.749**	**R7 743 464.136**	**R8 130 637.343**	**R8 537 169.210**
Discount factor	1.000	0.935	0.873	0.816	0.763	0.713
Discounted	**-R15 200 000.000**	**R6 564 065.642**	**R6 441 372.826**	**R6 320 973.334**	**R6 202 824.300**	**R6 086 883.659**
Net present value	**R16 416 119.760**					

DEVELOPING A LEAPFROGGING MODEL FOR THE AFRICAN SIGNALLING SYSTEMS TO LEAPFROG TO THE LEVEL OF DEVELOPED COUNTRIES

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ABSTRACT

This research conducts a gap analysis of the African railway signalling systems' ecosystems. Based on the gap analysis, a leapfrogging model that can elevate the African continent to the level of the developed world when it comes to railway signalling systems is developed. The outcome of implementing this leapfrogging model is expected to be the latest railway signalling system that will reduce the trackside equipment like signals and train detection systems. This will result in reduced maintenance costs, reduced theft incidents and improved systems availability. Safety in railway operations will improve as there will be fewer manual train authorisations. The improved safety and efficiencies will attract more customers to use rail to move their commodities which will result in reduced cost of logistics as transporting commodities via rail is cheaper compared to transporting them via road.

Keywords: railway, signalling system, fourth industrial revolution,

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1 INTRODUCTION

Railway signalling can be defined as all systems used to control rail traffic safely, essentially to prevent trains from colliding [1]. Railway lines are segmented into sections called blocks. Signalling systems ensure that one train occupies a block at a time to prevent collisions.

While the African continent is still using obsolete signalling systems and has not fully benefited from the industrial revolutions, European countries like France, Germany and Spain have already implemented the European Rail Traffic Management System (ERTMS) where trains communicate their locations with one another via the Global System for Mobile Communication-Railway (GSMR) network and can automatically adjust their speeds to avoid colliding with the other trains in a network. The trackside equipment like track circuits and signals are removed in sections where the ERTMS level 3 is implemented, and this significantly mitigates the risk of theft and vandalism of the signalling trackside equipment and results in reduced maintenance costs.

In Africa, we are faced with socio-economic challenges where the signalling trackside equipment is vandalised and stolen, and a shortage of spares as the systems have become obsolete. The technology absorption remains a challenge and the barriers include poor/absence of research and development departments within the structure of the railway operators and lack or absence of railway engineering curriculum in the African universities. These barriers result in skills shortage, poor flow of data and information in the railway signalling ecosystem and thus poor absorption of the latest railway signalling systems.

In developing a leapfrogging model that will help the African continent leapfrog and be at the same level as the developed countries, a thorough gap analysis was conducted to understand how far back we have fallen behind the developed countries. The gap analysis then informed the leapfrogging model that will be used by the African continent to catch up with the developed countries. For the purpose of this paper, a leapfrogging definition that is adopted is that of “changing the game, creating something new or doing something radically different that produces a significant leap forward” [2].

Given the research objectives, the research questions are as follows:

1. What are the main differences between railway signalling ecosystems in Africa, Europe, and Asia?
2. What are the fourth industrial revolution (4IR) linked technologies that can be used to develop a leapfrogging model that will elevate the African continent to the level of the developed countries when it comes to railway signalling systems?
3. What are the barriers that can prevent the African continent from catching up and leapfrogging the leaders in signalling technologies like Asia and Europe? and
4. What is the leapfrogging model that will be suitable for the African continent?

2 LITERATURE REVIEW

The literature review for this study covered Fourth Industrial Technologies like Internet of Things (IoT) sensors and Mobile Communication Systems and the leapfrogging models like stage following and stage skipping.

2.1 Fourth industrial revolution technologies

Today we have globally connected computers, smartphones, cameras, supermarket scanners, and payment systems. All these paved the way for the fourth industrial revolution. Internet,5G wireless networks and cheap computing, all promote digital convergence. 4IR connects various devices, databases, and a variety of digital networks over the cloud [3]. Several developments have been witnessed during this industrial revolution like movies on the cloud (Netflix, Hulu, Amazon Prime, and Disney +), Cloud Storage (iCloud, Microsoft One Drive, and Amazon S3), complex analytics and computing (Google App Engine, Microsoft Azure, and Amazon elastic compute). The IoT and Blockchains are probably two of the most relevant 4IR technologies.4IR uses Internet of Things (IoT) sensors and blockchains to track and trace the movement of goods and people by assigning unique digital IDs to everything and tracking these IDs movements over time and space [3]. The 4IR will lead to major developments in areas like robotics digital transformation, automated and connected sensors, machine learning and analytics, Metaverse, Transparent transactions and supply chains. To catch up with developed countries, Africa should at some point of leapfrogging invest in the signalling technologies that will emerge from the 4IR.

In 2012, Europe introduced the ERTMS whereby the European countries developed and implemented standardised systems with standardised architecture and information and uniform technical interfaces between subsystems. The adoption of the standard led to improved interoperability and safety in European railways. ERTMS is an international standard programme created to develop a common interoperable platform for railways, authority, and signalling systems [1]. European Traffic Control System (ETCS) refers to the signalling system and GSMR is the international wireless communication standard for railway communication and applications [1]. GSMR is used to ensure communication between the Train Control Centres and Train drivers and between Train drivers and the signalling systems (see Figure 1).

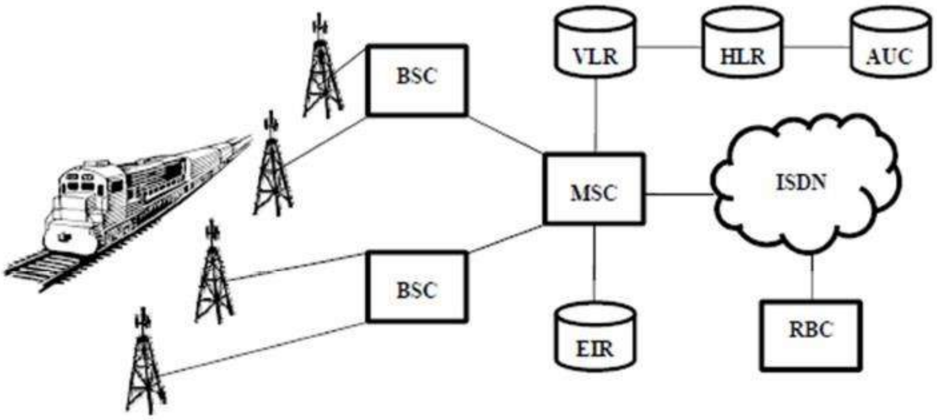

Figure 1: Global Network of the GSMR [1]

The ETCS is divided into Levels 1,2, and 3. The level is determined by the trackside equipment and how information from the trackside equipment is transmitted to the train. A train fitted with a complete ETCS can operate in any ETCS route.

In the ETCS level 0, the train is fitted with ETCS however the route is not fitted with ETCS. The train can monitor its maximum speed and the train driver needs to observe the trackside equipment (signals and points). At this level, the train can only monitor and control its speed but there is no interaction between the train and the track side equipment like the signals and track circuits.

The ETCS level 1 has the onboard ETCS, track side equipment like signals, track circuits and points machine and eurobalise. Eurobalise radio beacons pick the signal aspect(s) from the trackside signal(s) via the Lineside Encoder Units (LEU). The signal is then transmitted to the vehicle as a movement authority together with the route data. The onboard computer continuously scans this information and calculates the max train speed and the braking curve to ensure it stops at the next signal if, according to the movement authority, it must stop.

In ETCS level 2, the movement authority allows the train to drive itself. The signals are displayed on the train-borne cab hence the trackside signals can be removed. Track circuits are still used to detect the trains. All trains automatically report their exact position and direction of travel to the Radio Block Centre (RBC) at regular intervals through the GSMR network. Train movements are continually monitored by the RBC and train speed information and route data are transmitted to the train via GSM-R. The eurobalises are used as positioning beacons. The onboard computer continuously monitors the transferred data and the maximum permissible speed.

ETCS Level 3 provides an implementation of full radio-based train spacing. Track-side equipment like signals and track circuits are no longer needed. The position of the trains is determined using the beacons and via sensors. The route is no longer cleared in fixed track sections as the system calculates the distance between two trains. This is termed absolute braking distance spacing or moving block. It ensures optimal usage of the line capacity. The ERTMS benefited from developed computing and wireless networks (GSMR) which are key innovations in the Fourth Industrial Revolution.

2.2 Technology leapfrogging models

Technological leapfrogging can be defined as the process/strategy of bypassing stages in capability building or investment through which countries were previously required to pass during the process of economic development [4]. Hence the developing countries do not have to follow the same trajectory /path followed by developed nations when they were developing their technologies. In certain technologies like communication and railways, some of the stages can be missed. Steam trains form a major part of the railway's technology development phases, however, with the developments in the locomotives (diesel and electric locomotives are currently used and hydrogen locomotives are being developed), it would not make sense for developing countries to invest in steam locomotives. The development process is characterised by external influences. Referring to Figure 2, the normal path of technology development is the path followed by the developed countries and is followed by stage skipping where stage 3 of the normal path of development is skipped and lastly path creating is shown where stage 3 of the normal path of development is replaced by a new path.

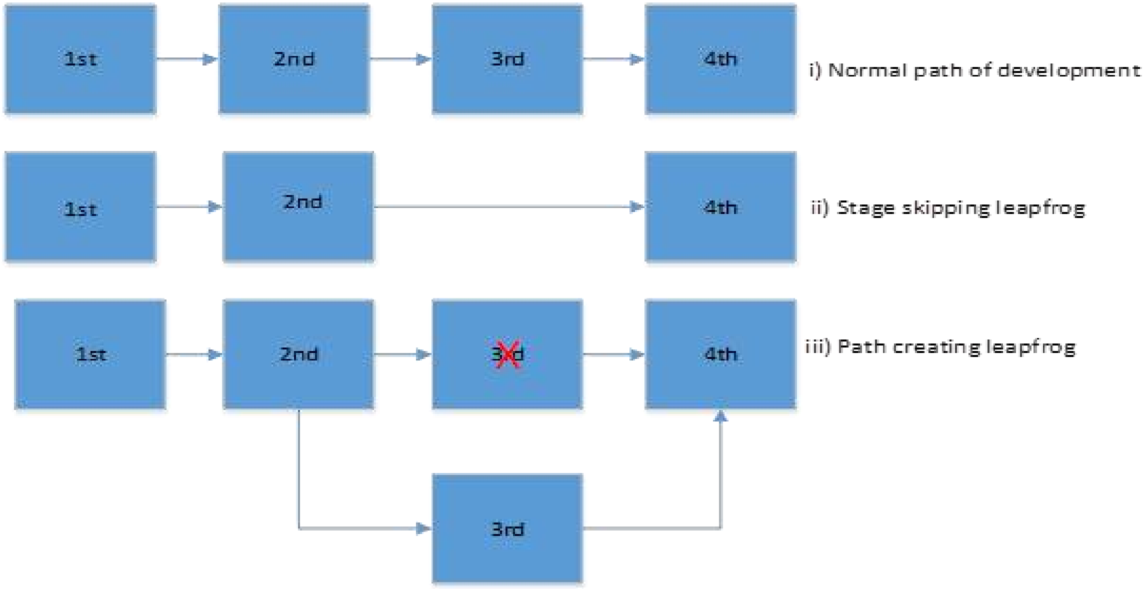

Figure 2: Pragmatic Process of Technological Development [5]

China was able to leapfrog into technologies such as the mobile phone [6]. They did not have to spend huge sums of money on physical infrastructure in terms of roads and phone wires to accommodate for a wired telecommunication network. Another way in which a leapfrog can occur is through the implementation of government policy [5]. This type of leapfrogging was used by China during the electric vehicle industry development. The path creating leapfrog in

Figure 3, requires a higher level of technological capability than in the other models. The model is risky. If it fails, it can lead to excessive project delays that result to financial losses.

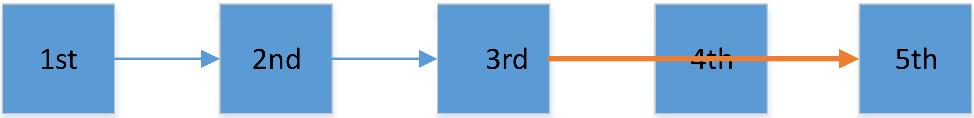

Figure 3: Paradigm Changing Leapfrogging [5]

Paradigm changing leapfrog shown in Figure 3, occurs when skipping over stages/generations results in the economic player leaping ahead of the other players and then becoming a leader in the technological field [6], This gives an inventor an advantage over its competitors over a period and allows an inventor to make a surplus profit. Korean steel industry successfully used a paradigm-changing leapfrog to outperform the former top steel producers. This strategy requires a sound strategy and technological and innovative capability. All the leapfrogging models require some form of technological capability [5].

Complex Product and Systems (CoPS) catch-up model relies on learning at both the technological and market level by the latecomers, acquisition of the indigenous systems through international technology transfer, assimilation of the acquired technologies by local Research and Development, improvement whereby the accumulated knowledge is used to develop more advanced products, and selection of the relevant catch-up strategies. China telecommunication firms first adopted path following and then path skipping towards the end. Japan and Korea used path path-creating strategy (see Figure 3) to be a global industry leader in shipbuilding. In addition, the secondary innovation model [7] focuses on latecomers in the Chinese context and emphasises the combination of acquired technologies and existing technology systems.

3 CONCEPTUAL METHOD AND PROPOSITIONS

The signalling systems in Africa have not benefited from the 4IR and the current ecosystem is not well developed, and it somewhat inhibits the absorption of signalling innovation technologies. Some barriers are limiting the absorption of the latest signalling systems in Africa. In this section, the signalling innovation ecosystems, 4IR technologies embedded in the current signalling systems and barriers that inhibit the adoption of the railway signalling systems, for Africa, Europe, and Asia, will be analysed. The analysed data will then be used to measure the gap between the African continent and Europe and Asia. The information will then be used to design the leapfrogging model that will be used by the African continent to leapfrog and catch up with the developed countries in Europe and Asia.

Figure 4 shows the research model which incorporates the following variables:

- Signalling innovation ecosystems in Africa (Xsie)
- Signalling innovation ecosystems in Europe (Ysie)
- Signalling innovation ecosystems in Asian (Zsie)
- Signalling systems (4IR technologies embedded in the systems) in Africa (X4ir)
- Signalling systems (4IR technologies embedded in the systems) Europe (Y4ir)
- Signalling systems (4IR technologies embedded in the systems) in Asia (Z4ir)
- Barriers to good signalling innovation ecosystems in Africa (Xb)
- Barriers to good signalling innovation ecosystems in Europe (Yb)
- Barriers to good signalling innovation ecosystems in Asia (Zb)

The gap analysis is then conducted where the three continents, Africa Europe and Asia will be compared against their railway signalling ecosystems, fourth industrial technologies that they have incorporated into their signalling systems and barriers that they encounter when they are developing their signalling systems. The results of the gap analysis will then be fed to the design, implementation, and testing of the leapfrogging model. The leapfrogging strategy will then focus on closing the signalling innovation ecosystems gaps, fourth industrial revolution technology gaps and barriers that exist between the three continents.

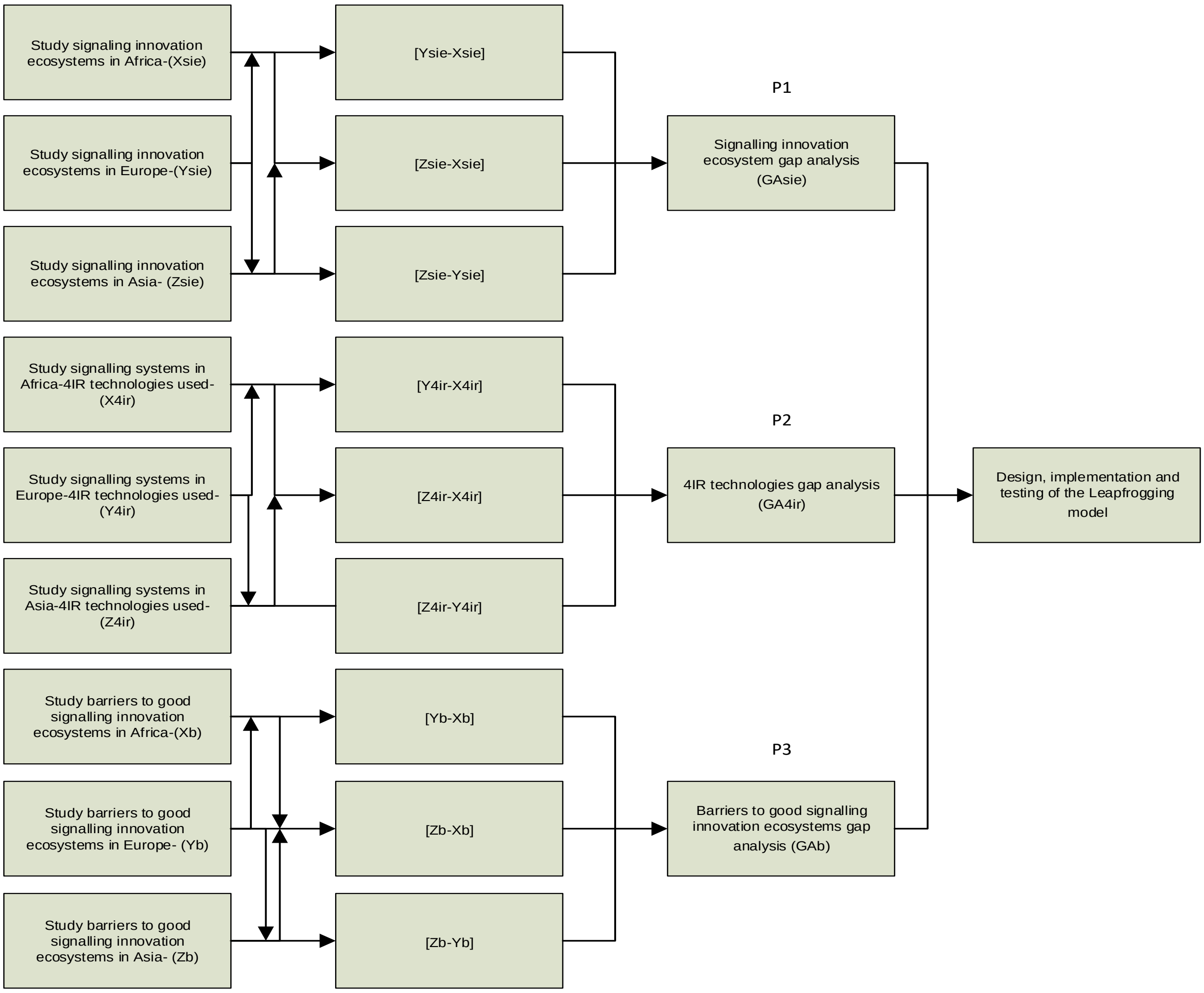

Figure 4: Conceptual model for the African signalling systems to leapfrog the European and Asian systems

Embedded in this research model, are the following propositions that were derived from the literature review:

- P1: The maturity of the ecosystem is linked to the absorption of technologies (ecosystems).
- P2: The developed countries benefited more from the 2IR, 3IR and 4IR compared to developing countries (4IR).
- P3: Due to the scarcity of signalling engineering skills in Africa, the absorption of signalling technologies has not been effective (barrier).

4 RESEARCH METHODOLOGY

For this research, a qualitative approach was adopted whereby a questionnaire was carefully prepared and shared with the participants before the interviews were conducted. Recorded interviews were held online. The interviews involved seasoned engineers, managers and lecturers in the field of railway engineering. A total of twelve interviews were conducted in South Africa, Kenya, the United Kingdom, Switzerland, and China.

In addition, the bibliometric analysis was conducted to measure the rail signalling systems' capacity of various countries. For this research, the articles related to railway signalling systems, and the fourth industrial revolution technologies like cloud computing, big data analysis, IoT, Long Term Evolution for Railways (LTE-R) and Future Railway Mobile Communication System (FRMCS) were sourced from the Web of Science Core Collection database. The advantage of using the Web of Science Core Collection is that it filters out other broad Web of Science databases, thus focusing on high quality research publications. Two types of analysis were conducted, namely performance analysis which looked at the contribution of research constituents to railway signalling systems and science mapping science which examined the relationships between research constituents.

Based on the interviews and bibliometric analysis data, gap analysis in terms of the railway signalling ecosystems, barriers encountered by various countries when developing their railway signalling systems, and fourth industrial revolution technologies incorporated in their railway signalling systems, was done. This was followed by the development of the rail signalling systems' leapfrogging model for developing countries.

5 SIGNALLING SYSTEMS GAP ANALYSIS BETWEEN AFRICA, ASIA AND EUROPE

5.1 Railway ecosystems

Using the collaborations that develop through citations, co-citations and co-authorship between authors in the same country and different countries, Africa has produced less number of articles on railway signalling systems, did not produce any articles on big data analysis in railway signalling systems, produced few articles on cloud computing and IoT and produced no articles on the Long Term Evolution for Railway mobile communication system and Future Railway Mobile Communication System. The low scientific productivity of the Africa continent denies the continent of creating strong collaborations between the countries in Africa and outside of the continent. The poor performance of the African continent is exacerbated by the absence of a railway engineering curriculum in most African universities.

5.2 Fourth industrial revolution technologies related to the railway signalling systems

According to the interviews, Africa has not started with the rollout of the fourth industrial revolution technologies. However, bibliometric analysis shows that Africa has done some research on cloud computing and the IoT in railway signalling systems.

Europe and Asia have produced more articles and received more citations on big data analysis, cloud computing, the IoT, LTE-R and FRMCS. Europe has received more citations (impact) than Asia on big data analysis, and LTE-R. Asia has received more citations than Europe on cloud computing, IoT, and FRMCS (see Table 1).

Table 1: Total articles and citations for the fourth industrial revolution-related technologies in railway signalling systems

	Big data analysis		Cloud computing		Internet of Things		Long Term Evolution-Railways (LTE-R)		Future Railway Mobile Communication System (FRMCS)	
Continent	Total Articles	Total Citations	Total Articles	Total Citations	Total Articles	Total Citations	Total Articles	Total Citations	Total Articles	Total Citations
Africa	0	0	5	2	5	1	0	0	0	0
Europe	48	130	11	8	35	161	9	35	47	24
Asia	48	97	22	137	53	314	53	27	57	779

5.3 Rail signalling system barriers

The gaps that hinder the adoption of the latest and emerging railway signalling technologies emerged from the interviews. **Table 2Table 2**, shows the gaps that emerged from Africa, Europe, and Asia.

Table 2: Barriers that emerged from Africa, Europe, and Asia

Barriers		
Africa	**Europe**	**Asia**
Funding	Capital	Integrated construction of signalling systems
Resistance to change	Concerns about the safety of the ERTMS system	Development of standards for cloud computing
Labour unions		Standards for big data technology
Misalignment of priorities	Decision-making takes time	Integration plan for railway signalling systems
Shortage of experienced Engineers	Staff changes	
Limited exposure to technologies		
Expensive latest systems	ERTMS installation is expensive	
Poor training of Engineers/On job training	Re training of staff	
Poor policy direction		
Lack of local suppliers	New spares	
Longer lead times		
Project financing	Not feasible to fit newly procured trains with ERTMS	
Poor availability of the systems		
Theft and vandalism		

6 RAILWAY SIGNALLING SYSTEMS LEAPFROGGING MODEL

According to the empirical data, the major challenges that the African continent is facing include low production of articles on railway signalling systems and technologies linked to the fourth industrial revolution (from bibliometric analysis), absence of collaborations amongst the countries in the African continent (from bibliometric analysis), limited collaborations between the African continent and the developed continents like Europe and Asia (from bibliometric analysis), shortage of railway signalling skills (from the interviews), theft and vandalism of the signals trackside equipment like train detection systems, signals and signals copper cables (from the interviews), shortage of funds to absorb the latest railway signalling systems (from the interviews), and poor policy direction (from the interviews). The leapfrogging models proposed for the African continent aim to resolve these challenges faced by the African continent.

Due to the increased theft and vandalism of the signalling trackside equipment, a system that can reduce the number of the signalling trackside equipment and reduce the length of copper used is ideal for our environment. To solve these problems, it is proposed that the African continent adopt the European Railway Traffic Management System (ERTMS) level 3. The project will be divided into four stages. The following leapfrogging model will be used where ERTMS levels 0 to ERTMS to level 3 will be installed in 4 phases.

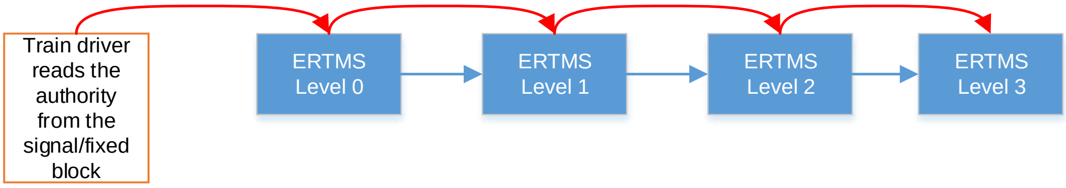

Figure 5: Stage Following Model by the African Continent from European Traffic Management Systems from Level 0 to Level 3

Stage 1

This will involve the fitting of locomotives and Electric Multiple Units (EMUs) with the on train ERTMS components like odometer pulse generators, doppler radar sensors, eurobalise antenna, European Vital Computer (EVC), Juridical Recording Unit (JRU), ETCS safety isolation switch, Driver Machine Interface (DMI) and Automatic Train Protection System (ATP). The rolling that will be procured from now on, should be fitted with the ERTMS systems/components. After stage 2 is completed, we will have ERTMS level 0, where the trains will be able to warn the driver if the speed restrictions are exceeded and automatically apply the brakes if the driver does not respond to the alarms/warnings. This will eliminate the speed-related train derailments and result in huge financial savings.

Stage 2

The second phase will involve the installation of the passive eurobalises and Line Encoder Units (LEU) that will interface the signals with the eurobalise and hence allowing the transfer of a Movement Authority (MA) from a signal to the eurobalise. Once the second phase is finalised, ERTMS level 1 will be achieved whereby the train will read the movement authority (signal aspect) from the eurobalise and the ATP will then adjust the speed according to the movement authority read by the train. For example, if the aspect of a signal ahead is red (stop), the ATP will use the distance between the eurobalise and a signal, to calculate/ select the speeds at which the train should traverse the track to be able to stop in front of the next signal. The implementation of ERTMS level 1, will eliminate the Signals Passed at Danger (SPADS) incidents and hence mitigate/eliminate the risk of train collisions.

Stage 3

Stage 3 will involve the implementation of mobile communication system equipment including the RBCs. This will be stage skipping leapfrogging model where the installation of the GSMR and LTER will be skipped. The FRMCS will be installed. FRMCS is developed by UIC in collaboration with the other railway stakeholders. It will replace the Global System for Mobile Communication- Railway (GSMR). It is currently being tested however by the time, phase 2 is completed, FRMCS will be tested and ready to be rolled out. The phase will also include the transfer of signals onto the train and the replacement of the track-side signals with ERTMS markers. Once this phase is complete, all the trackside signals will be removed, and the trains will receive the movement authorities via the mobile communication system (FRMCS) and ERTMS level 2 will be achieved. The removal of the signals will result in a significant decrease in the number of signals trackside equipment and a major reduction in the length of signals copper cables used. This will significantly mitigate the risk of theft and vandalism.

Stage 4

Stage 4 will involve the installation of a system that will accurately detect the position of trains in the network, their speed and direction. Each train in a network will send this information to the RBC via FRMCS. The trains will receive, in real-time, information about the whereabouts of the trains in a network, their speed and direction and the movement authority. Each train in a network will then use this information to calculate and set its speed which will result in the safe following distance between itself and the train in front (moving block). Once stage 4 is finalised, ERTMS level 3 will be in place and the moving blocks where the following distance between the trains is not fixed but are calculated based on the speed, location, direction of the other trains in a network and the braking capabilities of a train. Moving blocks result in reduced following distance between trains and optimum utilisation of the line. ERTMS level 3 will result in the removal of the train detection systems like track circuits and axle counters. So, with ERTMS, the trackside equipment like Signals and train detection systems are completely removed. This will result in a further reduction in the number of the signals trackside equipment and signals copper cables. The assets' maintenance costs will significantly decrease, and the risk of theft and vandalism will be mitigated.

Stage 3 which involves the installation of ERTMS level 3, will also include stage skipping leapfrogging model from the trunk radio/cell phones to the emerging FRMCS (see Figure 6). Each will take at least five years so the installation of the FRMCS will take place after 15 years. At that time the FRMCS will be matured, and we would have developed the African technology absorption capabilities, research and commercialisation economy and collaborations within and outside the continent.

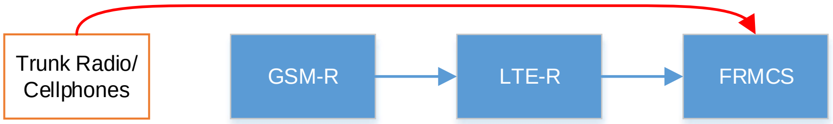

Figure 6: Stage Skipping Model from Trunk Radios to the Future Railway Mobile Communication System

The African universities will be supported by governments to introduce a railway engineering curriculum that will cover all the railway engineering disciplines like Perway (track and structure), electrical (substations and overhead track equipment), signals and telecommunications (signals interlocking systems and mobile communication systems) and rolling stock (electric motor units). According to the bibliometric analysis, the majority of the research work is conducted by the universities so by introducing the curriculum in African universities, the number of articles on railway signalling systems will increase, the collaborations between the countries within and outside the African continent will improve. The railway signalling model for the African continent will be included in the African countries' railways strategies and an African railways workgroup with representatives from the African continents will be formulated and it will be responsible for the implementation of the strategy/plan. The workgroup with be comprised of representatives from the railway operators, regulators, universities, railway policy makers, railway signalling start-ups, and railway signal systems suppliers. This will lead to a matured railway signalling ecosystem where there will be a free flow of information, knowledge and experience which will in turn result in new networks, clusters, and new actors, and increase railway signalling innovations which will improve our current systems and prepare the African continent from leapfrogging to the emerging railway signalling systems in the next 20 years. In the next 20 years, the African continent will have technology capabilities to adopt the emerging train management systems and mobile communication systems (see Figure 7) which will elevate the African continent to be a forerunner in railway signalling technologies.

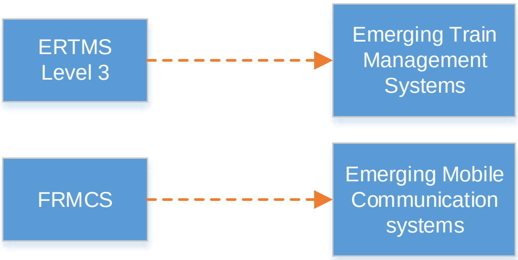

Figure 7: Adoption of the Emerging Technologies by the African Continent

7 CONCLUSION

As shown through the bibliometric analysis, there are few collaborations between the African countries and the countries outside of the African continent and for the African continent to improve its railway signalling ecosystems, the African Union should start work groups, that should be attended by the Railway stakeholders from all the African countries. These workgroups should meet at least half-yearly, to discuss the key challenges that the railways in Africa are facing and come up with solutions to resolve them. As a result, they will result in improved collaborations between the countries in the African continent and monitor the implementation of the leapfrogging strategy.

The bibliometric analysis highlighted that the African continent is not actively producing articles on railway signalling systems and the fourth industrial revolution technologies that the developing countries are already integrating with their current railway signalling systems. It also emerged from bibliometric analysis that most of the articles are produced by the universities hence for the continent to increase the number of articles produced in a year and citations received, the African universities, like the European and Asian universities, must offer undergraduate and postgraduate studies in railway engineering and consider introducing the curriculums in railway engineering. If they agree to revise their curriculums to include railway engineering, this will result in increased research in railway signalling systems and result in several local products/ideas reaching the manufacturing and marketing phase. It will help us deal with the technology colony that results in our overreliance on the overseas developed solutions which emerged from the interviews as a barrier to the absorption of the latest signalling systems.

It emerged from the interviews that signalling engineering skills are scarce in the African continent so to improve our engineering skills levels and be ready to adopt the latest and emerging technologies that will help the continent leapfrog the forerunners like Europe and Asia, the governments in Africa should offer scholarships to Engineering students to study Railway Engineering in the European and Asian universities. This will result in increased railway signalling capacity in the country and improved railway signalling systems absorption.

Once the African continent can compete with Europe and Asia in railway signalling research, the African continent will be ready to exploit the current railway signalling systems through exploitation and upgrading of the systems using the fourth industrial revolution technologies. The universities and research institutes to conduct more studies/research on how the continent can use some of the systems that come with the fourth industrial revolution and the next industrial revolution to improve our railway systems. This can help us leapfrog the developed countries and be at the forefront.

The interviews indicated that the African railways are disintegrated and the railway signalling systems are misaligned which limits the movement of trains throughout the borders in Africa. So, to solve the problem, a standard like the European Railway Traffic Management System for the African continent must be developed to deal with the interoperability issues.

Poor funding of the start-ups in railway signalling systems was one of the issues raised by the interviews. The governments in the African continent should consider funding the railway signalling start-ups in Africa. If the continent can develop systems in Africa to deal with the continent's challenges, the barriers like high costs of procuring and installing the latest signalling systems and long material lead time will be something of the past.

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EVALUATING AND ENHANCING VEHICLE FLEET MAINTENANCE: LEVERAGING PREDICTIVE ANALYTICS AND SMOTE FOR OPERATIONAL EFFICIENCY AND COST SAVINGS

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ABSTRACT

A good predictive vehicle maintenance system has the capacity to identify potential maintenance needs, mitigate unexpected breakdowns and increase the vehicle lifespan. Hence, the need for organizations such as logistics companies keeping vehicle fleets to develop such predictive systems. In this study, selected machine-learning techniques are used for predicting fleet maintenance using vehicle telematics and maintenance data from a logistics company. In addition, the study evaluates and compares the predictive performance of the machine learning techniques. To address the class imbalance affecting the predictive modelling, the Synthetic Minority Over-sampling Technique (SMOTE) was utilized to rebalance the class distribution of the dataset. Through SMOTE integration, data imbalance was successfully rectified notably enhancing performance metrics for the minority classes. Based on our prediction results, we discuss the pivotal role of data-driven decisions, and technological innovations in optimising fleet operations and revolutionizing traditional maintenance strategies.

Keywords: Fleet maintenance, predictive maintenance, machine learning models, SMOTE, class imbalance.

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1 INTRODUCTION

The digital transformation, chiefly driven by Industry 4.0 and the Internet of Things, has revolutionized our society into a data-driven landscape[1]. This evolution has become a cornerstone for refining operational procedures through insightful, data-backed decision-making. Within this context, predictive maintenance, empowered by machine learning, has emerged as a transformative capability [2]. By utilizing real-time data obtained from continuous condition monitoring, predictive maintenance aims to forecast maintenance needs, thereby optimizing resource allocation, minimizing operational interruptions, and significantly reducing costs [2].

In the logistics sector, the effective maintenance of vehicle fleets is critical for ensuring punctual deliveries, prolonging asset longevity, and sustaining a competitive edge. Traditional maintenance methods, which typically respond to issues as they arise, are increasingly seen as suboptimal [2], [3]. This has led to the advent of predictive maintenance, a proactive approach that leverages vehicle telematics and machine learning to identify potential maintenance needs, thereby averting unexpected breakdowns and ensuring uninterrupted operations. The core challenge in implementing effective predictive maintenance lies in accurately interpreting intricate sensor data from fleet vehicles, given the nuanced nature of the dataset and the potential for class imbalances in the labelled data which can result in skewed predictions [4], [5].

This study explores predictive maintenance using machine learning while also exploring related failure and cost analysis. Predictive maintenance strategies are essential not only for business competitiveness but also for maintaining reliability in delivering quality products and services. We aim to leverage machine learning algorithms to accurately predict maintenance needs, ensuring optimal fleet performance and minimizing potential downtimes.

We used a case study of Company X, a prominent logistics and courier enterprise based in Johannesburg, South Africa. A telemetric dataset was obtained from their fleet of approximately 1,500 vehicles. This dataset provides insights into the fleet's operational dynamics and is useful in the predictive study. This proactive approach is especially beneficial to enterprises such as Company X, which operates under service-level agreements that mandate the operability of machinery within designated timeframes to avoid penalties.

Our research question that forms the foundation for this study is given: "How can various machine learning models be effectively evaluated and optimized in their predictive capabilities for vehicle maintenance requirements while utilizing real-world operational data from a commercial fleet?”

Based on this question we intend to: (i) Evaluate multiple classification algorithms' predictive performance on Company X vehicle fleet maintenance dataset to predict whether there will be a breakdown or not. (ii) Optimize the performance of the classification algorithms by investigating the impact of external factors like class imbalance, dataset completeness, and feature relationships on predictive performance. (iii) Utilize the insights gained from the algorithm performance and enhance operational efficiency by improving the maintenance strategy and resource allocation based on the refined predictive analytical insights.

2 LITERATURE REVIEW

2.1 Maintenance of vehicle fleets

The significance of maintenance management in vehicle fleets is underscored by its impact on energy efficiency, the vehicle maintenance process itself, the primary transport process, and the overall environment [6]. Efficient maintenance management is essential for a well-run fleet, which in turn affects the business's overall operation, making it more cost-effective and smoother-running [3]. As indicated in [7] every fleet manager recognizes the crucial role of preventive maintenance (PM) for the health of fleet assets. Thus indicating the overarching importance of maintenance in ensuring the longevity and performance of vehicle fleets.

According to [8], traditional maintenance strategies in vehicle fleets typically range from reactive maintenance (post-failure analysis maintenance) to preventive maintenance schedules based on time or usage irrespective of the actual condition of the vehicles. Therefore an integrated approach to fleet maintenance management seeks to decrease total maintenance costs and increase energy efficiency through a blend of measures, actions, and decision-making.

The evolution of maintenance has progressed from reactive strategies (fixing equipment after a failure) to preventive strategies (scheduled maintenance regardless of equipment condition), and further to predictive maintenance, which estimates when maintenance should be performed based on the condition of in-service equipment. This evolutionary step promises cost savings over routine or time-based preventive maintenance as tasks are performed only when warranted, making it a condition-based maintenance approach [9].

Predictive maintenance (PdM) as highlighted in [10], is characterized by the utilization of data analytics and machine learning to monitor the condition and performance of equipment during normal operation. This monitoring helps in identifying and addressing issues as they occur, and in predicting the potential future state of the equipment to reduce risk. It leverages both historical and real-time data from various operational aspects to anticipate issues before they transpire. The core areas that factor into predictive maintenance include real-time monitoring of asset condition and performance and the analysis of work order data [11]. As shown by [2], predictive maintenance could be data-driven primarily relying on historical and real-time data collected from the fleet to make predictions about maintenance needs or model-based, utilizing mathematical or simulation models to predict maintenance needs [12]. Hybrid approaches are also discussed by [13] as combining both data-driven and model-based techniques to leverage the strengths of both methods.

Predictive maintenance offers numerous advantages over traditional maintenance techniques [14]. They noted that this could be by reducing the costs associated with sudden breakdowns and reactive maintenance or a proactive approach helping companies save money, reduce downtime, and increase equipment reliability. In addition, it could be by improving the efficiency and longevity of the equipment to ensure that vehicle fleets remain operational for a longer duration, thereby enhancing productivity.

Before predictive analytics are deployed for the maintenance of vehicles, data has to be collected. As described in [15], telematics is a technology that facilitates the digital transmission of data from vehicles. The data collected from vehicle telematics includes various details such as location, speed, time spent idling, incidents of sudden acceleration or braking, fuel consumption, vehicle faults, and more. This data is then processed and analysed to extract insights that improve both the efficiency and safety of driving. Furthermore, vehicle telematics is applied in other areas, including emergency response systems, car-sharing services, insurance assessments, and the enhancement of maintenance protocols [15]. According to [16], various types of sensors such as Speed Sensors, Temperature Sensors, Pressure Sensors and Vibration Sensors are utilized in vehicles to gather data useful in predictive maintenance. These sensors, along with others, form a network of data collection points that continuously monitor different parts and components of the vehicles.

2.2 Predictive Analytics and Maintenance

After data is collected using vehicle telematics it often needs to be pre-processed to ensure its quality and reliability for meaningful predictive maintenance insights [13]. Data preprocessing includes Noise Reduction and filtering out noise to obtain a clear signal. Also Normalization (Scaling the data to a standard range) and Outlier Detection (Identifying and handling anomalous data points) [13].

Predictive analytics is a subset of data analytics that identifies patterns within data to make forecasts for the future [17]. It identifies patterns and relationships in data using statistical algorithms and mathematical formulae in conjunction with IT tools [18]. Three types of Machine Learning (ML) techniques were described by[19], namely Supervised learning, Unsupervised learning and Reinforcement learning.

According to [19], in a supervised machine learning model, a dataset is trained covering examples of the inputs as well as target values or designated answers for the output, while an unsupervised model detects patterns without any defined labels or specifications. They further noted that in reinforcement learning, systems are not provided with inputs and outputs, but are instead given a description of the current state of the system, a goal, a list of allowable or permitted actions and their environmental constraints.

[20] discusses six types of machine learning algorithms commonly used namely; The Artificial neural network, Decision Trees, Support Vector Machines, Naïve Bayes, Logistic Regression and K Nearest Neighbours (KNN).

Machine learning algorithms can be employed in predictive maintenance to analyse the data based on one or more of the following categories: Regression Analysis (To predict continuous values for the remaining useful life of components), Classification (To categorize the condition of components into predefined classes, like 'healthy' or 'faulty'), Time-Series Analysis (To analyze temporal data and identify trends or anomalies over time, Clustering (To group similar data points together, which can help in identifying patterns or anomalies) [2] [21] [22].

2.3 Handling Imbalanced Data and SMOTE in Predictive Maintenance

In predictive maintenance, imbalanced data is a common challenge to encounter. It arises due to the disproportionate representation of classes in the dataset. Typically, there are far more instances of normal operating conditions than there are of failure conditions. This imbalance can significantly affect the performance of machine learning models, as they may become biased towards the majority class, leading to poor predictive accuracy for the minority class, which often represents the failure conditions that are crucial to detect [4].

The success of machine learning models largely hinges on the nature of their data - its quality, quantity, and how it's distributed. A key issue often encountered in practical applications of machine learning is whether the datasets are balanced[23].

A balanced dataset is characterized by having an approximately equal number of examples for each class. In binary classification, this means a 50-50 split between positive and negative examples. Balanced datasets are beneficial because they help enhance the model's ability to generalize and prevent biases toward particular classes. However, achieving a perfectly balanced dataset in real-world situations is uncommon, and artificially balancing datasets may not accurately mirror the true distributions of classes, which could hamper the model's effectiveness in actual use cases [24].

On the other hand, an imbalanced dataset occurs when one class is represented much more than the other(s). Such datasets are common in real-life situations, like in fraud detection or cancer screening, where one class naturally predominates [5]. The advantage of using imbalanced datasets is that they more accurately depict real-world class distributions. Nevertheless, this can lead to a skew towards the majority class, reduced generalization of the model, and potentially deceptive evaluation metrics.

As noted by [5], various techniques have been devised to address the class imbalance issue in predictive maintenance. Such as Under-sampling (Reducing the number of instances from the majority class), Over-sampling (Increasing the number of instances from the minority class by duplicating examples or generating synthetic examples) and synthetic data generation creating new instances that resemble the minority class to balance the class distribution). [25] describes a Synthetic Minority Over-sampling Technique (SMOTE) as a popular method used to address class imbalance in predictive maintenance and other domains. It generates synthetic examples of the minority class, thereby balancing the class distribution and improving model performance. [25] further detailed the steps as below:

- Identifying Minority Class Instances: The initial step involves identifying instances belonging to the minority class, which are rare or underrepresented within the dataset.
- Selecting k-nearest Neighbours: For each minority class instance, its k nearest neighbours from the same minority class are selected. The parameter k is a critical factor that must be carefully chosen.
- Generating Synthetic Examples: Synthetic examples are systematically generated for each minority class instance by interpolating between the instance and its k nearest neighbours. This interpolation is performed by selecting random values between 0 and 1, which are then multiplied by the differences between the feature values of the instance and its neighbours. The resulting synthetic examples are introduced into the dataset.
- Repeating for All Minority Instances: This process is repeated iteratively for every minority class instance present.

2.4 Real-world Implementations and Case Studies

A study employed a technology called COSMO for predictive maintenance in vehicle fleets, particularly focusing on detecting compressor failures in a fleet of city buses using sensor data [2]. Another simulation-based case study aimed at optimizing the maintenance schedule for a vehicle fleet, suggests that strategic maintenance scheduling can significantly enhance operational efficiency and reduce maintenance costs [26]. An unsupervised streaming anomaly detection approach was utilized for predictive maintenance in a vehicle fleet management setting, exploring a variety of unsupervised methods for anomaly detection such as proximity-based, hybrid (statistical and proximity-based), and transformers [12]. Real-world data collected from vehicle garages was used for training and testing Long Short-Term Memory (LSTM) Autoencoders, comparing this method with several support vector machine variants for predictive maintenance in vehicle fleets, specifically for a telecom-based company [13]. A novel Internet of Things (IoT) architecture was proposed for predictive maintenance in fleet management, featuring a semi-supervised machine learning algorithm aimed at improving sensor selection for better predictive accuracy [27].

3 METHODOLOGY

In this section, we describe the historical data analyzed, approaches, tools and quantitative techniques utilized in predictive analytics. Figure 1 provides a brief illustration of the methods employed.

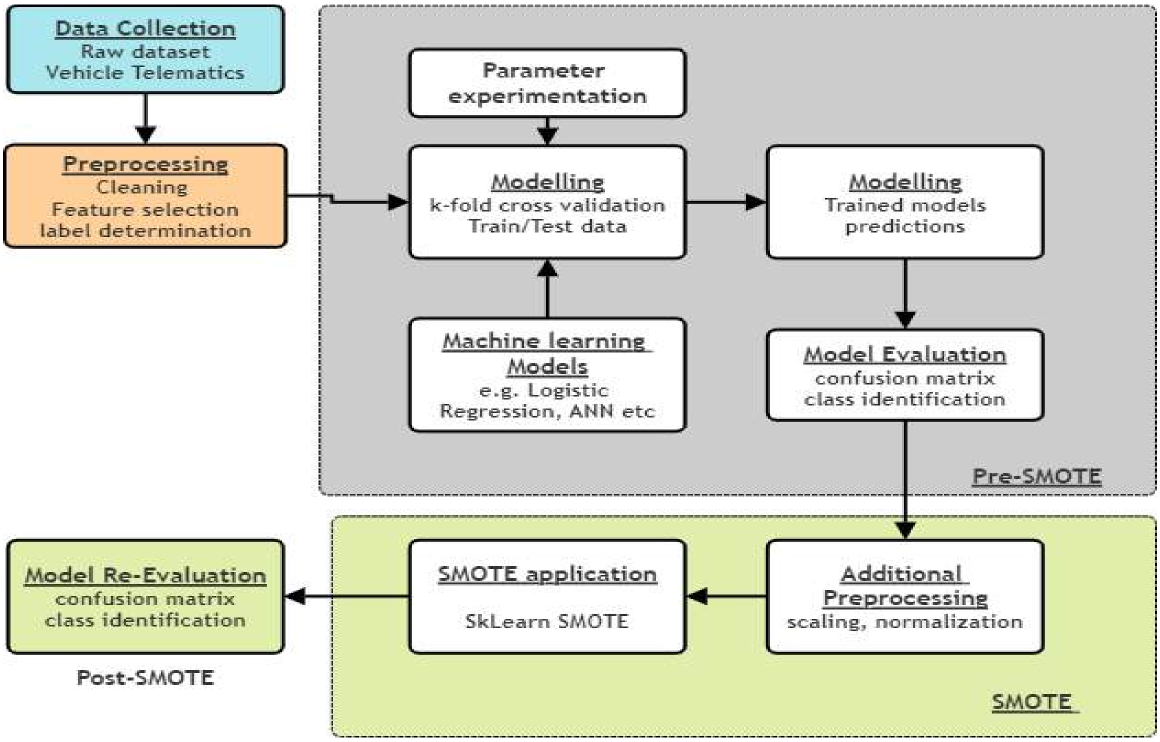


Figure 1: Methods in the research showing Pre-SMOT, SMOTE and Post-SMOTE analysis

3.1 Data collection and pre-processing

The vehicle data in this study comprised both regular operational metrics and rare failure events and was subjected to a preliminary analysis to understand its structure, quality, and the challenges it presented. This raw dataset consisted of thousands of data points and more than 20 possible features for the predictive study. Our feature selection was based on numeric features that relate to how the vehicle was being driven and treated during the investigation period and provide a seeming relationship to whether there could be a breakdown or not.

For this study, out of the 1,500 vehicles in the fleet, only vehicle types that are involved in delivering parcels from the warehouse to the customer were considered as these vehicles were sufficiently similar in terms of characteristics and function. Also, our target variable (outcome) was decided by identifying vehicles that were listed for Repairs and Maintenance based on major breakdowns such as if a mechanical part was mentioned as broken/replaced on the sheet. Lastly, if there was a mention of a breakdown in the raw data sheet. Breakdown due to routine maintenance like oil changes, windscreen damage, and tyre changing was not considered a major breakdown. Table 1 provides a summary of the data property and the pre-processing conducted while Table 2 shows the selected features used in the study and its attributes.

Table 1: Dataset properties and characteristics

Property	Description
Attribute Characteristics	Real
Associated Tasks	Classification,
Number of Instances (vehicles)	1,206
Number of Attributes	12
Missing Values (e.g. No repairs and maintenance records for an instance-vehicle)	Handled and removed from the dataset
Field of application	Logistics and Transportation
Data Collected	Over a 6-month period in 2023

Table 2: Dataset features and attributes

Features	Attributes
- Asset Number (Vehicle ID)	Numerical
- Row Labels (Number Plate)	Categorical
- Sum of Distance	Numerical
- Average Driver Score	Numerical
- Sum of Active Speeding	Numerical
- Sum of Speeding	Numerical
- Sum of Harsh Acceleration	Numerical
- Sum of Harsh Braking	Numerical
- Sum of Over Idle	Numerical
- Sum of Fatigue Driving	Numerical
- Age of Vehicle	Numerical (in years)
- Serviced in Period?	Numerical
- Breakdown (on Repairs and Maintenance List)	Numerical-Target Label

3.2 Modelling Approach

3.2.1 Initial modelling approach (Pre-SMOTE)

The use of the Anaconda Python distribution bolstered the study's validity. With its suite of standardized tools, including Classification Learner, Scikit-learn, and NumPy, the research benefited from accurate algorithm implementations for training-test splitting, training, validation and testing. This further reduced the likelihood of manual coding errors. Reliability was evidenced through consistent methodologies applied uniformly across all algorithm testing. This included performing repeated k-fold cross-validation of models to reduce variance and overfitting, as well as separating datasets into isolated training and testing splits.

After obtaining the data as discussed in section 3.1, the dataset was split into training and testing data sets using a 70-30 ratio for each algorithm. This separation ensured that the models were trained on one subset of the data and evaluated on a separate subset of the data to assess their generalization performance. Several ML techniques could be selected for analysis, each addressing the prediction task differently. However, the Naïve Bayes (NB), Decision Trees(DT), Random Forest(RF), Support Vector Machine (SVM), k-nearest Neighbours (KNN), Gradient Boosting(GB), and Artificial Neural Network (ANN) were chosen based on their suitability for the dataset and problem. The machine learning model settings used are listed in Table A1 of the Appendix. We note that the default configuration arguments from Scikit-learn (Sklearn) were used in the modelling. Specific parameters that were required such as the number of hidden layers and number of neurons in the Neural network were obtained through random experimentation.

After the training, the models were evaluated using the testing data. The evaluation process included generating the confusion matrix, and a detailed classification report for each model and using the accuracy metric for comparison. Additionally, model performance was assessed using metrics such as precision, recall, F1-score, and support for each class of the target outcome (breakdown or no breakdown).

Permission was obtained from the company to access and use the data for research purposes, and confidentiality and data protection were strictly adhered to throughout the research process, ensuring that the privacy and anonymity of individuals and the company were maintained. Hence the description of Company as “Company X”. The research was conducted with integrity and by ethical principles to uphold the trustworthiness and credibility of the findings.

3.2.2 Modelling approach with SMOTE

To ensure the precision of the SMOTE implementation, a well-structured series of steps were followed:

- Data Preprocessing: The workflow is initiated with thorough data preprocessing, encompassing essential data cleaning, normalization processes, and feature scaling to harmonize feature scales across the dataset.
- Minority Class Identification: The correct identification of the minority class, explicitly representing instances related to maintenance needs, formed the foundation of the approach.
- K selection: The optimal value of the parameter k was not arbitrarily chosen but was the result of exhaustive experimentation and validation, with dataset characteristics significantly influencing the choice.
- SMOTE Application: The integration of SMOTE into the data preprocessing pipeline was conducted with meticulous attention to detail, ensuring its seamless and accurate application.
- Continuous Monitoring: Post-SMOTE application, the resultant dataset was systematically monitored, evaluating class balance and scrutinizing the quality of synthetic samples continuously.

3.2.3 Metrics for model evaluation

The performance of the classification problem was evaluated using a confusion matrix. This matrix is essentially a table that has two dimensions: "Actual" and "Predicted." Within these dimensions, there are four components: "True Positives (TP)," "True Negatives (TN)," "False Positives (FP)," and "False Negatives (FN). Based on these components, the following metrics were used in evaluating the performance of the pre-SMOTE and post-SMOTE models as indicated in Table 3.

Table 3: Machine Learning Model Metrics [15]

Metric	Definition	Formula
Accuracy	The number of correct predictions compared to the total instances or cases	$\frac{TP+TN}{TP+TN+FN+FP}$
Precision	The number of true positives compared to the total predicted positives	$\frac{TP}{TP+FP}$
Recall	The number of true positives compared to the actual positives.	$\frac{TP}{TP+FN}$
Specificity	The number of true negatives compared to the actual negatives	$\frac{TN}{TN+FP}$
F1 Score	The harmonic mean of precision and recall, provides a balance between the two.	$2*\frac{Precision*Recall}{Precision+Recall}$

4 RESULTS

Table 4 summarizes the Models and their overall performances before the implementation of SMOTE, showing the overall accuracy of the models, weighted performance (based on the different proportions of the total class size of 362) and performance with regard to individual class identification (Class 0: No breakdowns, Class1: Breakdowns). The Naïve Bayes is shown to provide the best accuracy in prediction.

Table 4: Results Summary

	Weighted				Class identification	
Model	**Accuracy**	**Precision**	**Recall**	**F1**	**Recall (class 0)**	**Specificity (class 1)**
DT	0.73	0.74	0.73	0.73	0.16	0.84
GB	0.83	0.77	0.83	0.78	0.05	0.98
KNN	0.83	0.76	0.83	0.78	0.05	0.98
NB	0.84	0.79	0.84	0.79	0.12	0.97
ANN (Neural)	0.77	0.72	0.77	0.74	0.05	0.91
RF	0.82	0.73	0.82	0.76	0.03	0.97
SVM	0.83	0.7	0.83	0.76	0.00	0.99

Figure 2 shows each model as a function of True positives and negatives as well as false negatives and positives.

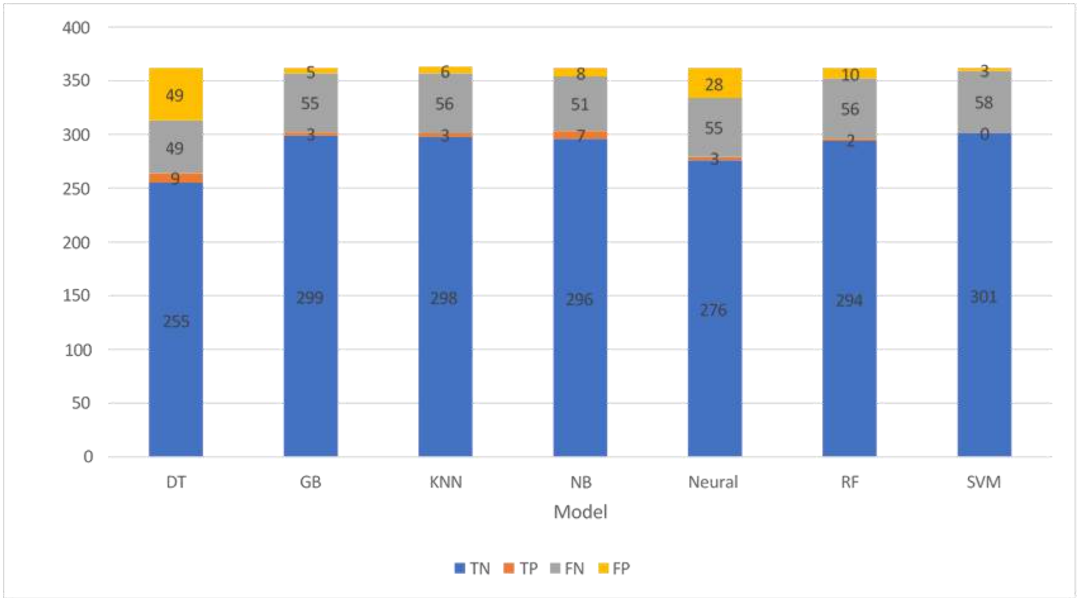
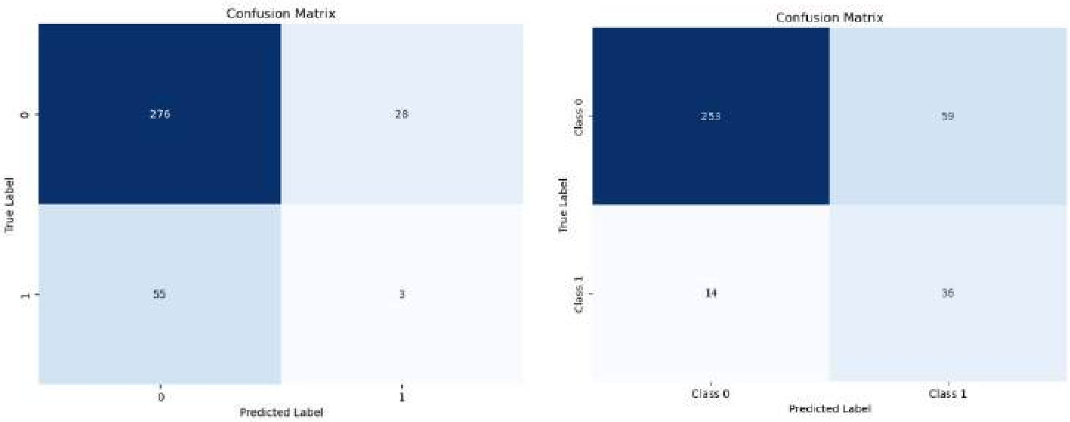


Figure 2: Summary of Pre-SMOTE results as a function of Confusion matrix components

After experimenting with the dataset and SMOTE for each of the models, it was found that the neural network outperformed all other models. The confusion matrix obtained for the neural network before and after SMOTE is illustrated in Figure 3.



Before SMOTE

After SMOTE

Figure 3: ANN(Neural) Confusion matrix Pre-SMOTE and Post-SMOTE results

Looking at the actual metrics from the confusion matrices in Figure 4 compares the performance of two models, one before and one after the application of SMOTE, across three key metrics — Precision, Recall, and F1 Score — for two different classes (Class 0 and Class 1).

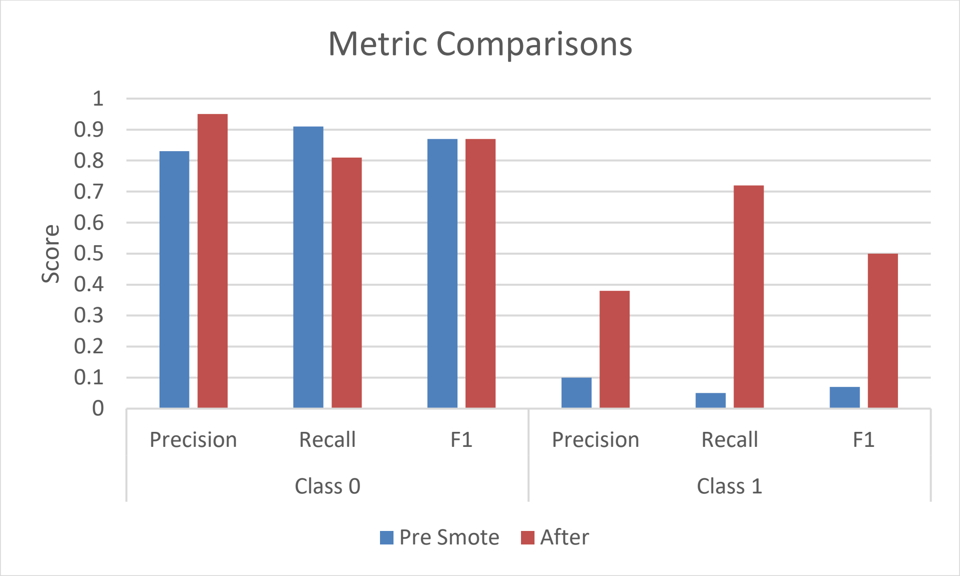


Figure 4: ANN (Neural) Metrics before and after SMOTE Applied.

5 DISCUSSION

5.1 Class Performance Analysis (Pre and Post-SMOTE)

As indicated in Figure 4, For Class 0, before applying SMOTE, the model demonstrates a high Recall of 0.91, meaning it successfully identifies 91% of actual Class 0 instances. However, its Precision is lower at 0.83, indicating that 83% of its Class 0 predictions are correct. The F1 Score stands at 0.87, reflecting a relatively balanced performance between Precision and Recall. Post-SMOTE, there is a notable improvement in Precision to 0.95, making the model more accurate in predicting Class 0, though Recall slightly decreases to 0.81. The F1 Score remains at 0.87, suggesting a balanced improvement in both metrics.

In contrast, for Class 1, the Pre-SMOTE model shows significantly weaker performance, with a Precision of only 0.1 and a Recall of 0.05. This indicates that the model rarely identifies Class 1 instances correctly and is often inaccurate in its predictions. The F1 Score of 0.07 further reflects poor performance. After SMOTE's application, there is a substantial improvement across all metrics for Class 1, precision increases to 0.38, Recall to 0.72, and the F1 Score to 0.50. This suggests that SMOTE effectively addresses the imbalance in the dataset, enhancing the model's ability to correctly identify and predict Class 1 instances.

Overall, the use of SMOTE significantly improves the model's performance for the minority class (Class 1), without compromising and even slightly enhancing the performance for Class 0. This underscores SMOTE's effectiveness in managing class imbalances in predictive modelling tasks.

5.2 Effects of Improved Class 1(Breakdowns) Identification

5.2.1 Downtime reduction

The analysis focuses on the recall of Class 1 (representing major or critical repairs) in two ML models: the original model and a Pre-Smote model, which presumably underwent a data balancing technique known as SMOTE (Synthetic Minority Over-sampling Technique) before training.

The improved model exhibits a high recall for Class 1 at 0.72. This suggests that it can correctly identify 72% of the critical repairs needed. With a total of 586 repairs listed according to the historical company records, the model can predict approximately 422 of these repairs. Given that each repair leads to an average downtime of 24 hours, the application of this model can potentially save around 10,126 hours of downtime.

In contrast, the Pre-Smote model, after data adjustment, shows a significantly lower recall of 0.05 for Class 1. This translates to correctly predicting only 5% of critical repairs, amounting to about 29 repairs from the same total of 586. Thus, the estimated reduction in downtime with this model is around 696 hours — markedly less effective than the original model.

To understand the full impact of these models, it's essential to consider a scenario where no predictive maintenance model is deployed. In such a case, none of the 586 repairs would be anticipated, leading to a total downtime of 14,064 hours (586 repairs × 24 hours per repair). These scenarios are indicated in Table 5 and illustrated in Figure 5.

Table 5: Downtime Comparison

Model	Class 1 Recall	Estimated Repairs	Average Downtime	Downtime	Total Downtime Saved (hours)	Downtime (hours)
No Model	N/a	N/a	24	14064	N/a	14064
Pre Improvements	0.05	29	24	14064	696	13368
Post Improvements	0.72	422	24	14064	10126	3938

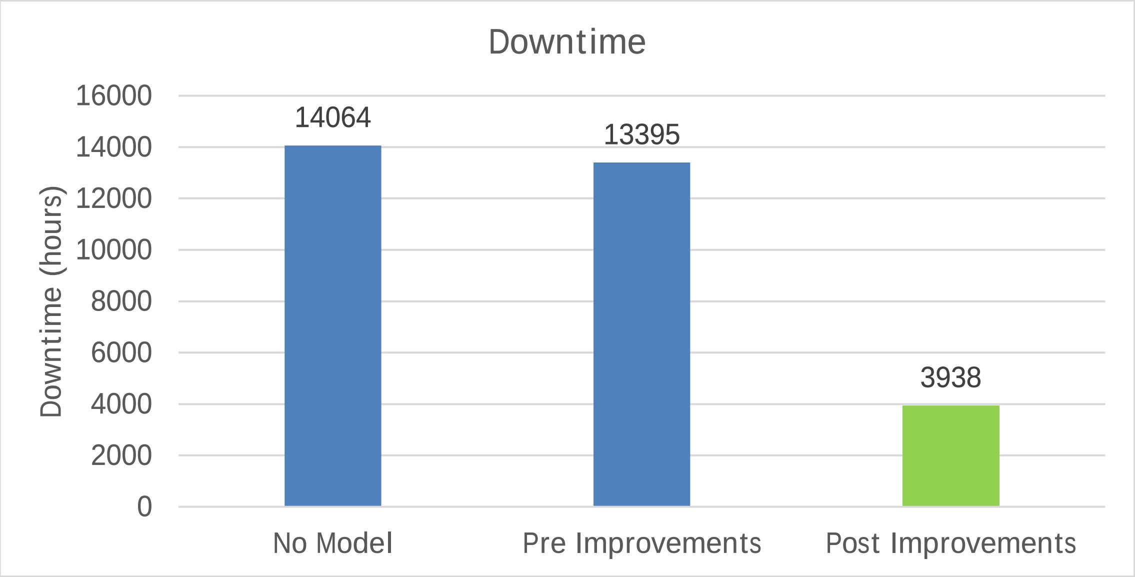


Figure 5: Downtime Reduction with Improved Class Identification

5.2.2 *Cost Savings Analysis*

In addition to reducing downtime, another critical aspect of applying predictive machine learning (ML) models in maintenance is the potential for cost savings. The following analysis evaluates the financial impact of two ML models - the Post-SMOTE and Pre-SMOTE models - in terms of their ability to predict and thus potentially prevent costly repairs. The costs of repairs were summed up from the maintenance sheet of Company X.

The effectiveness of each model is assessed based on its recall rate for Class 1, which signifies critical or major repairs. The recall rate is crucial in this context because it directly impacts the model's ability to identify repairs that, if missed, could lead to substantial costs and operational disruptions.

The improved ML model demonstrates a high recall for Class 1 at 0.72, indicating its proficiency in identifying 72% of the critical repairs. Given the total repair cost of approximately R3,597,930.31, as calculated from the company datasheet, the model's effective prediction capability translates to a substantial estimated cost saving of about R2,590,509.82. This figure represents a significant financial benefit, emphasizing the original model's effectiveness in reducing expenses associated with major repairs.

In contrast, the Pre-SMOTE model shows a markedly lower recall of 0.05 for Class 1. This low recall indicates that the model could only correctly predict 5% of the critical repairs. Consequently, the estimated cost savings are much lower, amounting to around R179,896.52. This stark difference from the post-SMOTE savings highlights the importance of a model's recall ability in cost-effective predictive maintenance.

To contextualize the benefits of these models, consider a scenario where no predictive maintenance models are deployed. In this case, none of the costly repairs would be preemptively identified, potentially leading to the full repair cost of R3,597,930.31. These scenarios are indicated in Figure 6 and underscore the substantial cost risks associated with reactive maintenance approaches.

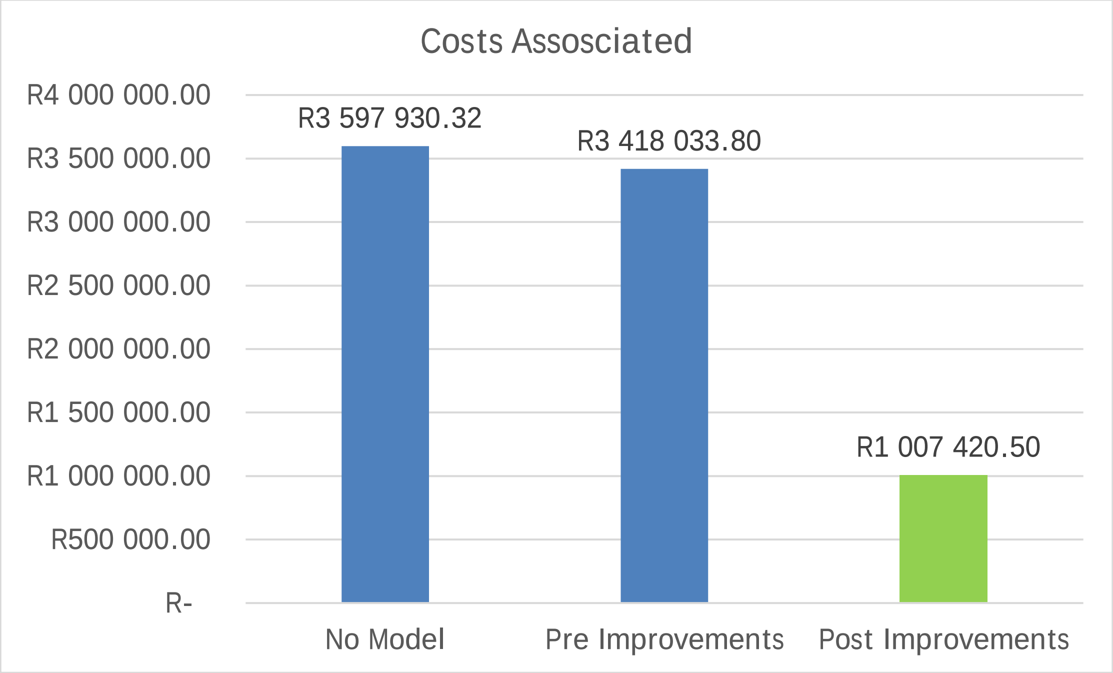


Figure 6: Cost reduction due to improved class identification

6 CONCLUSION

In this study we leveraged Machine Learning (ML) algorithms and procedures to accurately predict commercial vehicle maintenance needs, ensuring optimal fleet performance and discussing possible savings and gains from optimizing our predictions. Out of the selected machine learning algorithms evaluated the Naïve Bayes algorithm showed the best prediction accuracy. However, it performed poorly in identifying the breakdowns (class 1) similar to the other ML algorithms. A class imbalance problem-related issue with vehicle fleet data was identified and resolved using SMOTE.

The Artificial Neural Network (ANN) termed Neural in this model was identified in our experimentation as showing the best improvement in class predictions after implementation with SMOTE and hence the model was used as the basis to present the gains obtained from class identification improvement.

The improved Post-SMOTE model demonstrates a high recall for Class 1 at 0.72, indicating its proficiency in identifying 72% of the critical repairs. Given the total repair cost of approximately R3,596,930.31, the model's effective prediction capability translates to a substantial estimated cost saving of about R2,590,509.82. This amount represents a significant financial benefit, emphasizing improved prediction in class identification in reducing expenses associated with major repairs. In contrast, the Pre-SMOTE model shows a markedly lower recall of 0.05 for Class 1, indicating that it could only correctly predict 5% of the critical repairs. Consequently, the estimated cost savings are much lower, amounting to around R169,896.52. These savings highlight the importance of a model's recall ability in cost-effective predictive maintenance. To contextualize the benefits, consider a scenario where no predictive maintenance models are deployed. In this case, none of the costly repairs would be preemptively identified, potentially leading to the full repair cost of R3,596,930.31.

The improved Post-SMOTE model, with its higher recall rate, is exemplary not only in significantly reducing downtime — by potentially saving 10,126 hours — but also in offering remarkable cost savings, estimated at around R2,590,509.82. This dual benefit highlights the model's efficiency in ensuring timely management of critical repairs, enhancing both operational efficiency and financial sustainability.

While the Pre-SMOTE model yields some benefits, its relatively modest recall rate results in far less impact, saving only 696 hours of downtime and around R169,896.52 in costs. This differential effectiveness stresses the importance of choosing and refining predictive models that are adept at accurately identifying major repairs. The comprehensive validation and integration of SMOTE into the model-building process improved predictive accuracy, further demonstrating the necessity to not only build the predictive maintenance system but also to build the right system. Such rigorous development and application of accurate predictive models can substantially mitigate downtime and maintenance costs, bringing tangible time and resource savings to the company. This approach plays a pivotal role in bolstering the reliability and economic efficiency of operations in transportation and similar sectors, cementing the transformative effect of precision-driven predictive maintenance.

The modelling procedures in this study can further be enhanced by conducting different feature selection techniques and also further conducting more hyperparameter tunings beyond what was considered. Predictive maintenance models, even those enhanced with techniques like SMOTE, are not flawless. Predictive inaccuracies can arise from complex data patterns, leading to false positives or negatives. Additionally, these models may struggle with generalization, performing inconsistently across different vehicle types and ages, limiting their effectiveness in diverse fleets. Hence, more comparative analysis could be done with other methods that can further enhance the accuracies across different classes of data for predictions. Integrating additional data sources, such as sensors measuring vibration and oil analysis, will enhance predictive accuracy. Techniques for imputing missing values and detecting erroneous readings will ensure a clean dataset. Deep learning models like LSTMs and ensemble methods can be evaluated to optimize performance, with continuous online learning approaches keeping the model updated with new data.

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APPENDIX

Table A1: Machine learning modelling default and specific parameters obtained through random experimentation using Scikit-learn

Machine learning model	Parameters used from Scikit-learn(Sklearn)	Python command in SKlearn
Decision Trees(DT)	Default settings	DecisionTreeClassifier()
Gradient Boost (GB)	n_estimators=100, random_state=42	GradientBoostingClassifier(n_estimators=100, random_state=42)
k-nearest Neighbours (KNN)	n_neighbors=5	KNeighborsClassifier(n_neighbors=5)
Naïve Bayes (NB)	Default settings	GaussianNB()
Artificial Neural Network (ANN)	hidden_layer_sizes=(128, 64, 32), activation='relu', max_iter=500, random_state=42	MLPClassifier(hidden_layer_sizes=(128, 64, 32), activation='relu', max_iter=500, random_state=42)
Random Forest (RF)	n_estimators=100, random_state=42	RandomForestClassifier(n_estimators=100, random_state=42)
SVM	kernel='linear', random_state=42	SVC(kernel='linear', random_state=42)

AN EVALUATION OF THE RISK-BASED APPROACH IMPLEMENTATION IN ISO/IEC 17025:2017 CONFORMITY ASSESSMENTS - A CASE STUDY

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ABSTRACT

Accreditation bodies are faced with ensuring that both assessors and conformity assessment bodies (CABs) are familiar with implementing and assessing the risk based approach. The purpose of the study was to evaluate the risk based approach understanding of the standard amongst CABs and assessors. A survey questionnaire was emailed to 217 CABs and 41 assessors. The results indicate that there is a strong correlation between training and implementation of the risk-based approach. The data also reveals that not all the organisation assessors have been trained in terms of the risk-based approach, and therefore, do not use this approach in assessments. It is recommended that management consider assessing the impact of their trainings on assessors and CABs through structured interventions.

Keywords: risk-based approach, assessors, conformance assessment bodies, compliance, training.

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1 INTRODUCTION

Conformity assessments are key components that ensure that goods produced are safe for use in the country of origin and in the export country. Most importantly, they are key components that facilitate trade. In the compliance space, the risk approach is becoming more and more appealing to international bodies such as ISO (International Organisation for Standardization) [1]. This is evident in the publication of various standards that have been published in the last ten years. This includes the latest ISO/IEC 17025:2017, ISO/IEC 17011:2017 and the current review of ISO 15189:2012. These standards are evidence that the compliance/on-compliance approach is quickly fading and making way for a risk-based approach.

1.1 Problem Statement

Previous studies [1;2] have illustrated how risk management has contributed to organisations being able to improve their systems by mitigating, eliminating, or transferring the risks once they have been identified. This has changed organisations' strategies, as risk plays an important factor in determining if an organisation is able to meet its objectives and remain sustainable. Even with all the research that has been done, there have been little to no studies conducted on how the risk-based approach is applied in most fields, and what the change from a compliance/non-compliance based approach to a risk-based approach means to assessors/auditors. Some of the symptoms that were observed in the field of accreditation that supported the need for this research included the results obtained after the publication of the standard, and trends observed from ISO [2].

Research questions for this paper are as follows:

- **Research question 1:** What is the level of understanding amongst assessors and CABs on the risk-based approach?
- **Research question 2:** Examine assessors and CABs approach to conducting conformity assessments as opposed to the risk-based approach?
- **Research question 3:** What are the various factors that contribute to the assessor's ability to implement and carry out risk-based approach assessments?

2 LITERATURE REVIEW

2.1 ISO 9001:2015 "A new era"

In 1987, the first ISO 9001 was published, and in 2015, the newest version of the ISO 9001 was published. This was considered as the "beginning of a new era in the development of quality management systems" as new quality management principles were introduced [3]. Figure 1 shows the review process of the ISO 9001 standard since its first publication, which indicates that four reviews have since been done.

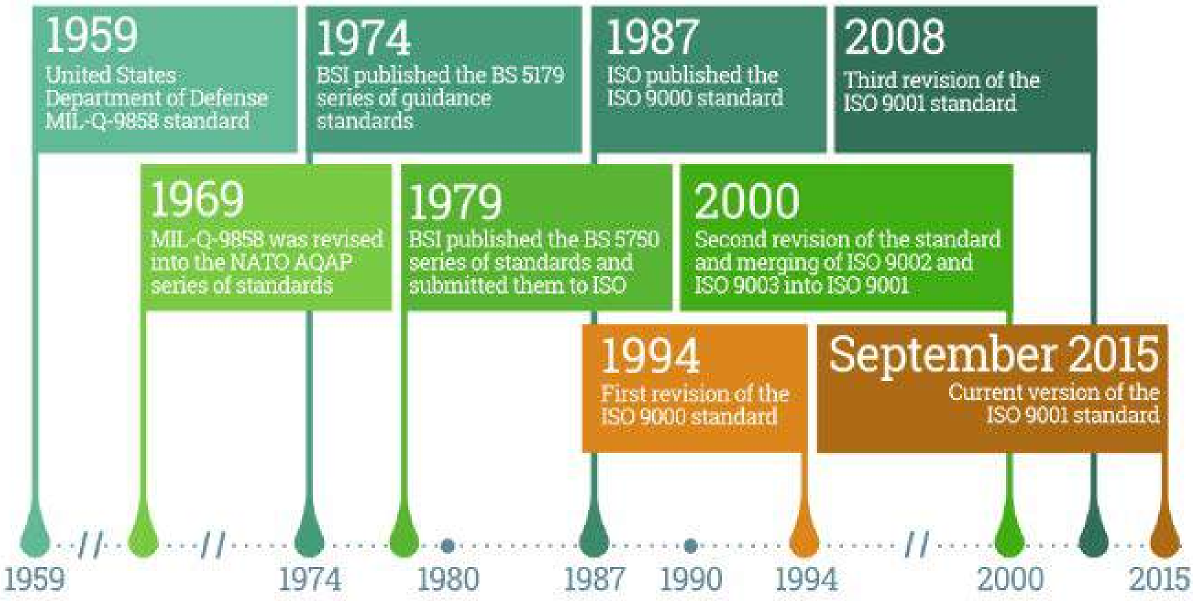

Figure 1: History of the ISO 9001 [1]

2.1.1 The review of ISO 17025:2017 - alignment with ISO 9001:2015

ISO/IEC 17025 is a standard applicable to both testing and calibration laboratories. This standard was initially published in 1995 as ISO/IEC Guide 25. In 2015, the second review of the standard was published with the standards changing to ISO/IEC 17025:2005 (Requirements for Testing and Calibration Laboratory), [4]. It is stated that the reviews from 2005 and 2015 were silent on the topic of risk, although experts believe that risk has always been a part of this standard because of the preventative action clause that was on the previous versions of the standard [4]. This clause required evidence that organisations could identify areas with potential non-conformities and correct them prior to identifying a non-conformance. According to [5] that the risk was implied in the standard. ISO 9001: 2005 treated risk as a separate component to quality management, focusing on prevention instead.

In 2017, the reviewed standard was published as ISO/IEC 17025:2017, which was in line with other standards of the ISO 17000 family [6].

2.1.2 Risk based approach for the accreditation body (ISO 17011: 2017)

The MRA allows results generated from one country to be accepted in another country without any disputes, due to the MRA that has been established between these countries that have been recognised [7]. The ISO/IEC 17011 is the standard that accreditation bodies comply with in order to retain their international recognition through ILAC, IAF, and in Africa, the African Accreditation Cooperation (AFRAC). The risk-based approach starts with the AB when determining the facilities accreditation cycle. The information gathered throughout the accreditation cycle, the risks associated with the field of accreditation, and the operational risks of the CAB contribute to determine whether the facility is high or low risk. The AB needs to have actions that will ensure that the risks are mitigated or eliminated in order to reduce and minimise residual risk. The risk-based approach does not only apply to the CABs, but also to every organisation, including the accreditation bodies that recognise these CABs. Clause 6.1.2.4 of the standard ensures that the risk-based approach is applied when the assessors conduct assessments. It forces the accreditation body to train its assessors on the risk-based approach. Hence, the importance of this research in ensuring that literature is available in future to understand the implementation of such an approach.

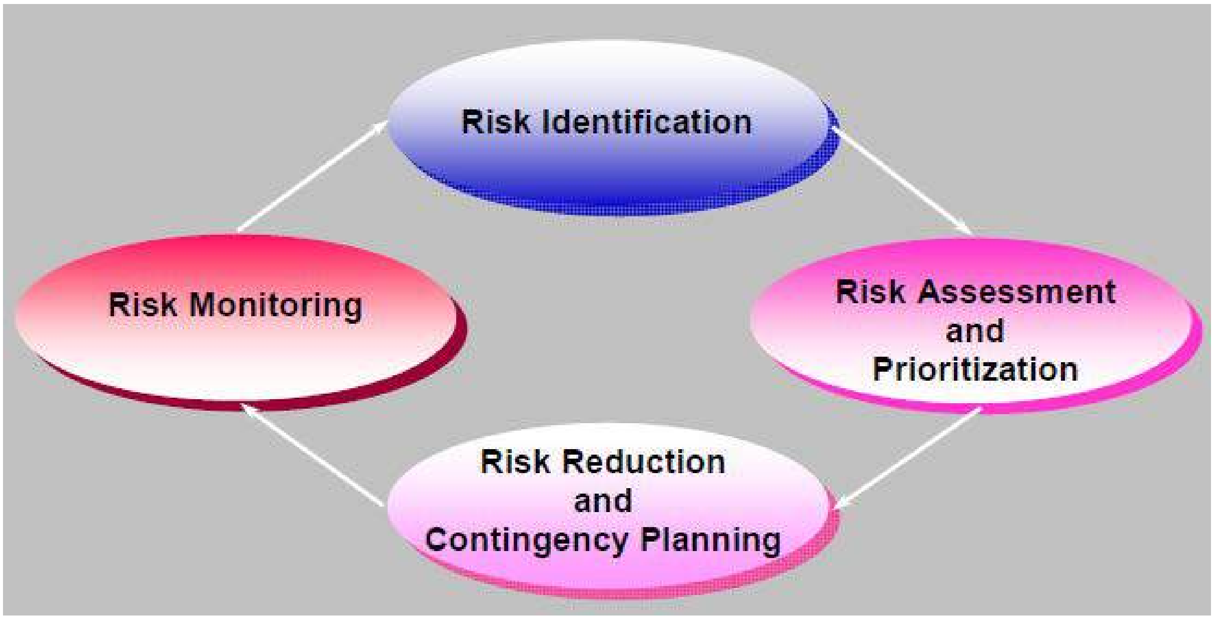

Figure 2 : Risk assessment process [4]

The AB needs to ensure that it does a risk assessment to identify its risk and mitigate, accept, or eliminate the risk. This process also applies to the AB that complies with the requirements of ISO/IEC 17011: 2017, and the process is detailed as per the ISO 31000 in Figure 2.

2.2 Regulations that support the risk-based approach

2.2.1 Financial Auditors vs Conformity Assessors

An effective risk-based approach builds on, and reflects, a country's legal and regulatory approach, the nature, diversity and maturity of its financial sector, and its risk profile [8]. Furthermore, this should not only apply to the financial sector, but to all sectors that use the risk-based approach[8]. For an approach to be effective, it needs to be built on the country's legal and regulatory framework. This is evident in the financial sectors where different legal and regulatory requirements govern. These regulations clearly explain how the sector operates, from the registration of the auditors.

*2.2.**2 Responsibilities of an organisation "Risk-based Approach"***

Various acts, including the PFMA (Public Finance Management Act), outline the terms of responsibility and accountability for financial statements that remain with the organisation's management. The auditors are there to obtain objective evidence to assure the different stakeholders that the financial statements are free from material misstatement, whether caused by error or fraud [8;9]. It remains clear to the different stakeholders that an organisation that fails to disclose its true finances or that provides false information on its statement is held accountable for its actions. This ensures that organisations understand that their actions, whether positive or negative, has consequences.

2.3 Key aspects in the implementation of the risk-based approach

2.3.1 Assessor training, continuous training and development

Employees are the backbone of any organisation and the accomplishments or issues experienced by the organisation are contingent on the performance of its employees [10]. For the accreditation body to be able to carry out its mandate, the assessors need to ensure that they understand their tasks and perform assessments as per the requirements [11]. This is reliant on proper training and ensuring the continuous development of assessors.

2.3.2 Assessor Age, Experience and Attitude on the implementation of the risk-based approach

A consensus is that elderly people are often more reluctant to accept specific technologies or concepts [12]. Another study revealed that age has a significant negative influence on both the short-term and long-term acceptance of an organisational information retrieval system[4,12]. Experience as knowledge, effect, influence, or skills gained through exposure to, or through involvement. Experience; however, does not talk to the number of years in a job/task [13]. It is evident that the more a task is carried out, the more the necessary experience is acquired, leading to better understanding, knowledge and troubleshooting on that task [14].

2.4 The AB’s systems (checklists and requirement documents) and their effect on the implementation of the risk-based approach

The South African AB has been in operation since the early 1980s, and its systems are well documented. As a result, it might leave no leeway for a risk-based approach to apply in conformity assessments. One can argue that this provides a solid background and foundation for the risk-based approach. What is certain is that a documented system allows for an organisation to ensure consistency in the implementation of its policies, procedures and requirements [15]. When processes are documented, it is clear which path needs to be taken in order to achieve a certain goal. Policies and procedures at times restrict companies’ abilities to make rapid decisions as they are bound by policies and procedures that need to be amended in order to make any rapid change. Furthermore, argues that policies and procedures restrict a company’s autonomy and mostly discourages spontaneous actions and decisions [16].

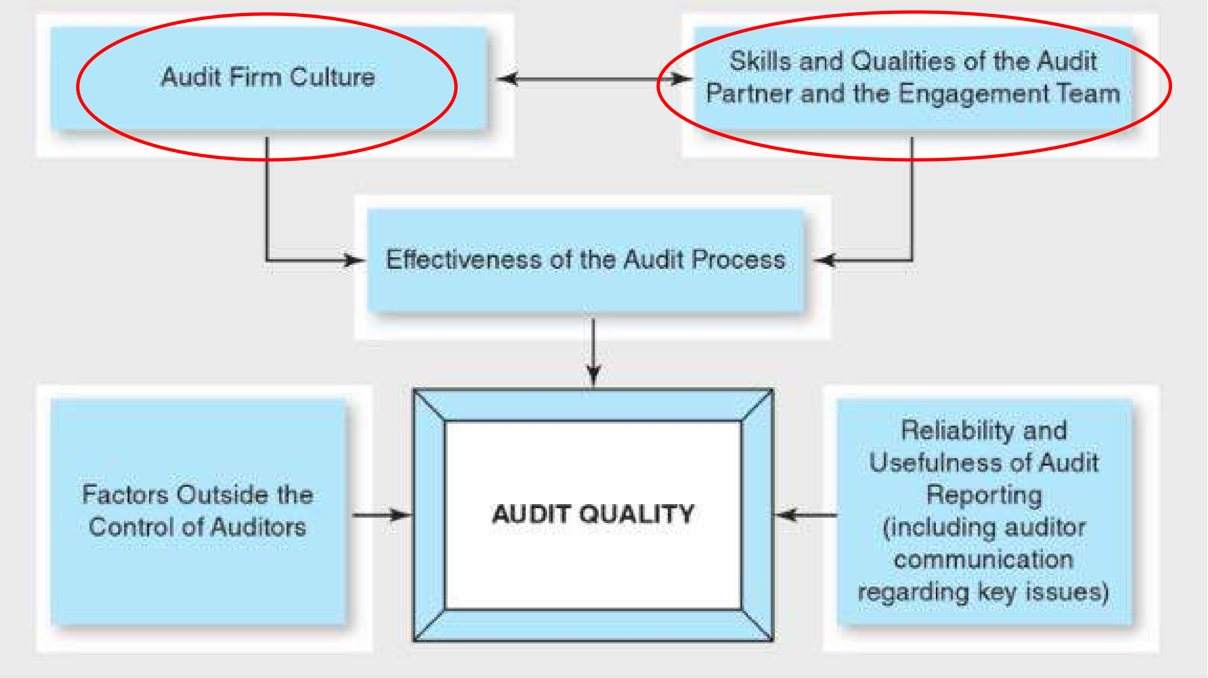

Figure 3: Factors that influence the quality of an audit [17]

Figure 3 details which factors may affect the quality of the audits done in an organisation. These include the cultures and the competency of the auditors and teams. The factors can influence how effective the CABs audits are and may in turn have an impact on whether the quality management system of an organisation improves or stays stagnant.

2.5 The effects of the number of the CABs years of accreditation and the calibre of internal auditors selected on the risk-based approach implementation

With an increase in the number of years a facility has been accredited, it is anticipated that a facility's experience and quality management systems will also improve. This is what is expected of any organisation; however, various studies have proven that this is not necessarily the case. A study that showed that even the most experienced quality management systems fall victims to complacency at times [18]. Being a process-based approach, the new approach requires that the CAB's management understands the term risk. In an international conference on training and development of new employees. It is a challenge to teach a new concept to already practicing employees instead of new employees [19]. This is because experienced employees tend to assume they know everything and do not verify processes on actual procedures anymore.

3 RESEARCH METHODOLOGY

3.1 Research Process

Once the research problem has been identified, the next important step is to find the methods that will be used to get possible answers to the research questions. This is where the research process comes in to provide directions for the research. Figure 4 identifies all the possibilities in different stages, and at the end of each stage, a decision must be made to ensure that a credible research report is generated.

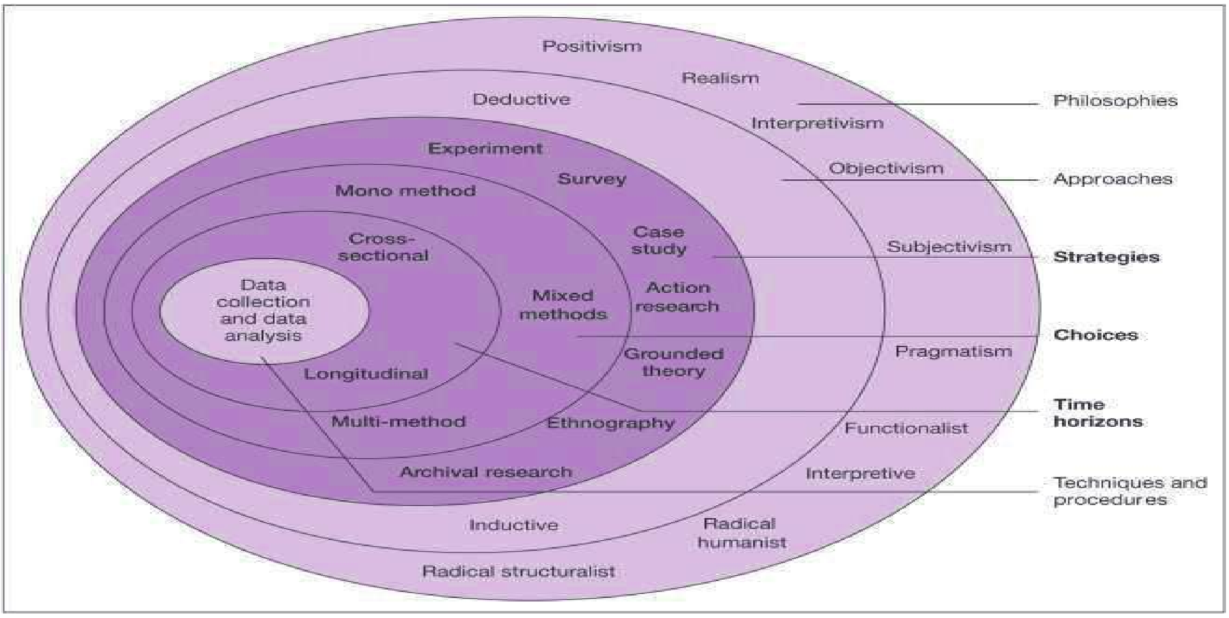

Figure 4: The Research Onion [20]

Leedy and Ormrod (2018) state that the research design refers to the general strategy for solving a research problem and the general plan for how the research question will be answered. According to Avella (2016), there are eight basic elements of a research design. These elements are the purpose statement, methodology, objectives, analysis method, measurements, timeliness, settings, and techniques.

The research onion [20] represents aspects that need to be covered to make the research credible. Firstly, the research philosophy deals with the set of beliefs around the topic at hand. Secondly, the research approach, which could be either deductive or inductive. Thirdly, the research strategy, that deals with how the researcher will collect data. The fourth layer deals with the research choices, for example qualitative, quantitative, and a mixed approach. The fifth layer deals with the timeframes for the research, therefore setting achievable timeliness is important in order to ensure that the researcher does not take on more than is realistically possible. The final layer deals with the collection and analysis of data [20]

3.1.1 Research philosophy and approach.

The research philosophy followed in this study is positivism as it utilised data or scientific evidence such as statistical data to verify the findings and hence used deductive reasoning.

3.1.2 Research strategy

In this study, an in-depth analysis into the assessors and conformity assessment bodies was done, which is one of the reasons for choosing a case study.

3.1.2 Population target and size

The researcher obtained permission to access the information of all the CABs and the assessors to conduct the research.

3.1.3 Justification of the sample and sample size

Sampling is the process of selecting units from a population of interest so that by studying the sample we may generalise our results back to the population from which they were chosen [21].

3.1.4 Calculation of the sample

A sample needs to be adequate and represent the population [21]. The following equations are used to determine the sample size for the research:

- Sample Size = (Distribution of 50%) / ((Margin of Error% / Confidence Level Score) Squared)
- Sample = (Sample Size X Population) / (Sample Size + Population - 1)

The sample for the research was as follows:

Participants	Expected Sample	Proposed Sample
Conformity Assessment bodies	217	217
Assessors	41	41

3.1.5 The margin of error and confidence level explained

A 95% confidence interval with a 3% margin of error indicates that the data is 3% within the real population 95% of the time (Jessop, 2018).

3.1.6 Data collection

The literature review was the primary research methodology to be used. The research methodology was identified as a limitation during the report writing stage. In one study, the research stated that, “the survey was quantitative in nature and therefore, did not allow respondents to further elaborate on their selected answers. As a result, in instances where respondents did not agree with the presented statements, it is not possible to understand why. Knowing this information would have provided the data analysis section with more value, thereby identifying more areas of weaknesses for the specific risk- based approach”. Based on this, this study followed a mixed approach in order to determine the number of facilities and assessors that are knowledgeable and can demonstrate effective implementation of the risk-based approach. Data that can be quantified was essential, as this is vital in a quantitative approach. However, data alone does not provide an explanation behind the data obtained; for example, why is the risk-based approach effectively implemented in some laboratories as opposed to others? Therefore, a qualitative approach in the form of a semi-structured questionnaire was used to allow the individual to elaborate and provide more insight into the topic at hand. The questionnaire was comprised of a mixture of both closed and open questions to allow respondents to elaborate on their answers. The question also covered the rating questions where: 1 = Strongly agree, 2 = Agree, 3 = Neither agree nor disagree, 4 = Disagree, 5 = Strongly disagree. The main aim of the questionnaire was to ensure that all research objectives were fulfilled at the end of the study. The questionnaire was emailed to respondents with a link to access the website.

The data was collected from assessors (n=41) and conformity assessment bodies (n=217) and

3.2.4 Data analysis techniques and methods

The questionnaire covered both closed and open questions. Closed questions ensured that the data obtained could be quantified, and open questions provided explanations, to elaborate on the closed questions.

3.2.5 Data validity and reliability

This study incorporates a quantitative. It was therefore imperative that important aspects were addressed to ensure the validity and reliability of the data obtained from this research.

3.2.6 Ethical consideration

Ethics pertains to morals, in accordance to the right standards or rules (Kagan, 2018). By obtaining the ethical clearance, a researcher can assure all relevant parties that all ethical standards are being adhered too.

3.2.7 Permission

A letter was sent to the Chief Executive Office of the Accreditation Body to obtain permission to conduct the research. Permission was granted. This allowed access to the assessor's data, which was used to sample the participants.

3.2.8 Voluntary participation and consent

Participants were encouraged to participate but not forced to do so.

3.2.9 Confidentiality

As the research was distributed via an email, participants had the option of sending it back via email, or alternatively depositing the questionnaire into Dropbox to further protect their anonymity. In assuring participants' confidentiality, participants were able to take part without fear or favour, ensuring that they provided honest responses with the assurance that their identity would not be exposed [22].

4 RESEARCH FINDINGS AND ANALYSIS

4.1 Themes

There were themes that were identified during the analysis of the assessor questionnaires.

- Understanding of the risk-based approach (Question 1, 2, 3 and 4)
- Processes and training of assessors (Question 5 and 8)
- Risk assessment processes employed (Question 9 and 10)

4.2 Analysis of Assessors

4.2.1 Section B of questionnaire: Assessors

This section presents a descriptive analysis on the assessors as follows:

The response rate 30% (n=12) for assessors.

- **My understanding of the risk-based approach is good**

Table 1 present the results on "Understanding of the risk-based approach". It is indicated that all of the respondents (100%) agreed that their understanding of the risk-based approach was good.

Table 1: Understanding of the risk-based approach

Question 1	Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
	4	8	0	0	0
	33.3%	67.6%	0%	0%	0%

Have you received training on risk?

According to Table 2, 10 (83%) out of 12, the majority had received training.

Table 2: Training

Question 2	Yes	No
	10	2
	83%	17%

- **Do you apply the risk-based approach in your assessments?**

Table 3 indicate that all the respondents applied the risk-based approach in their assessments.

Table 3: Application of the risk-based approach

Question 3	Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
	4	7	0	0	1
	33.3%	58.3%	0%	0%	8.3%

- **Do you see facilities fully implementing the risk-based approach to improve their quality management system?**

According to Table 4 the majority of respondents (8.3% + 33.3% = 41.6%) agreed that they saw facilities fully implementing the risk-based approach to improve their quality management system.

Table 4: Full implementation of risk-based approach

Question 4	Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
	1	4	5	2	0

- **Is the risk clause applied throughout the standard or only for those specific clauses?**

Table 5 indicates that the majority of respondents (16.7% + 50.0% = 66.7%) agreed that the risk clause was applied throughout the standard.

Table 5: Risk clauses application

Question 5	**Strongly Agree**	**Agree**	**Neither Agree nor Disagree**	**Disagree**	**Strongly Disagree**
	2	6	2	1	1

- **checklists are highly compliance/non-compliance based and do not allow the assessors to use the risk-based approach as specified in ISO/IEC 17011?**

Table 6 indicate that the majority of respondents (50.0%) disagreed but 33.3% agreed that checklists are highly compliance/non-compliance based and do not allow the assessors to use the risk-based approach as specified in ISO/IEC 17011.

Table 6: checklists

Question 6	**Strongly Agree**	**Agree**	**Neither Agree nor Disagree**	**Disagree**	**Strongly Disagree**
	0	4	2	6	0

- **Do you prefer the risk-based approach that the new ISO/IEC 17025 has taken?**

Table 7 indicate that the majority of respondents (33.3% + 50.0% = 83.3%) preferred the risk-based approach that the new ISO/IEC 17025 had taken.

Table 7: Preference of risk-based approach

Question 7	**Strongly Agree**	**Agree**	**Neither Agree nor Disagree**	**Disagree**	**Strongly Disagree**
	4	6	2	0	0
	33.3%	50.0%	16.7%	0%	0%

- **New assessors tend to embrace the risk-based approach more than experienced assessors?**

Table 8 indicate that, of the 12 respondents, 6 (50.0%) agreed but 3 (25%) respondents disagreed that new assessors tend to embrace the risk-based approach more than experienced assessors do.

Table 8: New assessors

Question 8	**Strongly Agree**	**Agree**	**Neither Agree nor Disagree**	**Disagree**	**Strongly Disagree**
	0	6	3	1	2
	0%	50.0%	25.0%	8.3%	16.7%

- **Which standard do you prefer, the new risk-based approach in the ISO/IEC 17025 or do you prefer the old standard and why?**

Table 9 indicate that the majority of respondents preferred ISO/IEC 17025: 2017.

Table 9: Preferred standard

Question 9	**ISO/IEC 17025: 2005**	**ISO/IEC 17025: 2017**	**Either 2005 or 2017 version**
	1	8	3
	8.3%	67%	25%

- **What are the common methodologies used to identify risks in facilities?**

The common methodologies used to identify risks in facilities. According to the results, risk register (3), ISO standard clauses (2), brainstorming (2) and SWOT (2) are the methodologies most commonly used in the organisation.

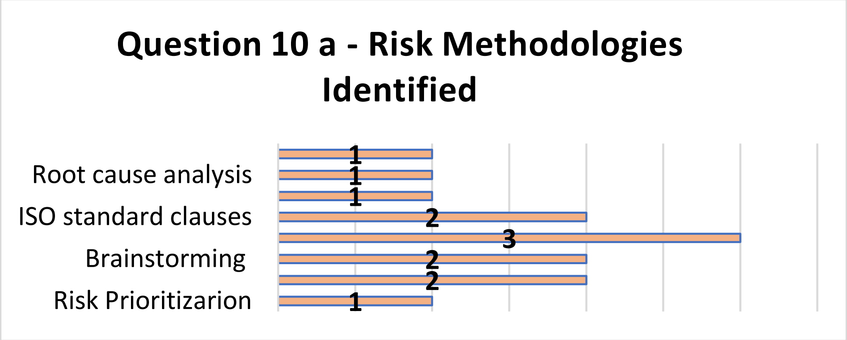

Figure 5: Risk methodologies

4.2.2 Section C of questionnaire: Analysis of CABs

The response rate was n= 62

- **Have you received training on risk?**

According to Table 10, 72% of the respondents received training on risk.

Table 10: Training

Training	Frequency	Percent
Yes	45	72.6%
No	17	27.4%

- **Our facility has fully implemented the risk-based approach and using this approach to improve the quality management system?**

The results in Table 11 indicate that the majority of respondents (30.7% + 59.7% = 90.4%) agreed that their facility had fully implemented the risk-based approach and were using this approach to improve the quality management system.

Table 11: Implementation of risk-based approach

Question 4	**Strongly Agree**	**Agree**	**Neither Agree nor Disagree**	**Disagree**	**Strongly Disagree**
	19	37	1	2	3
	30.7%	59.7%	1.6%	3.2%	4.8%

- **On a scale of 1 to 5, do you think risk and opportunity are clauses that are implemented in your organisation for the entire ISO 17025 standard or is it only for those specific clauses?**

According to the results Figure 6, the majority of respondents thought that risk and opportunity are clauses that are implemented in their organisation for the entire ISO 17025 standard.

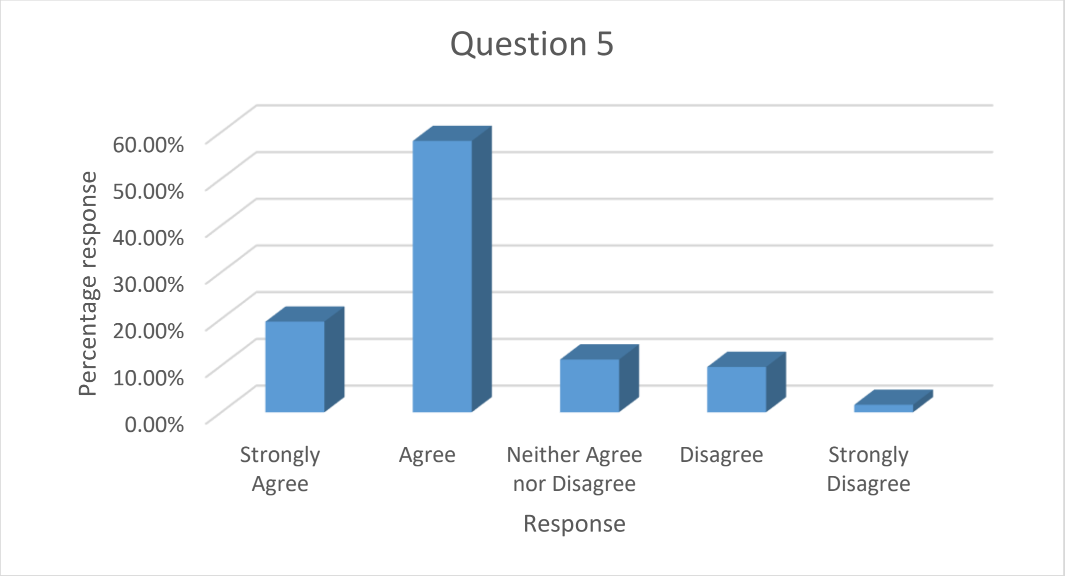

Figure 6: Implementation of risk and opportunity clauses

- **checklists are highly compliance/non-compliance based and do not allow the assessor to use the risk-based approach as specified in ISO/IEC 17011?**

A large number of respondents (12.9% + 35.5% = 48.4%) agreed that checklists are highly compliance/non-compliance based and do not allow the assessor to use the risk-based approach as specified in ISO/IEC 17011. See Figure 7.

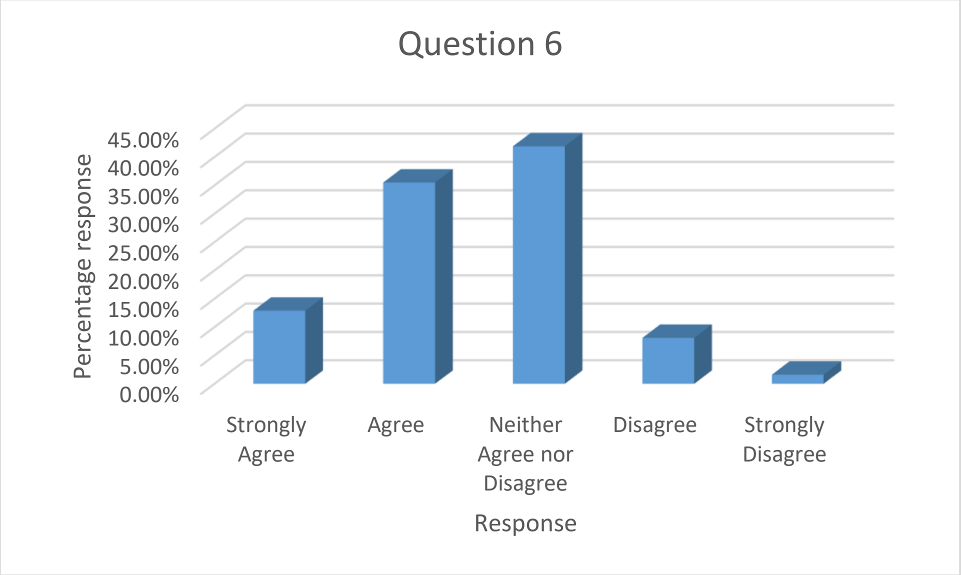

Figure 7: Compliance of checklist

- **Do you prefer the risk-based approach that the new ISO/IEC 17025 has taken?**

According to the results in Table 12, a large number of respondents (35.5% + 21.0% = 56.5%) prefer the risk-based approach that the new ISO/IEC 17025 has taken.

Table 12: Preference of risk-based approach

Question 7	Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
	22	13	9	13	5
	35.5%	21.0%	14.5%	21.0%	8.1%

- **In your opinion is it easy to implement the risk-based approach for new facilities as opposed to those that have been accredited for a long time e.g. more than 10 years?**

The results in Table 13 indicate that the majority of respondents (32.3% + 35.5% = 67.8%) agreed that in their opinion it was easy to implement the risk-based approach for new facilities as opposed to those that had been accredited for a long time e.g. more than 10 years.

Table 13: Implementation of risk-based approach

Question 8	Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
	20	22	12	8	0
	32.3%	35.5%	19.4%	12.9%	0%

- **Do you think your facility is open to the risk-based approach in the ISO/IEC 17025 or do you prefer the old standard and why?**

The results in Table 14 indicate that the overwhelming majority of respondents (25.8% + 53.2% = 79.0%) thought that the facility was open to the risk-based approach in the ISO/IEC 17025.

Table 14: Openness of facilities to the risk-based approach

Question 9	Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
	16	33	8	2	3
	25.8%	53.2%	12.9%	3.2%	4.8%

- **Do you believe that the risk-based methodologies used to identify risks in your facility is effective?**

Ninety - five percent (95.2%) of the respondents believed that the risk-based methodologies used to identify risks in their facility are effective. See Table 15.

Table 15 : Effectiveness of risk-based methodologies to identify risks

Training	Frequency	Percent
Yes	59	95.2%
No	3	4.9%

4.5 Correlational analysis

Pearson correlation coefficients were estimated calculated in the correlational analysis to indicate the correlations or relationships between the variables, more especially the correlations between the dependent variable (i.e., implementation of risk-based approach, which was question 4) and independent variables (i.e., other variables or questions). Table 16 shows the results.

Table 16: Correlation coefficients

4.2	**4.3 Knowledge of the RBA**	**4.4 Training**	**4.5 Application of RBA**	**4.6 Implementation of RBA**	**4.7 Implementation Risk & Opportunity clauses**	**4.8 check list**	**4.9 Preference of new ISO**	**4.10 Easiness of Implementation of RBA**	**4.11 Openness to RBA**	**4.12 Belief in RB methodologies**
Knowledge of the RBA	1									
Training	0.016	1								
Application of RBA	0.466*	0.087	1							
Implementation of RBA	0.442*	-0.168	0.253*	1						
Implementation of Risk & Opportunity clauses	0.501*	-0.291*	0.300*	0.721*	1					
AB checklist	0.185	-0.062	0.010	0.501*	0.286*	1				
Preference of RBA	0.286*	-0.141	0.146	0.520*	0.439*	0.122	1			
Easiness of Implementation of RBA	0.325*	0.007	0.280*	0.233	0.119	0.000	0.169	1		
Openness to RBA	0.505*	-0.395*	0.290*	0.785*	0.740*	0.408*	0.398*	0.269*	1	
Effectiveness	0.022	-0.198	-0.001	0.260*	0.043	0.129	-0.020	0.046	0.213	1

The results indicate that some of the variables are correlated at the 5% level of significance. The implementation of the risk-based approach (RBA) is positively correlated with Implementation of Risk & Opportunity clauses, Compliance of checklist, Preference of RBA, Openness to RBA, and Belief in RB methodologies.

4.6 Regression analysis

The following was the fitted regression model for the dependent variable, which was, “Our facility has fully implemented the risk-based approach and using this approach to improve the quality management system (**implementation of risk-based approach**).

Table 17 shows the results.

Table 17: Regression coefficients

Number of observations = 62

F(9, 52) = 20.85

Prob > F = 0.0000

Adj. R-squared = 0.7455

Source	SS	df	MS
Model	42.751	9	4.750
Residual	11.846	52	0.228
Total	54.597	61	0.895

Variable	Coefficient	Std. Err.	t	Prob.	[95% Conf. Interval]	
Knowledge of the RBA	-.054	.066	-0.82	0.418	-.186	.078
Training	.360	.157	2.29	0.026	.044	.676
Application of RBA	.042	.076	0.56	0.578	-.109	.194
Implementation of Risk & Opportunity clauses	.320	.109	2.95	0.005	.102	.538
AB checklist	.231	.078	2.96	0.005	.075	.387
Preference of RBA	.154	.050	3.05	0.004	.053	.255
Easiness of Implementation of RBA	.044	.067	0.65	0.518	-.091	.178

Openness to RBA	.410	.113	3.61	0.001	.182	.637
Effectiveness	.726	.298	2.44	0.018	.129	1.323
Constant	-1.67	.441	-3.79	0.000	-2.560	-.788

The results indicate that training (B=.360, prob.=0.026<.05), Implementation of Risk & Opportunity clauses (B=.320, prob.=0.005<.01), checklist (B=.231, prob.=0.005<.01), Preference of RBA (B=.154, prob.=0.004<.01), Openness to RBA (.410, prob.=0.001<.01) and Effectiveness (B=.726, prob.=0.018<.05) are significant. This implies that training on risk, implementation of risk and opportunity clauses in the organisation, compliance of checklists, the risk-based approach that the new ISO/IEC 17025 has taken, openness to the risk-based approach in the ISO/IEC 17025 as well as effectiveness of the risk-based methodologies affect the implementation of the risk-based approach positively. It is therefore recommended that training on risk, implementation of risk and opportunity clauses in the organisation, compliance of AB checklists, the risk-based approach that the new ISO/IEC 17025 has taken, and openness to the risk-based approach in the ISO/IEC 17025 should be encouraged. A positive attitude towards, or the belief that the risk-based methodologies used to identify risks in the facility are effective is also important. This will help the organisation to promote the implementation of the risk-based approach and hence improve the quality management system.

5 CONCLUSION AND RECOMMENDATIONS

This section provides findings, outlines recommendations, states the limitations, and finally, presents managerial implications. The research presented the following research questions:

5.1 Discussion of the findings in relation to the research questions

- **Research question 1: What is the level of understanding amongst assessors and CABs on the risk-based approach?**

The research question was linked to question 1, 2, 3, and 4 in the questionnaire. There was a consensus amongst assessors and CABs on their understanding of the risk-based approach. This came across even with individuals that had no training on risk. The understanding and training on risk results indicate a correlation with the results obtained from the implementation of the risk-based approach in the entire standard. A total of 17% of the assessors were not trained on the risk-based approach. Assessors also agreed that the facilities were not fully implementing the risk-based approach. The facility ends up implementing the approach for the specific clause in the standard as opposed to treating it as an approach that needs to be applied across the organisation. Training plays a major role in the correct implementation of the risk-based approach and considering the data obtained, it is clear that the risk-based approach is understood differently amongst assessors. Employees that are not trained, impact on the organisation's performance. ISO/IEC 17011: 2017 requires that all assessors be trained, be knowledgeable and can effectively implement the risk-based approach [12]. Training plays a vital role in ensuring that an organisation continues to deliver service with excellence. A great organisation can have the best technology, the best methods, and the most qualified personnel; however, if their training does not meet the requirements and if employees do not continue to undergo ongoing training, this may affect an organisations performance [10]. The lack of training affects the implementation of the risk-based approach. This is evident in the percentage of assessors that do not use the risk-based approach in their assessments.

- **Research question 2: Examine assessors and CABs approach to conducting conformity assessments as opposed to the risk-based approach?**

The questions used to attain the answers were questions 6 and 9. These questions dealt with the way in which checklists are structured, and the preference in terms of the old and new standard. When we think change is important, the way in which we do things also changes. The assessors might need to concentrate on the transfer of skills to ensure that new personnel are trained and deemed competent accordingly [7]. The CABs and assessors were asked in Question 5 whether the checklists support the risk-based approach. A third of the assessors agreed that the checklists are highly compliance/non-compliance based, leaving no room for the assessors to carry on with aspects that they believe need the most attention. Close to 50% of the CABs also agreed that the checklists did not allow the assessments that follow the risk-based approach. Various factors could influence the response, ranging from a lack of knowledge of how other AB's checklists are structured, or the lack of comparison as is the only accreditation body in South Africa.

The preference with regards to the 2005 and 2017 standards was also determined through Question 9 of the questionnaire. There was consensus amongst both the assessors and CABs on the standard they preferred. The 2017 version of the standard was preferred as opposed to the 2005, with a quarter of assessors preferring the old standard as opposed to the new version.

- **Research question 3: What are the various factors that contribute to the assessor's ability to implement and carry out risk-based approach assessments?**

The purpose of Question 3 was to determine various factors that influenced the implementation of the risk-based approach to ensure that the research can provide with recommendation that may assist in improving its systems and making conformity assessments better. A total of 87.9% organisations agree that the risk clause in ISO 17025 was implemented in the whole standard instead of the clause on risk. The risk-based approach was the most preferred approach amongst the CABs and only 56.6% of the assessors preferred this approach. The old standard was very specific on requirements and did not allow CABs the opportunity to move away from any implementation [6]. The new standard provides CABs an opportunity to concentrate on specific clauses that are high-risk areas. The questions above provide information on the training needs for both the assessors and CABs, looking at the components that may affect the implementation of the risk-based approach, such as whether the assessors' age plays a role in the implementation of the approach.

5.2 Recommendations

It is recommended that a bigger sample is included for the assessors. Also, more information is obtained on the reason behind the selection from the CAB representatives and how it is undertaken.

5.3 Limitations

The study did not gather information from the CAB representative on why they selected certain ratings, unlike the assessors who provided more information on the ratings selected. Finally, the study had a low response rate due for assessors and CABs due to employees availability.

5.4 Managerial implications

The assessors that had no training on the risk-based approach also stated that they did not use this approach in their assessment. It is highly recommended that managers delve into this finding to ensure that assessors are capacitated adequately. Furthermore, a theoretical framework explains why the research problem exists and limits the scope of the research by ensuring that the researcher concentrates on variables that are key to answering the research questions, and therefore addressing the research objectives. However, there is limited theory in the space of conformity assessments. There are, however, theories in the field of auditing which can be applied to assessments, as they are similar roles. One of the theoretical frameworks to be used includes agency theory. Others include those that identify key aspects that contribute to the quality of an audit while concentrating on the performance of auditors, training, development, and autonomy to implement audit techniques.

5.5 Conclusion

In general, the risk-based approach was preferred over the compliance/non-compliance approach used by the 2005 standard for CABs. Assessors, on the other hand, elaborated that the new standard makes it difficult for them to assess, and CABs use this approach to avoid meeting some of the requirements of the standard. Even with no training, CABs believed that they effectively implement the risk-based approach. The assessors that had no training on the risk-based approach also stated that they did not use this approach in their assessment.

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THE IMPACT OF THE BALANCED SCORECARD ON PRODUCT AND SERVICE INNOVATION IN SMALL MEDIUM ENTERPRISES

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ABSTRACT

Innovation is a specific function of entrepreneurship, whether in an existing business, a public service institution, or a new venture started by a lone individual in the family kitchen. It is how the entrepreneur either creates new wealth-producing resources or endows existing resources with enhanced potential for creating wealth. To be effective, an innovation must be simple, and it must be focused. It should do only one thing; otherwise, it confuses people.

The research design used a quantitative method approach, with questionnaire designed to evaluate the BSC four perspectives and their impact in driving product and service innovation in the SMMEs. The methodology found that a positive relationship exists between BSC four perspectives: financial perspective, customer perspective, internal perspective and learning and growth perspective and product and service innovation in the SMMEs.

Keywords: balanced score card; innovation; entrepreneurship; SMMEs; quantitative

1 INTRODUCTION AND BACKGROUND

Innovation means ‘something new’ or ‘something different’ that is not seen or experienced or understood earlier by the customer / consumer; this could need new knowledge or discovery and need an invention which is the technological and engineering aspect of innovations [1]. In addition, innovations could sometimes need imagination (or abstract innovation) and engineering skills to be combined; this is often called as inclusion of ‘Imagineering’. To create ‘something new’ or ‘something different’ is by itself is not sufficient and it is necessary that the innovation solve a customer problem, fulfil an unmet need of the market, or provide a new benefit (innovation must work for the customer or has to be exploited), this needs marketing skills. Innovation could thus be the creation of a new market or an addition or an extension / modification to the product / process / technology in the existing market or with the creation of new competitive space.

1.1 Problem statement

There are differences in the determinants of product innovation which could imply that much of the previous research is flawed, and it would certainly limit its practical applicability to decision-makers in small firms [2]. Although we realize that attempts at generalization are often made from complexity reasons, we feel that the rich diversity in SMEs should not be discarded. Although managers in small firms may regard new product development as something that just ‘happens’, for each industry we found a number of firm-level activities that seem to trigger product innovation [3]. In knowledge-intensive services, the introduction of new products first and foremost depends on managerial focus and market research, irrespective of the degree of newness of the product.

Most traditional indicators are based on accounting data and suffers from the following shortcomings in business practice [3]:

- There is a possibility of influencing the number of reported profits also by means of legal accounting procedures, very significantly, which is a “blind” way in long-term monitoring and.
- Accounting indicators do not consider the time value of money and the risk of investors. To deal with some of these challenges, the Balanced Scorecard, which can be defined as a strategic company performance measurement system that combines financial and non-financial performance measures, can be included as the principal representative of non-financial measures.

BSC is the transformation of a business unit’s strategy into an interconnected set of measures that defines both long-term strategic goals and mechanisms, i.e., strategic actions to achieve them. According to [1;3] BSC measures company performance with four balanced perspectives:

- financial (shows when the introduction and subsequent implementation of the company strategy led to significant improvements)
- Customer (identification of customer and market segments in which managers will conduct business and measures of business unit performance in these target segments),
- Internal company processes (identifying critical internal processes in which a company must deliver outstanding results).
- Learning to grow (dealing with the business infrastructure needed to create long-term growth and improvement).

The interconnection of individual perspectives forms the BSC framework or strategic map [3]. The four perspectives make it possible to establish a balanced between short-term and long-term objectives, between the desired outcomes and the driving forces of theses outcomes, and between hard and soft, more subjective measures [2;3].

Thus, this paper will therefore be focused on the following problem statement:

To determine if a positive relationship exist between Balanced Scorecard and product and service innovation in small medium enterprises.

1.2 Research questions

1. What factors impact BSC in SMMEs?
2. What is the relationship between BSC system orientation and product and service innovation in SMME's?
3. What recommendations can be made to implement BSC in SMMEs?

1.3 Research objectives

1. To determine the factors that impact BSC in SMMEs.
2. To identify the relationship between BSC system orientation and product and service innovation in SMME's.
3. To provide recommendations can be made to implement BSC in SMMEs.

Therefore, the BSC, is one of the tools that can used to determine of SMMEs performance can be improved.

2 LITERATURE REVIEW

2.1 Balanced Scorecard

The balanced scorecard is a strategy that creates a focus by translating an organization's visions and strategies into operational objectives and performance measures for the discernible perspectives [4].

2.2 BSC perspectives

- **Financial Perspective:** financial measures convey the economic consequences for the actions already taken by the organization, and focus on the profitability related measures on which the shareholders verify the profitability of their investment [5].
- **Customer Perspective:** this perspective captures the ability of the organization to provide quality goods and services, the effectiveness of their delivery, and overall customer service and satisfaction [6].
- **Internal Perspective:** to meet the organizational objectives and customers' expectations, organizations must identify the key business processes at which they must excel [5].

2.3 The relationship between product and innovation

A product is a combination of one or more of (a) ingredients (b) attributes (c) benefits (d) advantages (e) features (f) functionality (g) performance (h) business model (i) usage experience (j) consumption experience. Innovations that manifest in products as defined are called 'product innovation' [1]. Firms require product innovations to cope with competitive pressures, changing tastes and preferences, short product life cycles, technological advancement (or contrarily technological obsolescence), varying demand patterns, and specialized requirements of customers.

2.4.1 Financial Perspective, product and innovation link

When we talk about financial perspective of balanced scorecard it is not only a matter of shareholders satisfaction, ROI. To achieve this company must deal with people in such a way where organizational objectives need to be matched with individual objectives which in turn increase the financial status of the organization [7].

2.4.2 Customer Perspective, product and innovation link

There must be a focus of orientation on the customer, because employees are tightly in touch with the customers e. g. deal with customer complaints, provides good customer service and information [7]. Employees should always resolve problems quickly, efficiently and at the heart of customer service process.

2.4.3 Internal Business Process perspective, product and innovation link

The Internal Process Perspective focuses on all the activities and key processes required for the company to excel at providing the value expected by the customers [7]. Internal Processes are lead indicators where management intervention is possible to affect customer and financial outcomes.

2.4.4 Learning and Growth Perspective, product and innovation link

The Innovation Landscape Map - although each dimension exists on a continuum, together they suggest four quadrants, or categories, of innovation [8]– depicted in figure1.

- ***Routine innovation:*** a company's existing technological competences and fits with its existing business model—and hence its customer base [10].
- ***Disruptive innovation:*** Harvard Business School colleague Clay Christensen, it requires a new business model but not necessarily a technological breakthrough. given away free; the operating systems of Apple and Microsoft are not [11].
- ***Radical innovation:*** radical innovation is the opposite of disruptive innovation. The challenge here is purely technological. The emergence of genetic engineering and biotechnology in the 1970s and 1980s as an approach to drug discovery is an example [12].
- ***Architectural innovation*** combines technological and business model disruptions. An example is digital photography. For companies such as Kodak and Polaroid, entering the digital world meant mastering completely new competences in solid-state electronics, camera design, software, and display technology [13].

2.5 Conceptual framework for the study

The Four perspectives forms basis for the conceptual framework for this study

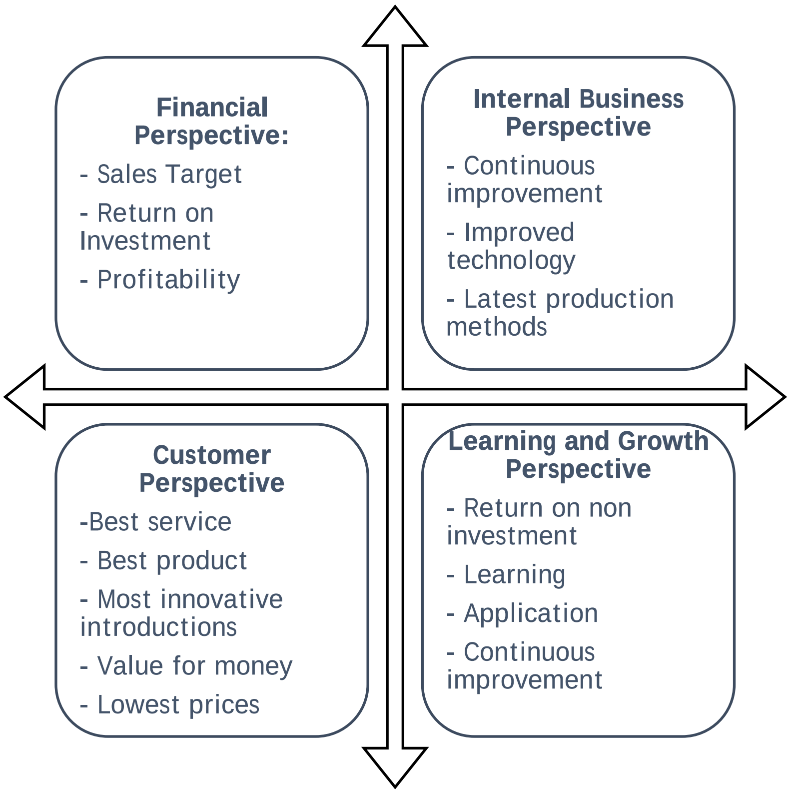

Figure 1: Adapted Balanced scorecard From Phillip Model [9]

3 RESEARCH METHODOLOGY

The research design for this study is discussed below. The Research Onion is shown in Figure 2, this design was developed by (Saunders, Lewis and Thornhill, 2016) and is used to guide the research design.

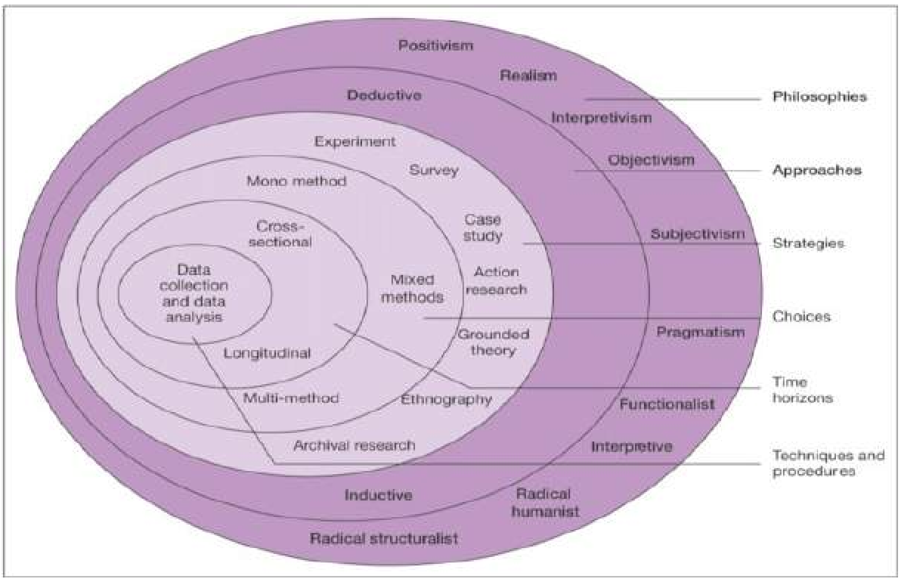

Figure 2: Research onion [14]

3.1 Quantitative research design

From figure 2, this study used quantitative design which is in line with a positivistic and deductive philosophy and approach. A descriptive research design was selected to obtain an in-depth comprehension and relevant perspective of the research problem and understanding the relationship between BSC and product and service innovation processes [15].

3.2 Population and sample framework

3.2.1 Population

The study adopted a survey approach (figure 2) with a mono method as the choice as this was justified from the research problem. The target population is the total workforce of about 300 employees accumulatively, currently employed by all 10 different organisations that forms part of this study.

3.2.2 Sample

The sample comprises 33.3 percent of the total population.

Table 1: Target population and sample

Division	Population	Sample	Percentage of Population
Research & Design	48	48	100%
Operations	52	52	100%
Marketing	30	30	100%
Management	20	20	100%
General support functions & Administration	150	10	30%
Total	300	100	33.3%

3.4 Data Collection

The quantitative collection method is the primary source of data and employed, a questionnaire containing 28 questions, with pre-determined answers for the respondent to choose from will be used.

3.5 Quantitative Data Collection

For the study, we used adapted questionnaire from [16]. The construct for this study measured innovation using four different types of innovation: 1) disruptive innovation, 2) routing innovation, 3) architectural innovation, routine innovation and 4) radical innovation. We used the scoring coefficients of the factor analysis to generate the factor score as a proxy for exploratory innovation.

3.6 Data analysis methods

Pre-coding of responses related to elements of the innovation process and use BSC was used. Coding involves assigning numbers or other symbols to answers so that the responses can be grouped into a limited number of categories. They are easier to code, record, and analyse [17].

3.7 Quantitative Data Analysis

Collation, capturing and tabulation of the raw data derived from each returned survey was conducted via Microsoft Excel spreadsheet data, checked, and verified for any lost data and improper items before being imported into a Statistical Package for Social Science (SPSS) for further data analysis and interrogation [18]. Employing this statistical tool, descriptive data analyses were based on inferential statistics that were conducted to characterise the respondents in terms specific criteria such as designation, fields of specialisation or occupation, age, gender, and years of employment.

3.8 Validity and Reliability

3.8.1 Reliability

For purposes of this study, Cronbach's coefficient alpha was used to determine the internal reliability of this research study.

3.8.2 Validity

Uni-dimensionality was tested by the Kaiser-Meyer-Olkinstatistics (KMO > 0.5) and Bartlett's test on item correlation (Bartlett's test = 0.00). Reliability was checked using Cronbach's alpha ($\alpha > 0.7$) [14].

3.8.3 Correlation coefficient analysis

For additional accurate interpretation for this study method, the Pearson correlation coefficient was employed to evaluate and compare correlations of BSC practices and product and service innovation processes in the SMMES.

3.9 Ethical considerations

A letter of informed consent and participation information to facilitate this research within the 10 selected organisations was also sent and all participants were asked to sign the letter of consent prior participating in the study.

3.10 Informed consent

Every potential participant received an introductory cover letter, together with the survey instrument, within all 10 selected organisations and each participant was thoroughly briefed and informed consent obtained prior formally participating in the study.

3.11 Protection from harm and right to privacy

All contents of this research study will only be provided to the research supervisor, the university and the participating organisations on request.

4 RESEARCH RESULTS AND FINDINGS

This section deals with the analysis and findings of results for each research question.

The total number of respondents were n=82. for a population of 300, a response of 33.00% is deemed acceptable. It is therefore affirmed that the response rate was acceptable, and the findings could be generalised over the community without reservation [20].

4.1 Demographic Details of respondents

Gender

Table 2 shows the percentage distribution of gender. Of the 82 respondents, (64 %) were males.

Table 2: Gender

	Frequency	Percent	Valid Percent
Male	53	64	64,6
Female	29	35	35,3
Total	**82**	**100**	**100**

Shows the percentage distribution of gender. Of the 82 respondents, (64 %) were males. This indicates more than half the respondents were male.

4.3.2 Reliability analysis

The main purpose and the information respondents were requested to furnish were fully explained through email correspondence prior participation.

i) Financial Perspective of BSC

The reliability statistics for the first construct, “Financial perspective of BSC”, are shown in Table 3. The results significantly indicate that the construct was reliable, at a Cronbach’s α of 0.84. Table 3 indicates that construct was positively correlated based on items that were used to measure.

Reliability statics (Financial perspective of BSC)

Table 3: Correlation matrix

	Fully aware	**Understand BSC**	**Managerial team focus**	**Strategic goals aligned to BSC**	**Market share growth**	**KPI aligned**
Fully aware	1					
Understand BSC	0,69*	1				
Managerial team focus	0,60*	0,43 *	1			
Strategic goals aligned to BSC.	0,50*	0,24 *	0,38 *	1		
Market share growth	0,25*	0,38 *	0,47 *	0,48 *	1	
KPI aligned.	0,28*	0,38 *	0,38 *	0,23 *	,088 *	1

Note: *significant at the 5% level.

The results presented in Table 4 significantly indicate that all the items belonged to the construct for any item, and if removed, the reliability measure remains high, that is, above 0.7 The Cronbach’s Alpha coefficient for the construct is 0.84.

Table 4: Reliability

	Obs.	**Sign**	**Item-test correlation**	**Alpha**
Fully aware	115	+	0,73	0,81
Understand BSC	115	+	0,72	0,82
Managerial team focus	115	+	0,68	0,81
Strategic goals aligned to BSC.	115	+	0,74	0,83
Market share growth	115	+	0,73	0,81

KPI aligned.	115	+	0,78	0,82
Scale reliability coefficient!				0.81

ii) Customer Perspective of BSC

Results in table 5 significantly indicate that all the items that were used to measure the construct were positively correlated to each other. The significance of this results is that such augurs well for the construct.

Reliability statistics (Customer perspective of BSC)

Table 5: Correlation matrix

	Product/service introductions	Customer retention	Market research	Customer profitability	Customer satisfaction	Market share growth
Product/service introductions	1					
Customer retention	0,59*	1				
Market research	0,55*	0,66	1			
Customer profitability	0,55*	0,58*	0,38 *	1		
Customer satisfaction	0,39*	0,48*	0,47 *	0,48 *	1	
Market share growth	0,28*	0,38 *	0,38 *	0,23 *	0,33*	1

According to the results in Table 6, they clearly indicate that all the items belonged to the construct and if removed, the reliability measure remains high, that is, above 0.7, except for customer satisfaction and market share statements with scores of 0.68 and 0.45 respectively. The Cronbach’s Alpha coefficient for the construct is 0.827.

Reliability statistics (Customer Perspective of BSC)

Table 6: Reliability

	Obs.	Sign	Item-test correlation	Alpha
Product/service introductions	115	+	0,73	0,75
Customer retention	115	+	0,83	0,77
Market research	115	+	0,77	0,79
Customer profitability	115	+	0,68	0,82
Customer satisfaction	115	+	0,45	0,81
Market share growth	115	+	0,55	0,82
Scale reliability coefficient.				0,79

iii). Internal Perspective of BSC

The reliability statistics for the third construct, “Internal perspective of BSC”, are presented in Tables 7 and 8. These results suggest strongly that the construct was reliable, at a Cronbach’s α of 0.81. Based on the survey of 10 SMMEs, the study found that firms using BSC obtained better product and service innovation outputs and financial performance. The aim of this of this study is to contributes to the field of BSC implementation and product and service innovation in the SMMEs.

Reliability statistics (Internal perspective of BSC)

Table 7: Correlation matrix

	Formal processes	Documented OP plans	Improvement plans	Shareholder expectation	Value proposition	Documented innovation plans
Formal processes	1					
Documented OP plans	-0,132*	1				
Improvement plans	0,58*	0,57*	1			
Shareholder expectations	0,57*	0,48*	0,62*	1		
Value proposition	0,39*	0,35*	0,47 *	0,55*	1	
Documented innovation plans	-1,22*	0,38 *	0,26*	0,23 *	0,48*	1

Reliability statistics (Internal Perspective of BSC)

Table 8: Reliability

	Obs.	Sign	Item-test correlation	Alpha
Formal processes	115	+	0,71	0,73
Documented OP plans	115	+	0,83	0,75
Improvement plans	115	+	0,06	0,77
Shareholder expectations	115	+	-0,15	0,80
Value proposition	115	+	0,39	0,79
Documented innovation plans	115	+	0,72	0,81
Scale reliability coefficient.				0,77

High positive correlations between items of the same construct are generally considered good internal consistency. This may indicate that these are the areas of weakness within many SMMEs that undermine their ability to increase their internal competencies to introduce new product and services to the market. Since performance is usually measured over a longer period, e.g. (year, quarter), there must be links between operational plans and documented innovation plans. Such must be clearly articulated in the form of KPI’s, and targets reflected under internal perspective of the BSC. If these links are measured they should contribute to long term survival and achievement of the company’s long-term strategy.

iv) Learning & Growth perspective of BSC

The reliability statistics for the fourth construct, "Learning & Growth perspective of BSC", are shown in Tables 9 and 10. The results indicate that the construct was reliable, at a Cronbach's α of 0.843.

Reliability statistics (Learning & Growth perspective of BSC)

Table 9: Correlation matrix

	Adequate training	Ongoing training	Product/service knowledge	Frontline training	Adequate feedback
Adequate training	1				
Ongoing training	0,75*	1			
Product/service Knowledge	0,62*	0,57*	1		
Frontline training	-0,136*	0,62*	0,62*	1	
Adequate feedback	0,39*	0,47 *	0,47 *	0,39*	1

Reliability statistics (Learning & Growth Perspective of BSC)

Table 10: Reliability

	Obs.	Sign	Item-test correlation	Alpha
Adequate training	115	+	0,69	0,71
Ongoing training	115	+	0,83	0,73
Product/service Knowledge	115	+	0,08	0,75
Frontline training	115	+	-0,15	0,78
Adequate feedback	115	+	0,37	0,77
Adequate training	115	+	0,7	0,78
Scale reliability coefficient.				0,74

High positive correlations between items of the same construct are generally considered good internal consistency."

Table 11: Mean scores

Item	Statement	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
Financial Perspective						
1	I am fully aware of the recent products/service introduction in the last two years	26,32	26,32	9,82	1,74	0
2	I understand BSC use and my individual and team contribution to its function	24,35	24,35	9,82	1,74	0
3	The Managerial team provide direction and focus on use of BSC to achieve financial and non-financial targets	22,25	22,25	9,82	1,74	0
4	The strategic goals are articulated in the BSC and strategic documents of the business	25,61	25,6	9,82	1,74	0
5	Market share/growth is directly linked to sales growth because of new products/service innovation	24,38	24,38	9,82	1,74	0
6	The key performance indicators are aligned to strategy and financial targets and are also stated in the BSC	22,36	22,36	8,7	1,2	0,87
Customer Perspective						
7	I'm fully aware of recent product/service innovations introduced by the customer	25,21	25,21	10,52	2,32	0
8	There is an increase in customer retention as a results of new products/services	26,32	26,32	9,2	3,2	0,87
9	I'm fully aware of Market research that has been conducted in the last two years	24,35	24,35	5,2	2,62	0,87
10	There is an increase in customer profitability as a results of new products/services	22,25	22,25	4,52	1,28	0,87
11	There is an increase in customer satisfaction as a results of new products/services	22,45	22,45	5,76	11,99	0,87
12	There is an increase in market share as a results of new products/services	22,85	22,85	7,08	22,78	0,87
Internal Perspective						
13	There is a formal process of identifying the needs of customer	22,45	22,45	6,68	22,38	0,47
14	There are documented operational plans linked to BSC	22,05	22,05	6,28	21,98	0,07
15	The process improvements plans are documented and updated regularly	21,93	21,93	6,16	21,86	0

16	The shareholder expectations of financial returns are regularly met, because of improved internal processes.	22,39	22,39	6,62	22,32	0,41
17	The value propositions of customers are regularly met for each segment	22,03	22,03	6,26	21,96	0,05
18	There are documented product/service innovation documents/plans	21,71	21,71	5,94	21,64	0
Learning & Growth Perspective						
19	I have been provided with adequate training on the use of BSC and understand its value and contribution	22,3	22,3	1,32	1,32	0
20	There is an on-going process of training and development aimed at improving my technical skills	21,31	21,31	5,54	21,24	0
21	I have been provided with continual product/service knowledge training and upgrades	20,91	20,91	5,14	20,84	0
22	Frontline personnel continuously receive training about product and service innovation plans and idea generation	20,79	20,79	5,02	20,72	0
23	There is adequate feedback about BSC given by management	21,25	21,25	5,48	21,18	0

Table 12: t test results

Item	Statement	Mean	Std.dev	t-value	Result	Verdict	Meaning
Financial Perspective							
1	I am fully aware of the recent products/service introduction in the last two years	5,264	2,014	11,48	0	Reject	Agree
2	I understand BSC use and my individual and team contribution to its function	4,87	1,62	11,09	0	Reject	Agree
3	The Managerial team provide direction and focus on use of BSC to achieve financial and non-financial targets	4,45	1,2	10,67	0	Reject	Agree
4	The strategic goals are articulated in the BSC and strategic documents of the business	5,12	1,87	11,34	0	Reject	Agree
5	Market share/growth is directly linked to sales growth because of new products/service innovation	4,876	1,626	11,1	0	Reject	Agree
6	The key performance indicators are aligned to strategy and financial targets and are also stated in the BSC	4,472	1,222	10,69	0	Reject	Agree
Customer Perspective							
7	I'm fully aware of recent product/service innovations introduced by the customer	5,042	1,792	11,26	0	Reject	Agree
8	There is an increase in customer retention as a results of new products/services	5,264	2,014	11,48	0	Reject	Agree
9	I'm fully aware of Market research that has been conducted in the last two years	4,87	1,62	11,09	0	Reject	Agree
10	There is an increase in customer profitability as a results of new products/services	4,45	1,2	10,67	0	Reject	Agree
11	There is an increase in customer satisfaction as a results of new products/services	4,49	1,24	10,71	0	Reject	Agree

12	There is an increase in market share as a results of new products/services	4,57	1,32	10,79	0	Reject	Agree
Internal Perspective							
13	There is a formal process of identifying the needs of customer	4,49	1,24	10,71	0	Reject	Agree
14	There are documented operational plans linked to BSC	4,41	1,16	10,63	0	Reject	Agree
15	The process improvements plans are documented and updated regularly	4,386	1,136	10,61	0	Reject	Agree
16	The shareholder expectations of financial returns are regularly met, because of improved internal processes.	4,478	1,228	10,7	0	Reject	Agree
17	The value propositions of customers are regularly met for each segment	4,406	1,156	10,63	0	Reject	Agree
18	There are documented product/service innovation documents/plans	4,342	1,092	10,56	0	Reject	Agree
Learning & Growth Perspective							
19	I have been provided with adequate training on the use of BSC and understand its value and contribution	4,46	1,21	10,68	0	Reject	Agree
20	There is an on-going process of training and development aimed at improving my technical skills	4,262	1,012	10,48	0	Reject	Agree
21	I have been provided with continual product/service knowledge training and upgrades	4,182	0,932	10,4	0	Reject	Agree
22	Frontline personnel continuously receive training about product and service innovation plans and idea generation	4,158	0,908	10,38	0	Reject	Agree
23	There is adequate feedback about BSC given by management	4,25	1	10,47	0	Reject	Agree

5 DISCUSSION AND CONCLUSION OF QUANTITATIVE SURVEY RESULTS

The research questions for this study are as follows:

1. What factors impact BSC in SMMEs?
2. What is the relationship between BSC system orientation and product and service innovation in SMME's?
3. What recommendations can be made to implement BSC in SMMEs?

5.1 Problem statement and methodology

A survey instrument was utilised in the study. Quantitative survey was performed with 100 participants. The data was collected using Word document Forms that were downloadable from emails and were resend back to the researcher upon completion by the participants. The quantitative data was analysed for results and conclusions for the three research questions. Cronbach's alpha was used to test reliability. Research instrument addressed four sections of BSC, related to the relevant research questions premised upon the theoretical framework.

5.2 Research questions

The main purpose of this study was to thoroughly examine the impact of BSC on product and service innovation in SMMEs. The responses collected through quantitative research using the questionnaire furnished us with adequate feedback to address the specific research objectives and answer the research questions.

5.2.1 Research question one: What factors impact BSC in SMMEs?

The first research question aimed to identify factors impact of the BSC in SMMEs. An in-depth and concise literature review based on approximately 15 accredited publications and previous studies were used as part of the literature review and it is presented in literature review of this paper.

- The adoption and application of BSC in the SMMEs is a function of manifold factors from owner/manager deliberate actions to drive its adoption to having formal processes of managing performance measures beyond over reliance on traditional measures. The findings of this objective and study are supported by previous work by [3]
- Also, area findings relate to strategic documents and goals not adequately linked to BSC or reflected correctly in the BSC using non-financial measures associated with four perspectives and cascaded all the way to implementation levels of the organisation.
- Furthermore, the issue revealed by results, relates to the use of key performance indicators. Critical success factors can be defined as “the limited number of areas in which results, if they are satisfactory, will ensure successful competitive performance for the organization. Once the CSFs are identified, there shall be KPIs for each CSF identified. T
- Finally, the sixth issue revealed by results, relates to the need for frontline training on the use and understanding of BSC and their own responsibilities and contributions they can make towards achieving targets and strategic goals of the organisations.

Results revealed that in approximately 60% of the organisations - such plans did not exist and when they existed they were not linked directly to documented product and service plans of the organisation, coupled with inept to link those documents appropriately through CSFs and KPIs to nonfinancial measures of the BSC. These results in many SMMEs focusing exclusively on traditional performance measures such as Net profit, Return on total assets, Return on equity capital, Earnings per share and Market price of shares/earnings per share ratio.

5.2.2 Research question two: what is the relationship between BSC and product and service innovation in SMMEs?

The research question in establishing the relationship between BSC and product and service innovation was answered by identifying the main contributing factors affecting the use of the BSC to drive the products and service innovation in the SMMEs. The main contributing factors were concluded to be:

1. ***Financial Perspective of BSC***

The results revealed there was a strong link between financial perspective and product and service innovation when measures for Market share/growth are directly linked to sales growth because of new products/service innovation.

2. ***Customer Perspective of BSC***

results concluded there was a strong influence between the BSC and product and service innovation outputs when measures for customer acquisition and customer profitability were used. .

3. ***Internal Perspective of BSC***

The results revealed there was a strong influence between the BSC and product and service innovation when efforts of management were focused on finding new processes at the organisation must excel at, to meet the product and service innovation targets and financial objectives.

4. ***Learning and Growth Perspective of BSC***

The results revealed there was a strong influence between the BSC and product and service innovation when employee training and employee skills – along with specific drivers of these generic measurers, such as detailed indexes of specific skills required for the new competitive environments were being used.

5.3.3 Research question three: what recommendations can be made to link BSCs in small medium enterprises.

This study determined that linking traditional financial measures and non-financial measures entails using a different set of documents. Financial measures are based on accounting documents and statements based on the previous year financial results. For SMMEs to successfully implement BSC and incorporate the measures that can have most positive impact on product and service innovation, it was concluded that a greater emphasis will have to be invested in establishing formal processes and procedures stated in formal documented product and service innovation plans and KPI targets.

5.4.Managerial focus

Most SMMEs are under the stewardship of owner/manager, who plays a pivotal role in setting the direction of the business and deciding what the business will focus on. This result is consistent with the findings of [16] that gains in efficiency that result from the use of BSC are not restricted to financial outcomes; they are also reflected in the incremental development of existing organizational capabilities.

5.5 Recommendations

The results recommend that SMEs benefit from the use of BSC for feed-forward control, such that firms that use it present higher financial performance and higher exploitative innovation outcomes. This positive effect on financial performance is stronger for more established firms.

5.6 Limitations of the study

The main limitation, owing to constraints in terms of funding and research time to complete this study, a very small sample size was used as part of this study, reducing the generalizability to the rest of the population.

5.7 Future research

This research study was limited to a very small number of SMMEs operating in manufacturing and service sectors of the economy and a small sample size used and therefore recommend that future research be inclusive of a larger group of SMMEs, with design in research methodology making a distinction between manufacturing and service SMMEs, as they differ remarkably in their product and service innovation practices.

5.8 Conclusion

In conclusion, the research study answered the research questions and supported the urgent need to employ BSC as means of enhancing organizational efficiencies, formalization of control systems and measures without compromising the less rigid management systems and the flexibility synonymous with SMMEs in general, to accelerate the speed of product and service innovation in their among SMMEs.

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A STRATEGY FOR CRITICAL ELECTRICAL SERVICE RESTORATION IN UNDERGROUND MINES USING GRAPH THEORY

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ABSTRACT

Underground mine blackouts can cripple safety, productivity, and equipment assets. Despite redundant design of the power distribution systems, inefficient switching procedures during outages lead to excessive downtime and loss of production. The number of switching operations must be reduced. This paper implements a LIP onto a graph to deliver a switching strategy, to restore critical electrical services faster than the current procedures allow.

By employing distributed generators, the proposed method aims to minimise electrical blackout impact through efficient load reconfiguration. Application on a case study mine in South Africa demonstrated a 58% reduction in switching events (from 117 to 54) compared to the mine's current approach, achieving 77% faster critical service restoration time. This method enhanced safety and efficiency, and reduced equipment damage during mine blackouts and should be considered for application across the entire Southern African mining industry.

Keywords: Mining, Electrical reticulation, Electrical distribution, Service restoration, Blackout, Critical load

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1 INTRODUCTION

Mining is a global industry that plays a crucial role in providing raw materials essential for modern society. By optimising the extraction process, mining companies can enhance their profitability and contribute to the long-term viability of the industry [1-3].

The application of electricity on the mining sector represents a distinctive domain, which is distinguished by its challenging operational environment, dynamic power loads, cyclic and mobile operations, and strict adherence to safety standards. To optimise safety, efficiency, and productivity, it becomes imperative to address the specific challenges posed by this sector [4].

The hazardous underground environments are often dusty, humid and contain toxic gases. These harsh environmental factors can lead to accelerated equipment degradation, corrosion, and potential short-circuits or electrical failures [4].

There is limited space for installing electrical distribution equipment in underground mines. This constraint can make maintenance, repair, and expansion of the electrical system more challenging. Many mines are in remote areas, making it difficult to access them for maintenance and repair. This can lead to longer downtime in case of equipment failure [6].

The risks of extended power outages are numerous and based on the specific equipment underground. The main risks in underground mining are [5-14]:

- Flooding due to pumps not running
- Loss of life due to insufficient ventilation
- Loss of production and injury due to insufficient lighting
- Failure to transport personnel leading to exhaustion or death
- Loss of production due to material transportation
- Loss of production due to lack of compressed air supply

All the risks listed above either lead to injury, death, or production losses which are critical drivers to mitigate in mining. Underground mining relies on real world underground electrical distribution systems to power equipment to effectively and safely mine. However, power outages occur and range in severity.

Service restoration planning is an important tool for improving modern distribution network resilience stated by Shen, et al. [15]. Improper handling of partial failures can lead to chain reactions that cause large scale damage to electrical distribution systems, budgets and human resources [16].

Service restoration plans are implemented to mitigate the risk of inefficiency and loss of life involved with extended power outages. Service restoration efforts in underground mines however face many challenges that lead to ineffective distributed generation utilisation and prolonged implementation periods.

This study aims to deliver a feasible service restoration plan for critical electrical services in underground mines' real-world distribution systems that employ distributed generation. Furthermore, it will attempt to shed light on service restoration plan efficiency through switching optimisation.

2 LITERATURE ON SERVICE RESTORATION SOLUTIONS

2.1 Network reconfiguration objectives and constraints

For this study, 37 papers were evaluated and categorised according to the objectives denoted by the studies. These studies were categorised further to determine the distribution network state (normal operations, abnormal operation and network design phase) that the network reconfiguration techniques were applied to. The outcome is shown in Figure 1.

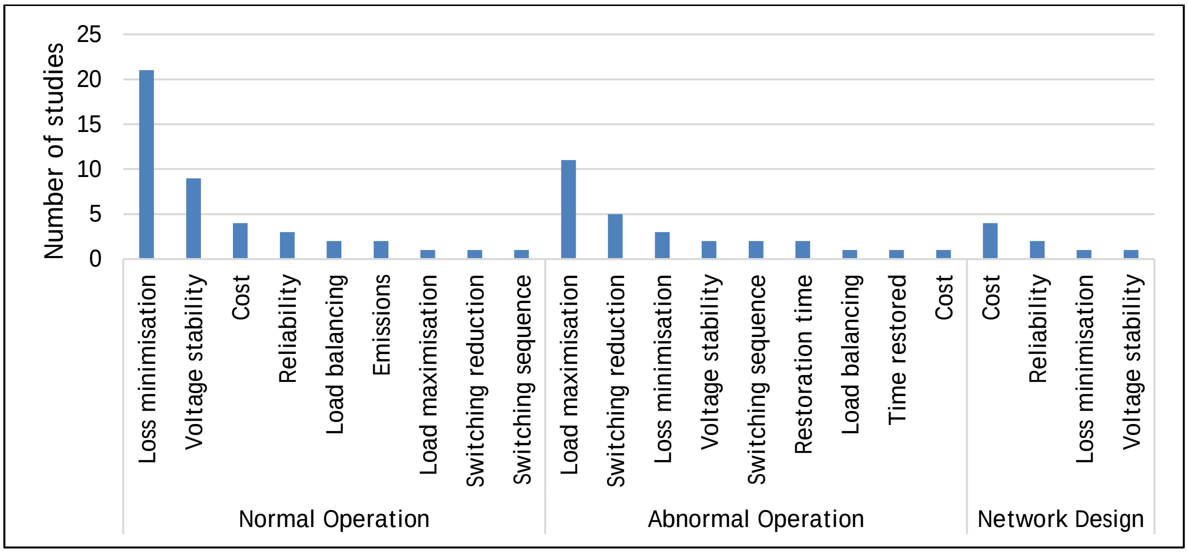

Figure 1: Studies within the network reconfiguration field categorised according to objective

Many studies in the network reconfiguration space denote objectives as multi-objective problems and are formulated as such. These are also included in Figure 1. Objective investigations are done using the objectives attempted in the most network configuration studies, as listed below:

- Loss minimisation [17-39]
- Voltage stability [17, 30-35, 37-41]
- Load maximisation [17, 36, 38-44]
- Cost minimisation [21, 43, 45-51]
- Switching minimisation [38, 41, 52-54]

From the most popular objectives load maximisation and cost minimisation are specifically used during abnormal operation of distribution systems.

Next, when solving service restoration problems, the solution is required to adhere to a set of constraints. The specific constraints can vary depending on the type of network and the optimisation goals, some common constraints are often encountered in network reconfiguration problems [37]:

- Radiality
- Bus voltage limits
- Loading limits of feeders/transformers
- Sequence of switching operations
- Number of switching operations

These constraints play a crucial role in defining the feasibility of service restoration solutions and ensuring that the resulting configurations are safe, reliable, and compliant with various operational and regulatory standards.

2.2 Graph Theory

A problem space is required for modelling the optimisation of objectives and constraints above. Graphs are mathematical structures used to model relations between objects. An undirected simple graph is an ordered pair shown in Equation *(1)*.

$$G = (V, E) \tag{1}$$

Where G is the graph, V is a set of vertices/nodes, and E is a set of edges. Edges are defined in Equation *(2)*.

$$E \subseteq \left\{\{x, y\} \middle| x, y \in V \text{ } and \text{ } x \neq y\right\} \tag{2}$$

Here, edges E is a set of unordered pairs of vertices with endpoints $\{x, y\}$; x and y is joined with an incident on x and on y.

Graphs is used to model a wide range of real-world phenomena, including social networks, transportation networks, computer networks, biological networks, and logistics problems.

2.3 Network Reconfiguration Techniques

A literature review was conducted to establish what techniques are used to solve different service restoration problems. Categorisation was performed by multiple studies [19, 55-57] based on the type of solution models used. Two of the studies Mahdavi, et al. [19] and Mishra, et al. [55] specifically focussed on producing a comprehensive review that would categorise the state of the art by the following three solution model types:

- Mathematical Optimisation Methods
- Heuristic Methods
- Metaheuristic Methods

When considering the categories of solution models [55, 56, 58, 59] the following was noted:

- Network reconfiguration through **mathematical optimisation** can be slow due to complex search spaces and integer variables.
- **Heuristic methods** offer faster solutions to network reconfiguration problems by using simpler searches but may not find the absolute best answer.
- **Metaheuristics** are higher-level procedures that guide the search for solutions in optimisation problems with large solution spaces, aiming to find good solutions more efficiently than traditional methods.

2.4 Testing Methods

Network reconfiguration studies implement solution methods on test systems such as the IEEE bus systems, while service restoration studies focussed on scenario-based testing within the same test systems. The scenarios include faults on various equipment types, extending to multiple fault scenarios.

Figure 2 shows the standard test systems used in the studies considered in this literature review, split between service restoration studies and network optimisation studies.

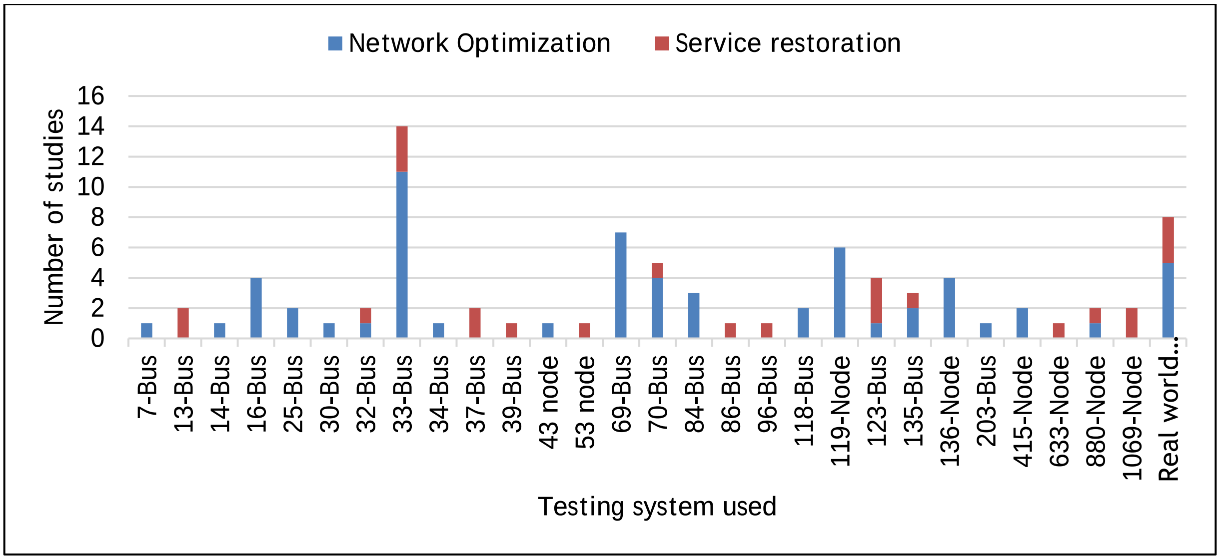

Figure 2: Testing considered in literature review [17-54]

For service restoration problems there are fewer specific systems that are used for testing. This may be due to the different scenarios that can be tested on one test system. Faults can be induced in multiple ways on a single test system, which is less work than characterising multiple test systems to form separate problem spaces.

2.5 Need for the study, and its objective

The previous sections showed that the shortcomings in this research field still require further illumination. Two of the shortcomings observed is optimising switching events and uncertainty as to how a LIP solution compares with a benchmark solution on a real-world electrical distribution system.

This study aims to apply a LIP solution method to deliver a feasible service restoration plan for critical electrical services in underground mines' real-world distribution systems that employ distributed generation. Furthermore, it will attempt to shed light on service restoration plan efficiency through switching optimisation.

3 A NEW METHOD FOR SERVICE RESTORATION IN UNDERGROUND MINING

3.1 Step 1: Gather data

A strategy of data gathering is used as described by Pascoe [5]. Identifying data sources, acquiring data and validating data.

The sensor data generated by the system must be stored to facilitate subsequent analysis and modelling. Data validation is an essential process that safeguards the integrity and accuracy of collected data. It encompasses a series of crucial steps to maintain the veracity of data within data collection systems [60].

Once data has been validated, it can be used to create a verified graph.

3.2 Step 2: Characterise problem space

The data gathered is used to populate a graph model based on the technique used by Ibrahim, et al. [38] and Zhang, et al. [61].

The purpose of a graph model is to emulate an electrical reticulation system. The graph model is required to model load, bus, source and line components as nodes and edges to emulate a distribution system. Combining these components, models an electrical distribution network as a graph. The IEEE 13 feeder test system [62] is shown in Figure 3.

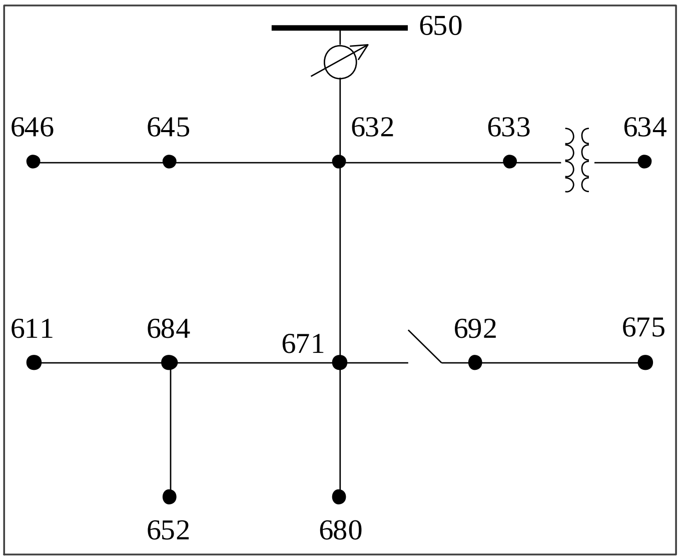

Figure 3: IEEE 13-node test feeder [63]

This small circuit model, operating at 4.16 kV, serves as a benchmark for evaluating common features of distribution analysis software. Its distinguishing characteristics include a short length, a relatively high load, a single voltage regulator at the substation, a combination of overhead and underground lines, shunt capacitors, an in-line transformer, and unbalanced loading.

The system is now converted to a simplified graph model shown in Figure 4.

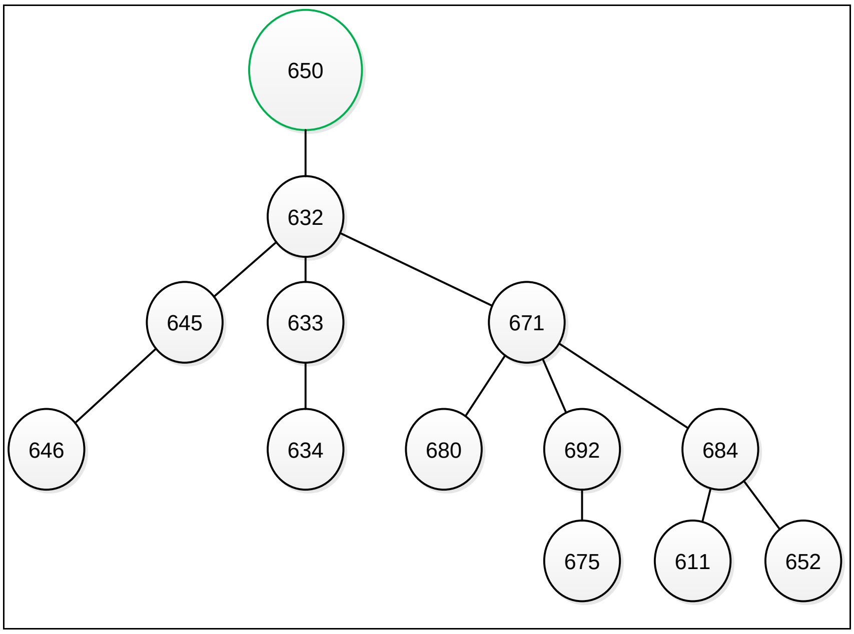

Figure 4: Graph model of 13-node test feeder

As seen in Figure 4, the graph model is developed based on the buses and edges of the system. As shown in this system, one of the constraints of this study is that the solution must remain radial for any source and bus combination. Next, the need to traverse the system using a graph optimisation algorithm is needed.

3.3 Step 3.1: Construct restoration trees

To construct restoration trees, the distribution system was modelled as an undirected graph. Nodes representing critical loads are termed critical load nodes. The restoration path between a given "source-critical load" pair is defined as any path with the minimum weight among all paths connecting them. Dijkstra's algorithm is employed to determine restoration paths from a given source to all critical loads. These paths are validated through power flow analysis, and unfeasible ones are removed, resulting in a feasible restoration tree.

To minimise the number of power flow calculations and dynamic simulations, the programme initially checks if the total load on the restoration path exceeds the maximum power that the corresponding source can provide. If it does, the restoration path is deemed infeasible without a power flow calculation. Conversely, a power flow calculation is performed if the load does not exceed the source's capacity. If any operational constraint is violated during the calculation, the restoration path is considered infeasible.

3.4 Step 3.2: Form load groups

Next, load groups are formed by exploring all possible combinations of critical loads on the restoration tree for a given source. Each combination forms a load group, consisting of loads on the restoration path spanning from the source to each critical load in the combination. Load groups containing two or more critical load zones undergo feasibility evaluation through power flow calculations. Infeasible load groups are removed from the set, leaving only feasible ones.

3.5 Step 3.3: Analyse constraints

The constraints noted in literature have been considered and in accordance with most of the reviewed work, the following operational constraints have been identified that will be considered when determining the feasibility of a solution.

Power flow:	Balanced power flow equations must be satisfied.
Bus voltage:	Steady state bus voltages should be maintained within acceptable operating limits.
Line Current:	Steady state line currents should not exceed their limits.
Power balance:	Each microgrid's steady state output power should not exceed the maximum amount of power that it is able to provide.
Radiality:	Adhering to a radial network structure is crucial, meaning that each critical load should be supplied by a single microgrid through a unique path.

3.6 Step 3.4: Solve restoration problem

The optimisation problem is formulated based on these load groups. Suppose load group j corresponds to source k and covers critical load zones $i_1, i_2, \ldots, i_p$ $(p \geq 1)$. This implies that zones $i_1, i_2, \ldots, i_p$ can be restored by source k without violating any constraints along their respective restoration paths. The goal is to select a set of disjoint load groups where any two distinct load groups in the set correspond to different sources. Therefore, the critical load restoration problem is framed as an optimisation problem that aims to maximise the total number of critical loads and reduce the number of non-critical loads as follows:

Objective:

$$max \sum_{j:g_j \in G_{uni}} y_j c_{sum,j} \qquad (3)$$

for each load group j in universal set of load groups G_{uni}. Where y_j, is the control variable, and the status of load group j: If load group j is selected $y_j = 1$; otherwise $y_j = 0$. $c_{sum,j}$ is the total weighting factor of load zones in load group j and are the state variables.

No more than one load group associated with the same microgrid is selected, i.e.

$$\sum_{j:g_j \in G_k} y_j \leq 1, k \in \boldsymbol{M} \tag{4}$$

Here G_k is a set of load groups corresponding to microgrid k and $\boldsymbol{M}$ is the set of available microgrids. Lastly no more than one load group including the same load zone is selected, i.e.

$$\sum_{j:i \in g_j} y_j \leq 1, k \in \boldsymbol{Z}_{uni} \tag{5}$$

where $\boldsymbol{Z}_{uni}$ is a universal set of load zones.

The optimisation problem can be formulated as a Linear Integer Program (LIP). Numerous tools are available for solving LIPs such as python libraries and MATLAB.

3.7 Determine restoration actions

To ensure that the constraints outlined are upheld, careful consideration is given to the feeders and incomers from each substation within the load group combination. The sequence of actions involves initially opening the main above ground substation feeders and then executing switching events to apply the load groups effectively. Lastly, actions to disconnect all busses that are not included in the load groups are removed, thus ensuring the restoration process is carried out in compliance with the defined constraints.

4 RESULTS AND FINDINGS

4.1 Case study overview

An underground platinum mine situated in South Africa was selected as a case study. The mine has an underground electrical distribution system that reticulates energy up to 1.3 km deep underground.

The mine employs standard scenario-based restoration procedures developed by system experts in the case of full power loss from power providers. This procedure is implemented as a measure to protect personnel and mining assets using distributed generation and reducing the energy demand of the network to essential equipment only.

The electrical distribution system operates at 6.6 kV and has a maximum supply capacity of 67.6 MVA. The layout of the underground mining operation is shown in Figure 5.

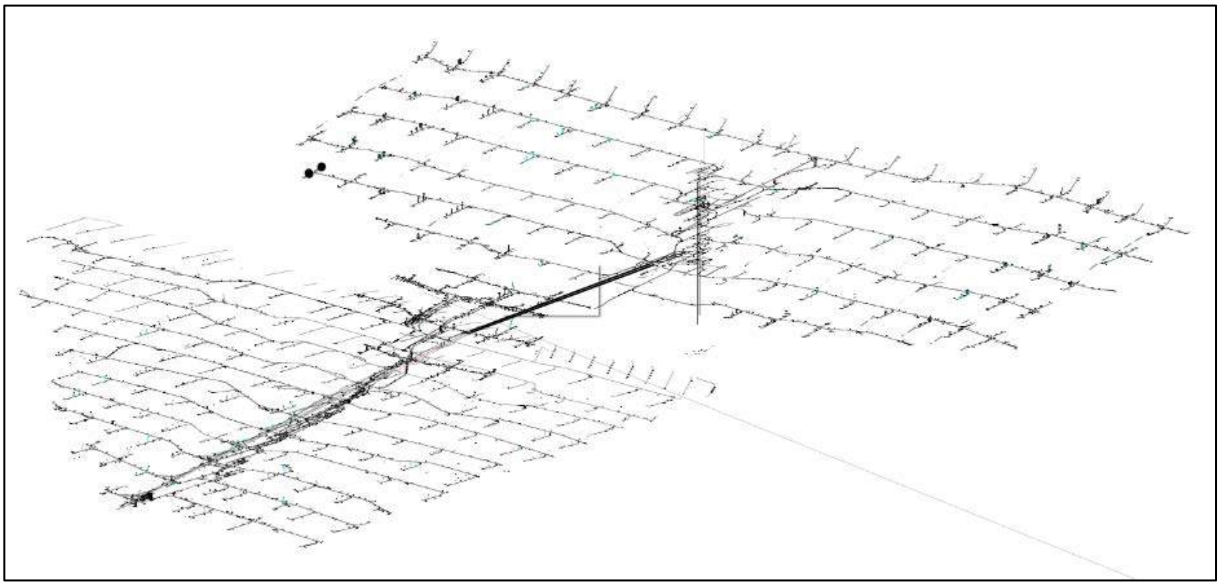

Figure 5: Case study underground mining operation

In the case of a full blackout scenario, the total system supply capacity reduces to 9.7 MVA. The system in Figure 5 has five usable supply points (three PP incomers and two distributed generators). There are 88 loads and 49 buses.

The distribution system has seven critical loads as shown in Table 1, which are defined by a restoration procedure document. Active mining areas are on Level 10 to Level 28; where all personnel will be located.

All switches are manual. The travel time to substations is linear and for safety purposes a maximum of two switching teams are dispatched when a service restoration procedure is implemented. The first team operates the main consumer substation and the second operates the underground substations.

4.2 Step1: Data gathering

Data spanning an entire month, collected at half hour intervals, was acquired from the existing Electrical Monitoring System for each feeder. To ensure the accuracy of this data and its alignment with the system's characteristics, the validation processes was rigorously applied. Table 1 indicates the critical loads.

Table 1: Critical loads identified in the case study

Name	Level	Load (kW)	Comment
Man Winder	Surface	214	Main transportation from level 15 and above to surface for personnel
Service Winder	Surface	28	Secondary transportation from level 15 and above to surface for personnel
CL 15L-23L	Level 15	36	Chairlift that extends from level 23 to 15
CL 23L-28L	Level 23	57	Chairlift that extends from level 28 to 23
15L Pump No. 1	Level 15	140	Main shaft dewatering pump for pumping water to surface reservoirs from level 15
22L Clear water pumps	Level 22	36	Intermediate pumpstation to pump water to Level 15 reservoir

Name	Level	Load (kW)	Comment
28L Pump No. 1	Level 28	139	Shaft bottom pump to pump water to level 22 reservoirs

The location of critical loads was identified through inspection of the single line drawing and the emergency response procedure document. These critical loads are required to protect personnel and mining assets in the event of power loss.

The system's generation capabilities were also identified by inspection of the energy system while the size was confirmed by the data management system. Table 2 shows the supply equipment in the distribution system.

Table 2: System generation

Name	Location	Maximum Capacity	Level
Diesel Generator	Surface	3.6 MVA	Surface
Diesel Generator	Surface	3.6 MVA	Surface
Turbine Generator	Surface	2.5 MVA	Surface
Eskom Incomer 1	Surface	20 MVA	Surface
Eskom Incomer 2	Surface	20 MVA	Surface
Eskom Incomer 3	Surface	20 MVA	Surface

During a blackout scenario the Eskom incomers shown in Table 2 are unavailable as a supply to the distribution system as they will be out of commission. The mine must then rely on the 9.7 MVA generators to provide power to the network and the critical loads.

Switching procedures for the response to a black start scenario was provided by the electrical engineering team on site and is used as a baseline. The full switching procedure aligns with the goal of switching on all necessary equipment to sustain life and protect assets.

4.3 Step 2: Characterise problem space results

From the data gathered the distribution system has 50 loads of which 7 loads are considered critical during the blackout scenario. Table 1 shows the characteristics of the 7 critical loads.

The priorities of these loads are based on their switching priority and the usefulness of each piece of equipment to either evacuate staff from the underground area, sustain life or protect mining assets.

Non-critical loads' have a lower priority compared to their critical load counterparts. This is done to ensure speed of service restoration. It is evident that the expected sum of critical load on the system is 6.8 MW. The following graph in Figure 6 was developed using the components described above.

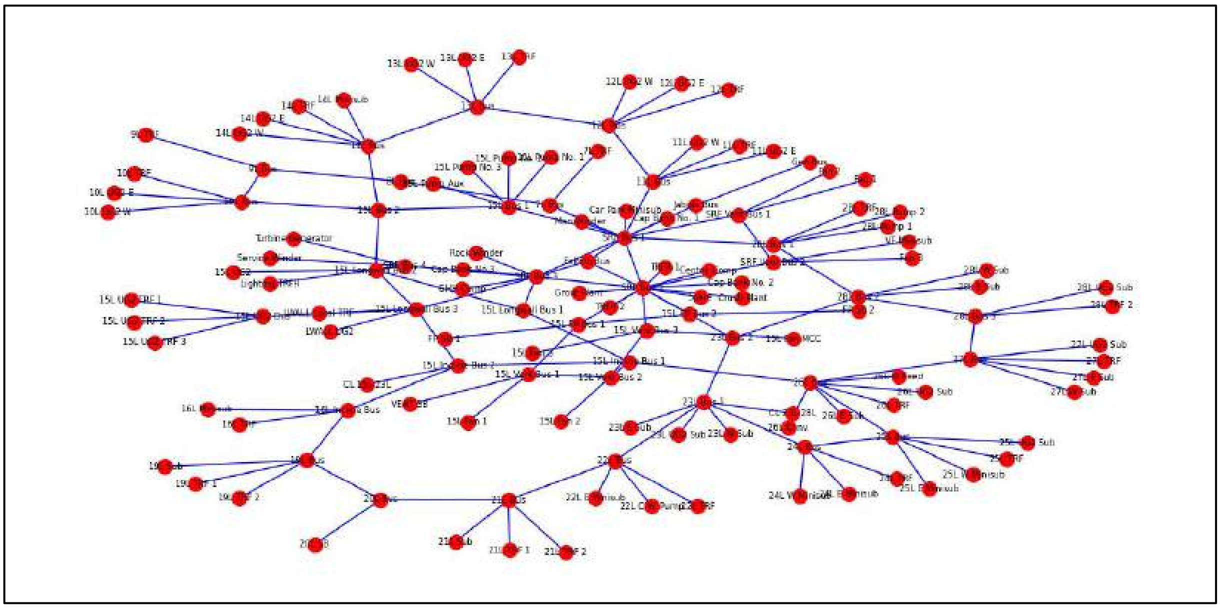

Figure 6: Graph model developed of case system

Figure 6 is developed with the components discussed above to form a complete unidirectional graph that represents the electrical distribution system. The edges are all available for transition as all switches are considered accessible to the solution model. All switches are weighted equally for the purpose of this study focusing on reducing switching events and restoring the most critical load.

4.4 Step 3.1: Construct restoration trees results

Restoration trees are constructed for the graph model to route from each feasible source to critical load node. Seven restoration paths are produced for diesel generators and seven more restoration paths for the turbine generator. The restoration paths are tested for feasibility through load flow analysis, which lead to zero exclusions as each generator can supply each restoration path with sufficient power.

It is assumed that the restoration paths are isolated from bus nodes around them whilst determining feasibility. Therefore, all loads connected to intermediate bus nodes will remain connected, however bus-bus edges are removed to reduce the cold load pick-up and maximum load required by each restoration path.

Critical loads have different path lengths based on the source of the restoration path. This is due to the topological location of the sources in the graph. It is noted that the main difference between the length of restoration trees seem to occur on the surface nodes, i.e. how the surface bus is configured to energise the bus that leads to an underground area. The underground switching is similar for each bus.

This is found to be positive as employing similar tactics when switching allows for less confusion and therefore improved execution performance from switching teams [24, 64]. That in turn, should lead to more reliable switching times. To find efficient solutions within the given constraints, load groups need to be formed to ensure the best combination of critical load to source connections are formed.

4.5 Step 3.2: Form load groups results

Load groups are formed using the restoration trees constructed in the previous section. From the combinations 256 load groups are formed which are available for inspection and testing.

Initial feasibility testing led to 50 load groups being eliminated due to the critical load nodes' load being larger than the power that the specific sources could supply. All the eliminated load groups were from the turbine generator load groups as it has a lower capacity than the total load required to supply all consumers.

Weighting factors $C_{sum,j}$ and load capacity are calculated for each load group. These are not just totalled, as the routes for certain restoration paths are superimposed on each other as can be seen for critical loads CL 23L-28L and 22L Clear water Pumps. Therefore, efficient bus navigation will be achieved by implementing each load group.

As discussed earlier, power flow analysis is required to test the feasibility of load groups.

4.6 Step 3.3: Analyse constraints results

The constraint results are analysed using basic load calculations to verify that none of the generated load groups are unfeasible and will overload the sources or lines. The solutions that will overload are disregarded from the pool considered.

4.7 Step 3.4: Solve the critical load restoration problem results

After all feasible load groups were verified using power flow analysis developed in the previous section, the optimisation problem was solved to deliver the best combination of load groups. The results of the optimisation algorithm formation are shown in Table 3.

Table 3: Solutions found through solving optimisation problem

Sources	**Critical Loads**	$C_{sum,j}$	**Load (kW)**
Diesel Generators	Man Winder, Chairlift 23L-28L, 15L Pumps, 22L Pump, 28L Pumps	4.8	4200
Turbine generators	Service Winder, Chairlift 15L-23L	1.8	700

The load groups selected are a subset of the full set of loads groups. The turbine generators function far below their power capacity indicating the diesel generator is better centralised to deliver power to the critical loads. A visualisation of the graph model is shown in Figure 7.

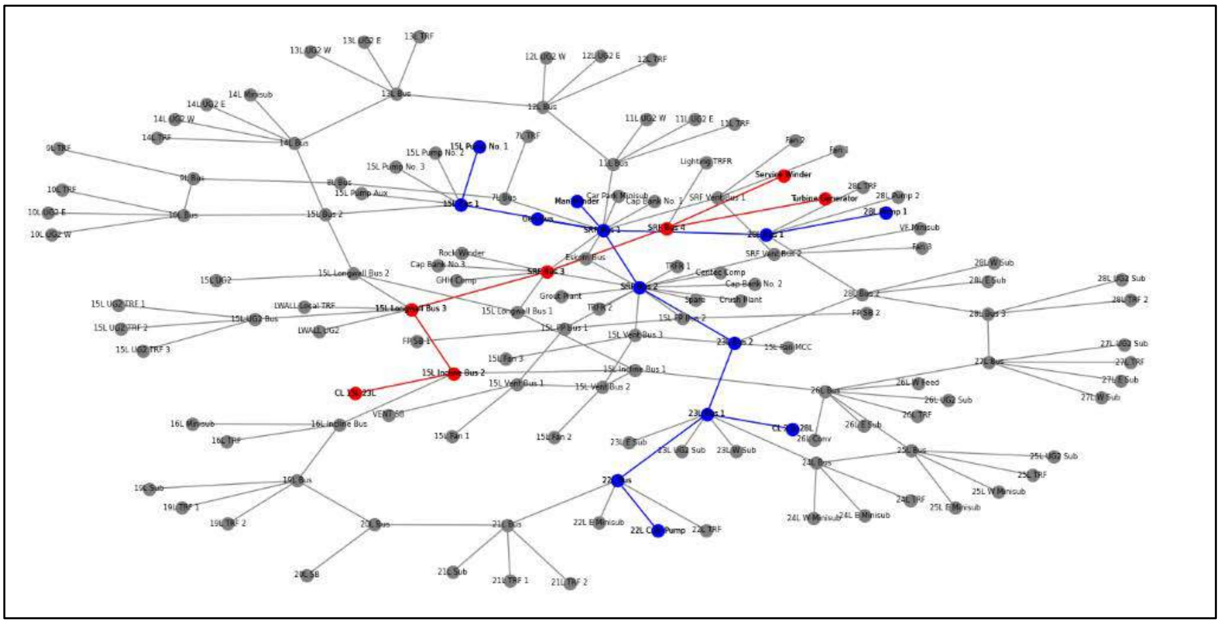

Figure 7: Service restoration graph developed from solution model

The system shows two separate trees that are radial in nature which indicates a successful application of the solution model to restore load to the graph model. The physical constraints of the network are described by the equipment rating in the distribution system. None of the constraints are exceeded by this solution.

Next, the focus will be on the last problem to solve, which is the application of the solution to the electrical network. The objective function was solved and visualised using python and with the networkx library used to generate the graph

4.8 Step 3.5: Determine Restorative Actions

The solution for the graph model was converted into a switching procedure that can be applied to the necessary electrical grid as described in the previous section. If the power balance between the generation capacity and the load cannot be maintained. This leads to an overload due to non-critical load connections on the network.

Firstly, the system does not maintain radial structures within the graph space leading to loops. A radial structure is one of the main constraints to the service restoration problem. Secondly, when tested for feasibility the load exceeds the capacity of the generator. This led to the implementation of the last step of the solution method which involves opening all switches that lead out of the substations that are being traversed that do not specifically lead to the solution.

The interim steps are numbered in such a way that they define the sub actions that need to be completed before the main action is executed. This leads to a combinatorial action switching procedure shown in Table 4.

Table 4: Combinatorial restorative action table

Critical load	Step	Substation	Panel	Action	Effect
Initial	0A	Main consumer sub	All	Open	Disconnect all loads
Man winder	1	Gen Bus	3	Close	Gen Bus - SRF Bus 1
	2	Main consumer sub	2	Close	Gen Bus - SRF Bus 1
	3	Main consumer sub	3	Close	SRF Bus 1 - Man Winder
Service Winder	4	Main consumer sub	30	Close	Link Turbine Gen - SRF Bus 4
	5	Main Consumer sub	31	Close	SRF Bus 4 - Service Winder
28L Pumps	6	Main Consumer sub	1A	Close	SRF Bus 1 - 28L Bus 1
15L Pumps	7	Main Consumer sub	4	Close	SRF Bus 1 - 15L Bus 1
CL 15L-23L	8A	15 Level Incline Shaft sub	Open	6	Disconnect entire 16L Bus to 23L Bus
	8	Main Consumer sub	29	Close	SRF Bus 4 - SRF Bus 3
	9	Main Consumer sub	25	Close	SRF Bus 3 - 15L Longwall Bus 3
CL 23L-28L & 22L C.W.	10A	23L Cluster sub	12	Open	Disconnect 28L Bus 3 Feeder
	10B	22L sub	5	Open	Disconnect 21L Bus
	10	Main Consumer sub	10	Close	SRF Bus 1 - SRF Bus 2

Critical load	Step	Substation	Panel	Action	Effect
	11	Main Consumer sub	20A	Close	SRF Bus 1 - 23L Bus 2
	12	23L Cluster sub	10	Close	23L Bus 2 - 23L Bus 1

When the service restoration procedure is applied, the restoration trees will be implemented effectively as shown in Figure 7. At this point all the steps in the solution procedure are complete.

4.9 Evaluation of results

Power flow analysis is used to test feasibility in the previous sections and evaluation of solution found. A MATLAB simulation package, Simscape, was used as a tool to conduct the power flow analysis.

This network had power meters on the main consumer substation only. This led to the need to approximate each individual load by averaging the power across all loads per feeder power meter.

4.9.1 Restored Load

Similar load restoration results were achieved in the baseline switching procedure that was developed by system experts using practical experience. However, the experts only leveraged one of the distributed generators as a source of power. Figure 8 shows the comparison of load restored in the case study.

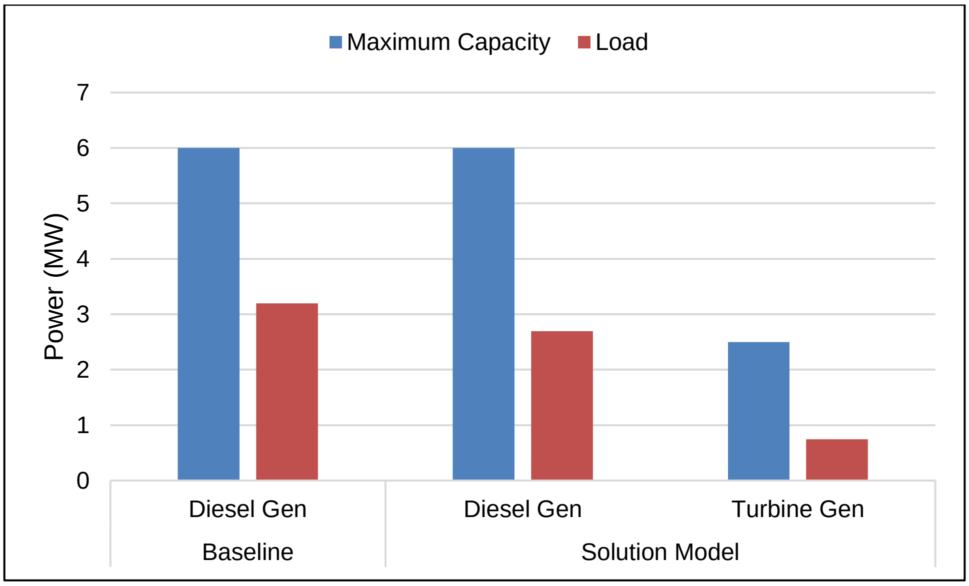

Figure 8: Load restored comparison in case study

Figure 8 shows that both switching procedures restore service to each critical load in the distribution network. The solution model result has a slightly higher load of 246 kW. To save time, loads on restoration path buses are not removed.

The instructions on the baseline service restoration plan indicated that the man winder should run at half speed due to limited capacity of the system. With the inclusion of the turbine generator, the man winder can run at full speed as shown by the loads.

4.9.2 *Switching event evaluation*

The generated switching procedure shows the solution method for a full blackout scenario. The goal is to deliver electrical energy from the diesel generators to the critical loads in the electrical network. Table 5 evaluates the number of switching events of the baseline and solution method.

Table 5: Evaluation of switching events between baseline and solution

Index	Critical Load	Baseline Switching events	Solution model Switching events
0	Pre-emptive isolation	40	39
1	Man Winder	3	3
2	Chairlift 15L-23L	23	3
3	Service Winder	5	2
4	Chairlift 23L-28L	22	5
5	15L Pumps	13	1
6	22L Pumps	1	0
7	28L Pumps	13	1
Total		117	54

For the specific scenario where switches are placed as described by the switching events required in the baseline, switching events are more than double that of the solution model as shown in Table 5. When comparing the worst-case scenario for each case, the number of switching procedures required with the restoration paths, was 117 switching events and the solution presented reduced switching events to 54. In this case study the 22L Bus and 23L Bus are joined. Therefore, Chairlift 23L-28L and 22L Pumps are connected without any switching.

One of the key areas where the baseline switching procedure is outperformed by the solution model, is when load is disconnected from the planned path. Instead of routing underground restoration paths through 23L, the experts used a similar path to normal operations reticulating from level to level instead of using feeders that travel directly from surface to buses near the critical loads. This in turn, requires de-loading each bus in the network by opening load switches at each underground substation. This then prevents overloading due to unnecessary load that is connected during normal operation and isolating the restoration path.

The switching procedure for activating Chairlift 15L-23L is reduced by 20 events and Chairlift 23L-28L switching events are reduced by from 22 to 5 events. Lastly, all pump switching has been reduced to 2 switching events.

In terms of switching event reduction, the solution model switching procedure is an improvement on the baseline switching procedure.

4.9.3 *Restoration time comparison*

As stated earlier the implementation of the solution switching procedure was not cleared by the on-site personnel that preferred to rely on the baseline switching plan. An electrical blackout test is performed on the real-world equipment. The total time of the test lasted 1 hour 43 minutes from initial power loss to power restoration on for all critical loads.

The switching performance of underground teams is of interests as this is where the most impact will be made on the number of switches required. Table 6 shows the time to restoration for each of the critical loads underground.

Table 6: Time estimation of underground switching reduction

Index	Critical Load	Baseline Switching events	Baseline restoration time (minutes)	Solution model Switching events	Estimated restoration time (minutes)
2	Chairlift 15L-23L	23	92	3	12
4	Chairlift 23L-28L	22	103	5	23
5	15L Pumps	13	59	1	4.5
6	22L Pumps	1	100	0	12
7	28L Pumps	13	101	1	7.7

It is seen that there is a long initial switching time before services are restored to the first critical load. The teams implement the switching plan of restoration of the first critical load. This is due to most of the switching being done before re-energising each area. As there where an upper shaft team responsible for critical loads two and four the switching of this team was completed simultaneously with critical load four, six and seven. This is why there is a small amount time between switching load two and four in the baseline case.

Estimated restoration times are based on an average switching rate for each critical load. The teams are also allocated to the same areas during implementation. The switching times are seen to be greatly reduced.

The 22L Pumps service restoration is performed during the switching of critical load two. This further reduces the switching time required from underground switching teams. However, the estimated restoration time will be the same as critical load two.

Through the efficiencies generated by the solution model switching procedure a total time of implementation is reduced from 103 minutes to 23 minutes. The 77.6% estimated improvement in implementation of the baseline service restoration plan is achieved.

The method is feasible for application of the solution method to deliver an adequate switching plan to improve critical electrical service restoration efficiency. This reduces the risk involved with power outages in underground mines through improved planning and reduced implementation time.

Risk reduction of power outages in underground mines are one of the factors that will allow for a bright future in the mining industry that can achieve zero-harm.

5 CONCLUSION

This study illuminates the critical challenge of minimising downtime caused by electrical outages in underground mines. Inefficient utilisation of redundancy within the electrical distribution networks can lead to extended downtime during maintenance, faults, or blackouts. This research investigated optimisation techniques for network reconfiguration to improve service restoration during blackouts.

The proposed solution leverages graph theory and optimisation methods to develop a switching procedure that restores power to critical loads using distributed generation. A case study from a South African platinum mine demonstrated the effectiveness of the approach. Compared to the mine's current procedure, the proposed method achieved service restoration with significantly fewer switching events (54 vs. 117) and ensured full restoration of critical loads.

These findings highlight the potential of the proposed solution method to enhance service restoration plans in underground mines. By reducing the number of switching events and guaranteeing complete critical load restoration during blackouts, this approach can significantly enlighten overall mining reliability, safety, and efficiency.

This is a step towards a bright zero harm future in mining.

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SYSTEM DYNAMICS MAINTENANCE MODELS - SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

To learn from the published maintenance system dynamics (SD) models to build the dust and ash plant SD model and enhance its uptime. This was done through analysis of the 26 studies using systematic literature review methodology. These studies were reviewed for the stocks and flows, mathematical relationships or equations provided, operating dynamics, maintenance dynamics, type of publication and SD software used. Most of the maintenance SD models (69%) developed were not linked to the specific plant operation dynamics and this was found to be the hurdle in translating developed models into improved industrial plant performance. Majority of the software in studies used Vensim. SD research articles lacked standard structure as scholars using same methodology produced articles that were structurally misaligned. Learnings obtained from the studies (12%) were fully transferrable to the future model. The strengths and weaknesses identified shall be adapted in the future plant maintenance model.

Keywords: maintenance, system dynamics, model, and operating dynamics.

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1 INTRODUCTION

Forrester [1] reasons "that our social systems are far more complex and harder to understand than our technological systems. Why, then, do we not use the same approach of making models of social systems and conducting laboratory experiments on those models before we try new laws and government programs in real life?". Forrester [2] argues that we do not live in a "unidirectional world" in which a dust and ash plant problem leads to an action that leads to a high plant availability (solution) and [3] describes this view as an "event-oriented view of the worldview which leads to event-oriented approach to problem-solving".

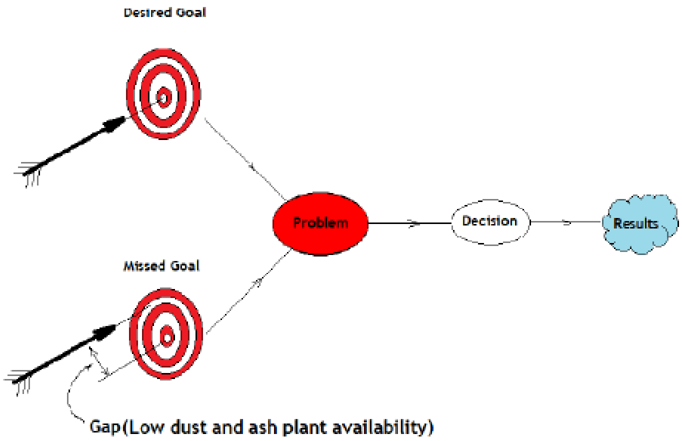

Figure 1: Event-oriented view of the dust and ash plant world. Source: Adapted from [3]

Instead, according to [2] we live in an on-going circular environment (see Figure 2).

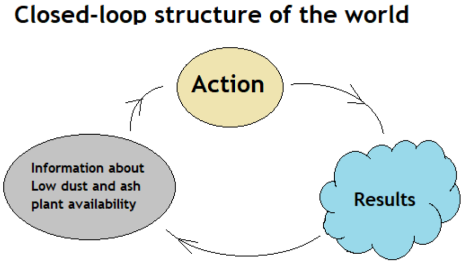

Figure 2: On-going circular environment about dust and ash plant. Source: Adapted from [2]

According to [2], the system dynamics procedure "untangles several threads that cause confusion in ordinary debate of the dust and ash plant availability in a coal-fired power station. The modelling process separates consideration of underlying assumptions (structure, policies, and parameters) from the implied behaviour. System dynamics models build from the inside (endogenous versus exogenous) to determine and to modify the processes that cause *desirable* and *undesirable behaviour*. Information is available from many sources: the mental database, the written database, and the numerical database. Forrester argues that there is no written description adequate for building an automobile, or managing a family, or governing a country. People absorb operating information from apprenticeship and experience. The dominant significance of information from the mental database is not adequately appreciated in the social sciences".

Numerical data can contribute to system dynamics model building in three (3) ways:

- First, numerical information is available on some parameter values. For example, average delivery delays for filling orders, etc.

- Second, numerical data has been collected by many authors in the professional literature summarizing characteristics of economic behaviour such as average periodicity of business cycles and phase relationships between variables.
- Third, the numerical database contains time series information that in system dynamics is often best used for comparison with model output rather than for determining model parameters.

The mental and written databases are the only sources of information about limiting conditions that have not occurred in practice but which are important in determining the nonlinear relationships that govern even normal behaviour. Model building should be a circular process of creating a model structure, testing behaviour of the model, comparing that behaviour with knowledge about the real world being represented, and reconsidering structure [3].

Kirkwood [4] reasons that with a systems approach, the internal structure of the system is often more important than external events in generating the problem. If one shifts from event orientation to focusing on the internal system structure, possibility of improving dust and ash plant performance increases. Once pattern of behaviour of the problem has been identified, system structure that is known to cause that pattern can be addressed. Lane and Sterman [5] argue that Forrester's first principle was that the *puzzling or counter-intuitive behaviour of companies, economies, indeed, all systems, whether physical, physiological, economic, or social, emerged endogenously from their structure*. The second principle is that *nonlinearity* plays a central role in the dynamics of complex systems. Forrester's third principle, that *simulation* was needed to explore system behaviour, led to the development of a practical computer simulation methodology for business, economic and social systems.

Meadows [6] posits that all models serve as a simplification of the real world. This includes everything that people know about the world, i.e. the equations, maps, books, computer programs and mental models. Senge [7] argues that mental models are deeply ingrained assumptions, generalizations, or even picture or images that influence how we understand the world and how we take action. According to [3] mental models include impressions, stories that people tell, their understanding of the system and how decisions are actually made, how exceptions are handled. Kim [8] suggests that mental models are beliefs and assumptions that people hold about how the world is configured. The common thread amongst these authors is that the models rest in the people who are experienced with the phenomenon. Mental models cannot be accessed directly as these are based on experience and assumptions that are not stated anywhere. In order to obtain these dust and ash plant mental models from the users who are experienced with the plant, elicitation was conducted from multiple angles like through interviews, observation, surveys, data reports, analysis of the written documentation and other methods by the system dynamics modeller.

Dust and ash plant has a low plant availability and debate continues to be event-oriented and high plant availability continues to be elusive owing to lack of mental models from the experienced maintenance team and operators. These principles that were advocated and developed by Forrester shall be applied in the development of the dust and ash plant maintenance SD model with the objective to explore the system behaviour and enhance its availability.

2 RESEARCH OBJECTIVE

The aforementioned background data formed the foundation for the systematic literature study that was implemented to look at the system dynamics maintenance models research that have been developed up to this point. This study aims to answer the following question:

What are the characteristics in the published system dynamics models that can be transferred to dust and ash plant model with the aim to build a robust model that will assist maintenance managers to identify undesired behaviours and enhance plant's availability?

The research under consideration includes information on the following: *Publication models with operating dynamics, models with maintenance dynamics, models with stocks and flows, system dynamics models with equations and System Dynamics (SD) software applied*.

The study's findings will be employed to construct the system dynamics maintenance model and to investigate the connection between plant operations and maintenance in order to pinpoint the dust and ash plant's vulnerabilities.

3 RESEARCH METHODOLOGY

On the 15th of February 2024, Sciencedirect and Google Scholar were indexed using a systematic literature review tool to extract relevant books, conference papers, journals, and theses that had an effect on the industry as a whole. The researcher manually included articles from 1991-2024 as they contained findings that were pertinent to the research question. Subsequently, data was categorized, extracted from the handbook, and research papers were added to enumerate and assess the results and clarify how the maintenance model influences plant availability. In total, this study mapped about 26 SD articles. Throughout the inquiry, a clear and consistent search strategy was used, and studies were either included or omitted in accordance with the criteria. Because the benefits and drawbacks of this methodology were well understood, study controls were implemented to ensure that bias was removed. This research might examine multiple SD maintenance model cases from different socio-cultural contexts [9].

4 SEARCH STRATEGY AND SELECTION PROCEDURE

In order to find levers that can be utilized to improve plant energy availability factor and make South African power plants more environmentally friendly, the studies covering SD maintenance models were evaluated and reported using the modified Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) systematic review criteria [10]. The research approach that was used is shown in Figure 3. The search term *System dynamics" "Maintenance model" were used by the search engine. A total of 26 articles were identified for the systematic literature review, to select the final articles to be included in this review, a practical screening was conducted, this was based on the setting of inclusion/exclusion criteria and flow diagram in Figure 3.

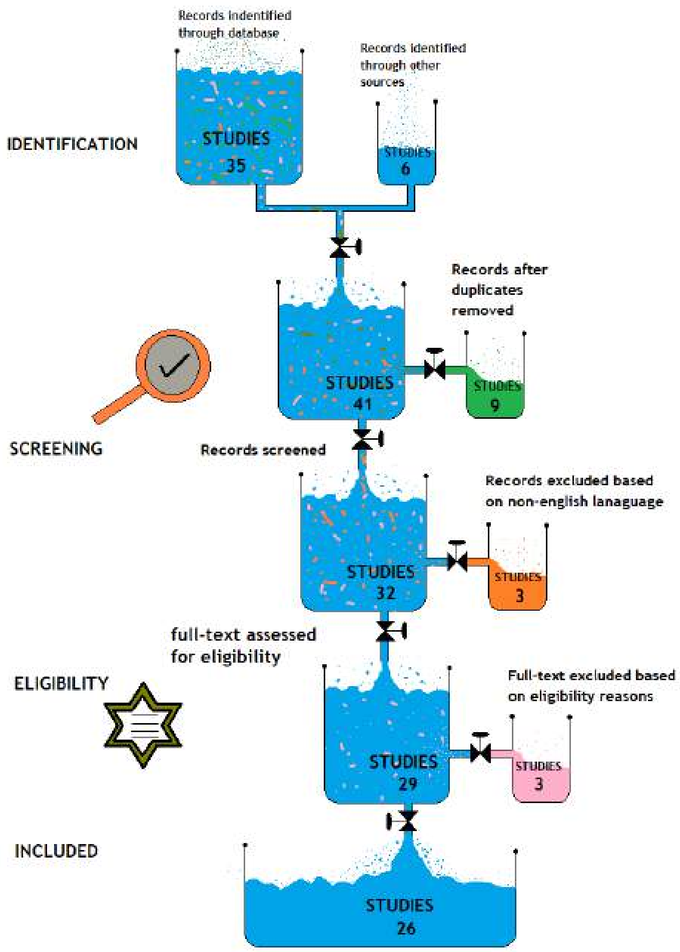

Figure 3: Systematic review flow diagram. Source: Adapted from [10].

5 INCLUSION AND EXCLUSION CRITERIA

The 41 records from the original search were loaded into the Mendeley program. The remaining 41 abstracts and titles were then assessed using the criteria in Table 1 after 15 papers were eliminated with various reasons as provided in Figure 3. Studies were included if they appeared between 1991 and 2024 (Appendix A17-A42). The 26 books, theses, journal articles and conference papers were included. This procedure was followed to improve the study's replicability.

Table 1: Inclusion and exclusion criteria

Item	**Description**
Database searched	Science Direct , Google scholar and Manual selection
Language	English
Timespan	1991-2024
Search string	“System Dynamics” “Maintenance models”
Questions	**Review focus**

Item	Description
Population - who?	SD maintenance model studies globally.
Intervention - what?	SD maintenance model that had been duly developed and tested so that the learning could be easily transferred to the South African coal-fired power plants.

6 STUDIES SELECTION

The articles in this study underwent a double filtration process, which involved removing the 15 articles that didn't match the requirements for criteria. Using qualitative data analysis, all articles that complied with the requirements were examined and coded [11]. Thematic analysis, according to [12], "is a method for identifying, analysing, and reporting patterns (themes) with data." This followed six (6) steps process as outlined in figure 4 below.

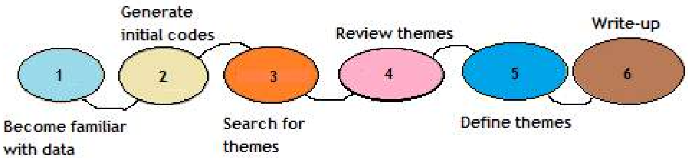

Figure 4: Framework for doing thematic analysis. Source: Adapted from [12] and [13].

Detailed results of the thematic analysis have been included in Appendix A. The studies were heterogeneous and did not follow PRISMA guidelines and as a result, meta-analysis could not be executed.

7 STUDY CHARACTERISTICS

7.1 System dynamics maintenance models with plant operating dynamics

7.1.1 Publication models with operating dynamics

Majority of the studies (69%) developed system dynamics maintenance models without integration of the plant operation dynamics. Defects were constantly generated for as long as the model was running, in the real-world maintenance and operating teams become better at what they are doing in line with the learning theory [14] and [15] and this factor was also scarce in the models considered.

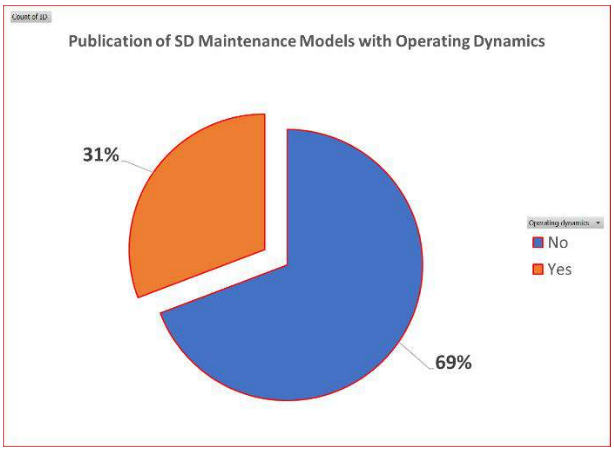

Figure 5: Publication models with operating dynamics.

As plant ages, damage mechanisms that are time-dependent and dust and ash quality-dependent start to show stress and ultimately bring the production to a standstill. Operating styles of the various plant drivers have a dynamic relationship with the plant's long-term health. Most of the model developers have failed to cater for some of these phenomena (see appendix A details). Operating dynamics of the plant also has an influence on the adopted maintenance strategy for the following reasons:

Table 2: Operating dynamics influence on plant maintenance.

Function	**Variables**
Predictive maintenance	• Condition monitoring on real-time operating conditions (*Eg.: Temperature, Pressure, wall thickness of submerged scrapper conveyor (SSC) chain, clinker formation in the boiler and its effect on SSC performance, etc.*). • Failure prediction (*Historical operating data to forecast the incipient plant failures*). • Maintenance scheduling (*Planning maintenance tasks based failure trends*).
Improved reliability and availability	• Reliability engineering (*Eg.: Dynamic or Static Failure, Mode, Effect and Critical Analysis (FMECA), Use of the reliability models, etc.*) • Downtime management (*Elimination of breakdown failures by leveraging on failure forecasts*). • Spare parts management (*Procurement of spares to be available on time during the outage*).
Cost efficiency	• Preventive maintenance (*Eliminating costly maintenance repairs*). • Maintenance efficiency (*Eliminating unnecessary maintenance but executing what is only essential*) • Life cycle management (*Total cost of ownership versus focusing only on the capital expenditure -assist maintenance manager to invest in plant items that are cost-effective*)
Optimisation of the maintenance strategy according to prevailing conditions	Operational changes (Dust and ash *quality* and *quantity*, *load factor*, etc.).
Resource allocation	• Requirement of more *skilled maintenance crew*. • Requirement of *more plant spares* to cater for operating dynamics.
Improved safety	• Ensuring compliance with the Occupational Health and Safety Act, Water Use License, National Environmental Management Act, etc. • Incidents prevention through risks identification and mitigation. Reduction of the likelihood of the accidents through optimal maintenance based on operating data.
Integrating operating dynamics with other systems that drive plant	• Systems engineering (*including all phases of the plant items*). • Feedback loop (establishment of feedback loop based on *tonnage* or *hours* gained while in operation - this is used to optimise maintenance strategy)
Decision-making	• Subjective plant maintenance that is based on the opinions of the workers. • Objective plant maintenance that is based on real-time operating data. • Communication delays effect on plant performance.

Plant operating dynamics' impact on maintenance have been demonstrated by [16], in this article product's life is captured from design to decommissioning and the relationship between maintenance phase and all other phases is clearly described. See Figure 6 below for details.

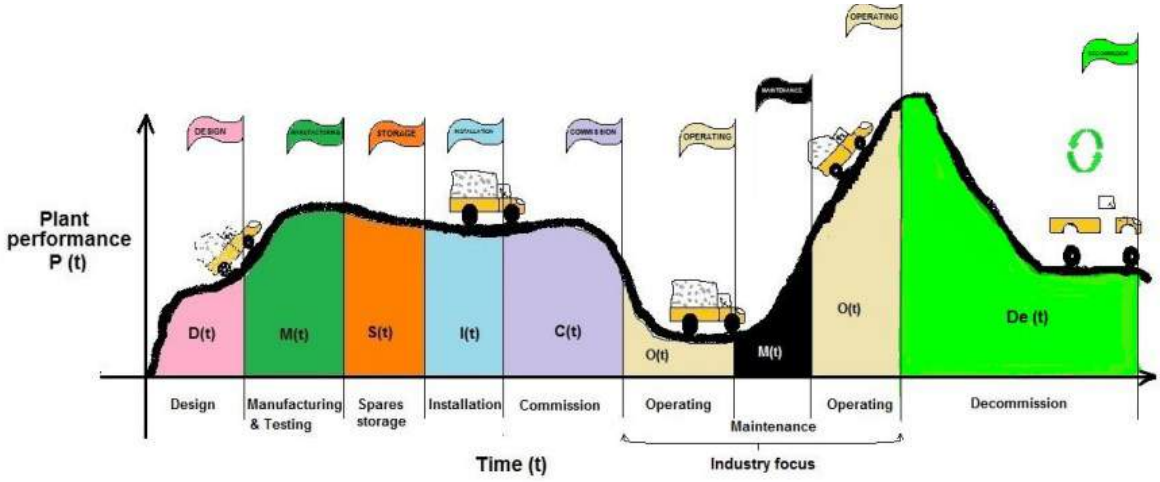

Figure 6: Relationship between maintenance and operating phases of a plant. Source: [16]

7.2 Publication models with maintenance dynamics

Most of the studies (92%) that met the inclusion criteria had developed the maintenance models and this was described in detail. This was also due to the design of the selection criteria. Minority (8%) of the articles did not describe their maintenance model using system dynamics tool.

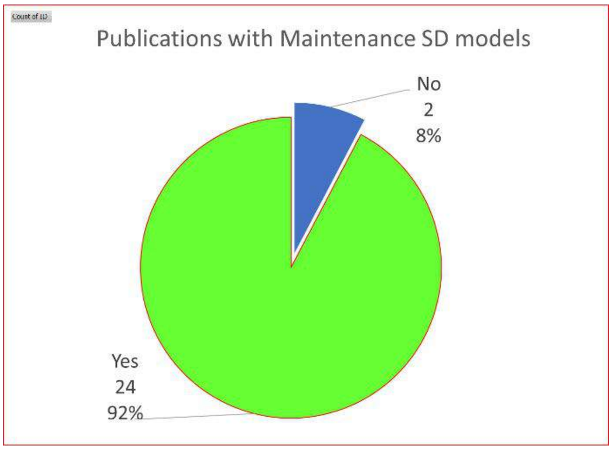

Figure 7: Publication models with maintenance dynamics.

7.3 Publication models with stocks and flows

Minority of the studies (23%) did not provide the stocks and flows of their maintenance models while 77% provided the stock and flows. This practice contradicted the foundation that was laid by Forrester regarding system dynamics modelling. Lack of these section made it difficult for the learnings to be transferred to the dust and ash plant maintenance model.

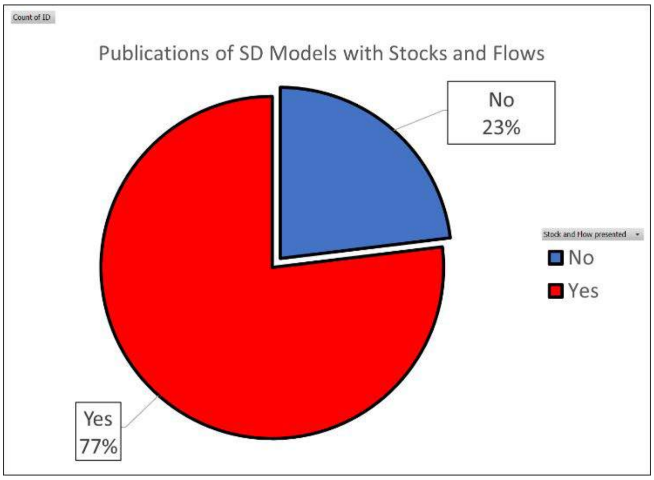

Figure 8: Publication models with stocks and flows.

7.4 Publications models with system dynamics with equations

Minority of the authors (46%) of these studied have failed to provide mathematical relationships of their system dynamics maintenance models. This raised questions about the integrity of the publications as they failed the basic test of transparency and these models could not be independently replicated. Most of the articles (54%) were transparent for the researchers to independently replicate their findings, learnings in this category could be easily transferred to the dust and ash plant to enhance the plant uptime.

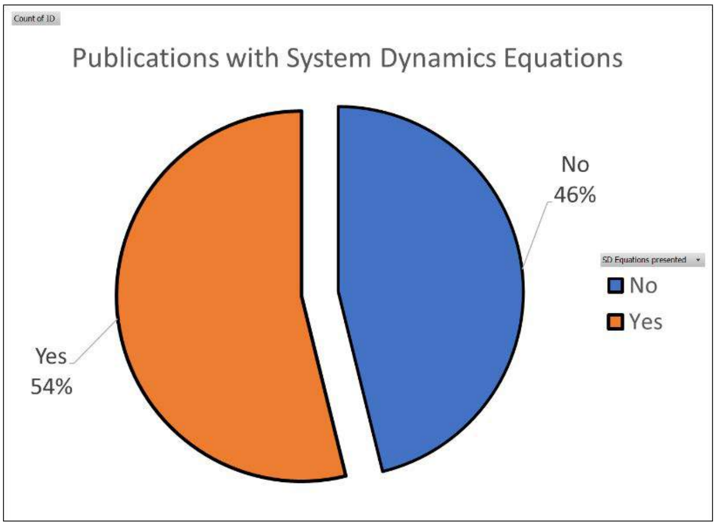

Figure 9: Publications with system dynamics models' equations.

7.5 System Dynamics software applied

Majority of the software (69%) that were used to model the maintenance plants was through various versions of the Vensim.

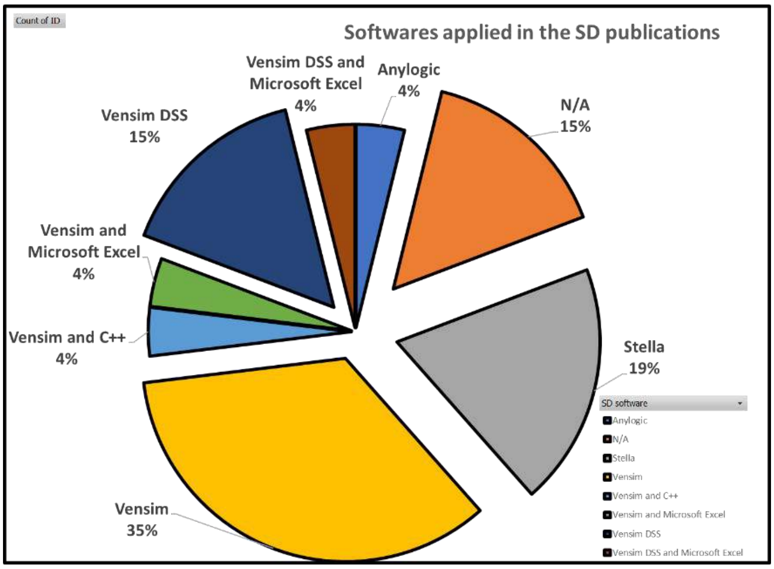

Figure 10: System Dynamics software applied.

7.6 Research location

The studies that were considered in this research came from 21 different parts of the world and these provided the researcher with an unbiased SD maintenance model views with the objective to enhance dust and ash plant.

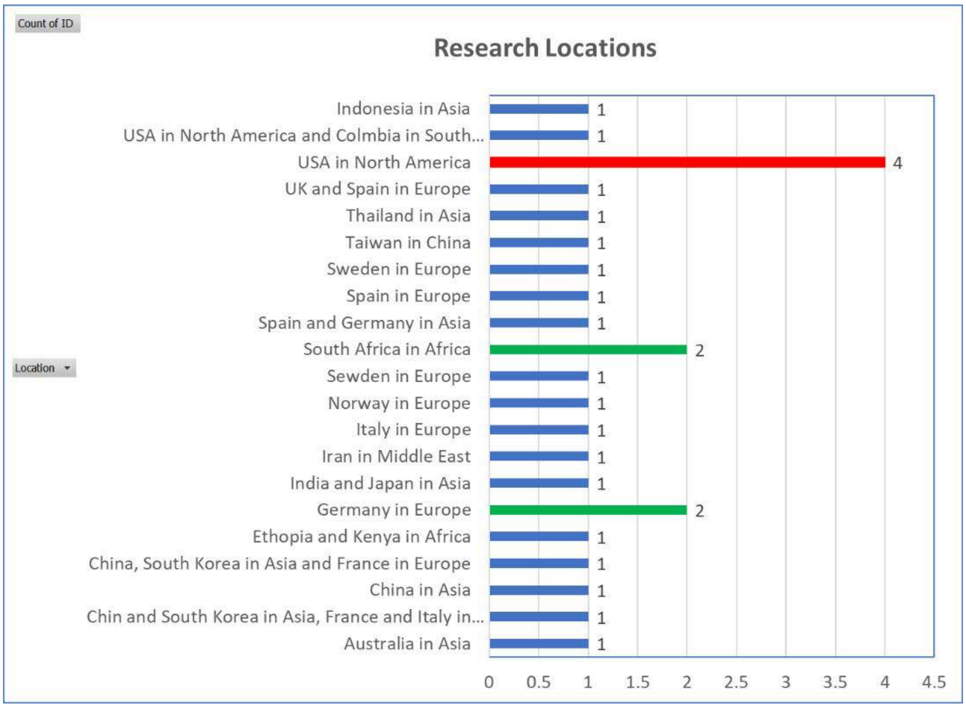

Figure 11: SD publication research location.

7.7 Publication type

Articles that were considered for this study were Journals, Conference papers and Theses that were peer-reviewed for rigour and reliability.

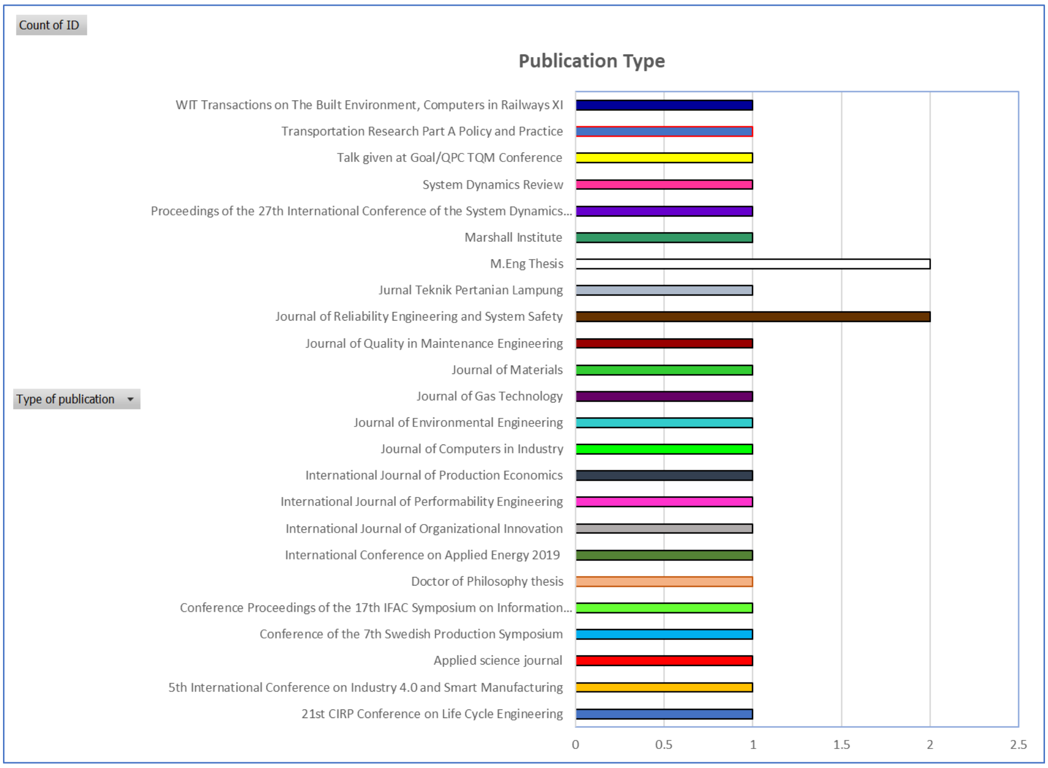

Figure 12: SD publication classification.

7.8 Publication trend

The studies that were selected for the system literature review ranged from 1991-2024. Some of the older studies were included due to their value in assisting the researcher to build dust and ash plant maintenance model using SD tool.

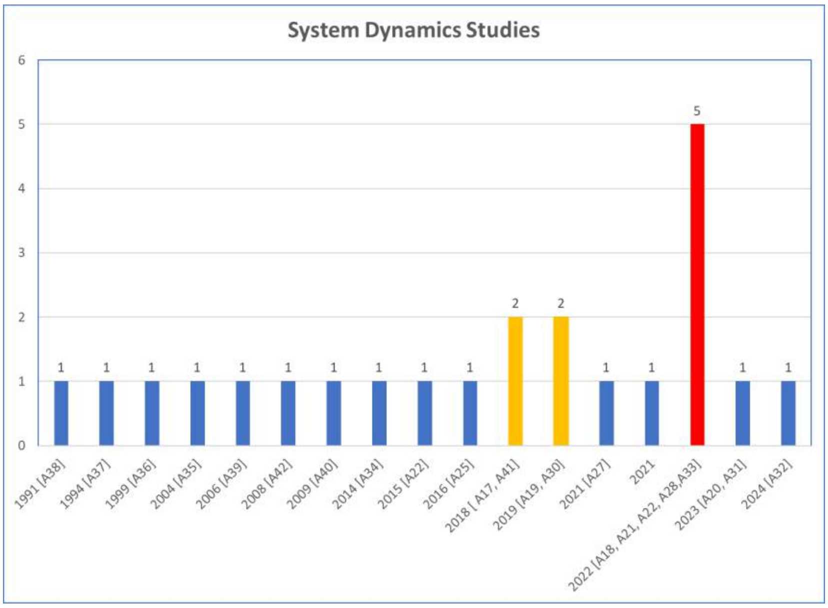

Figure 13: SD publication trend in the studies.

8 DISCUSSION OF THE REVIEW FINDINGS

Appendix A is based on reference [17]- [42] and Table 2 below provide a summary of the findings in the 26 studies that was under review. Comments have been provided by the researcher regarding their appropriateness in answering the research question.

Table 3: Review of the SD findings.

ID	Operating dynamics	Maintenance dynamics	Stock and Flow presented	SD Equations presented	Is this beneficial for building dust and ash plant maintenance model?
[A17]	Yes	Yes	Yes	Yes	Learnings were fully transferrable.
[A18]	No	Yes	Yes	No	Learnings partially transferrable. Maintenance have no relationship with plant operation.
[A19]	Yes	Yes	No	No	Learnings partially transferrable.
[A20]	No	Yes	Yes	Yes	Learnings partially transferrable.
[A21]	Yes	No	Yes	No	Learnings partially transferrable.
[A22]	No	Yes	Yes	Yes	Learnings partially transferrable.
[A23]	Yes	Yes	No	Yes	Learnings partially transferrable.
[A24]	Yes	No	Yes	Yes	Learnings partially transferrable.
[A25]	No	Yes	Yes	Yes	Learnings partially transferrable.
[A26]	Yes	Yes	Yes	Yes	Learnings fully transferrable.
[A27]	No	Yes	Yes	Yes	Learnings partially transferrable.
[A28]	No	Yes	No	No	Learnings partially transferrable with limited success.
[A29]	Yes	Yes	Yes	No	Learnings partially transferrable.
[A30]	No	Yes	No	Yes	Learnings partially transferrable.
[A31]	No	Yes	Yes	Yes	Learnings partially transferrable.
[A32]	No	Yes	Yes	No	Learnings partially transferrable.
[A33]	No	Yes	Yes	No	Learnings partially transferrable.

ID	Operating dynamics	Maintenance dynamics	Stock and Flow presented	SD Equations presented	Is this beneficial for building dust and ash plant maintenance model?
[A34]	No	Yes	No	No	Learnings partially transferrable.
[A35]	No	Yes	Yes	Yes	Learnings partially transferrable.
[A36]	No	Yes	Yes	Yes	Learnings partially transferrable.
[A37]	No	Yes	Yes	No	Learnings partially transferrable.
[A38]	No	Yes	Yes	Yes	Learnings partially transferrable.
[A39]	No	Yes	Yes	No	Learnings partially transferrable.
[A40]	No	Yes	Yes	No	Learnings partially transferrable.
[A41]	No	Yes	No	No	Learnings partially transferrable.
[A42]	Yes	Yes	Yes	Yes	Learnings fully transferrable.

9 CONCLUSION

In this study, 26 studies were reviewed using the systematic literature review methodology to identify the characteristics that can assist in the development of a robust SD maintenance model.

Most of the studies (69%) developed SD maintenance models without integration of the plant operation dynamics. Minority (8%) of the articles did not use SD tool to describe the maintenance model and studies (23%) did not provide the maintenance models' stocks and flows. Minority of the authors (46%) of these studies have failed to provide mathematical relationships of the variables in the models. The 26 studies came from 21 different parts of the world.

Sources of the SD publications came from the reputable Journals, Conferences and Academic theses. Vensim was the most popular SD software to simulate maintenance model.

Learnings (12%) obtained from the studies were fully transferrable to the future SD dust and ash model while (88%) were partially transferrable. This will assist the student to construct a robust SD plant model.

The authors also found that the system dynamics research articles lacked standard structure, SD academics using the same research methodology produced articles that were structurally misaligned. This deviation amongst the SD scholars could be a source of replication crisis and there is need to standardise SD academic work so that learnings could be easily transferred and industrial performance be enhanced.

10 COMPETING INTERESTS

The authors declare that they did not have competing interests.

11 ACKNOWLEDGMENTS

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13 APPENDIX

ID	Author(s)	Operating dynamics	Maintenance dynamics	Stock and Flow presented	SD Equations presented	Simulation	Source of data	Type of publication
A17	L. Gary, N.H.C. Amos and A. Tehseen	Yes	Yes	Yes	Yes	Yes	No	International Journal of Production Economics
A18	H. Meng, X. Liu, J. Xing and Enrico Zio	No	Yes	Yes	No	Yes	Assumed values	Journal of Reliability Engineering and System Safety
A19	I. El-Thalji and H. Nordal.	Yes	Yes	No	No	No	N/A	International Conference on Applied Energy 2019
A20	A, Telukdarie and M. Munsamy and M. T. Manenzhe	No	Yes	Yes	Yes	Yes	Numerical date -Plant A and B	Journal of Quality in Maintenance Engineering
A21	M-W. Tsao and Y-C. Wang	Yes	No	Yes	No	Yes	N/A	International Journal of Organizational Innovation
A22	W. N. Cahyo	N/A	Yes	Yes	Yes	Yes	Archive, focus group	Doctor of Philosophy thesis
A23	P. Winkler, S. Gallegmonel García and M. Groten	Yes	Yes	No	Yes	No	Vensim	Applied science journal

ID	Author(s)	Operating dynamics	Maintenance dynamics	Stock and Flow presented	SD Equations presented	Simulation	Source of data	Type of publication
A24	I. L. Francesca, M. Salvatore and R. Elpidio	Yes	N/A	Yes	Yes	Yes	N/A	Conference Proceedings of the 17th IFAC Symposium on Information Control Problems in Manufacturing.
A25	G. Linnéusson, A. Ng and T. Aslam	No	Yes	Yes	Yes	Yes	N/A	Conference of the 7th Swedish Production Symposium
A26	M. Rahman, B. Pramudya, M. Y. J. Purwanto and M. Solahudin.	Yes	Yes	Yes	Yes	Yes	Observation and archives	Jurnal Teknik Pertanian Lampung
A27	H. Khedry, G. Jamali and A. Ghorbanpour.	N/A	Yes	Yes	Yes	Yes	Interviews	Journal of Gas Technology
A28	A.Libey, P. Chintalapati, S. Kathuni, B. Amadei and E. Thomas.	No	Yes	No	No	Yes	Observations and Interviews.	Journal of Environmental Engineering
A29	Nikhil Bugalia, Yu Maemura, Rohit Dasari and Manoj Patidara	Yes	Yes	Yes	No	Yes	Archival data	Transportation Research Part A Policy and Practice
A30	R. Na, X. Li, J. Liu and Y. Liu.	No	Yes	No	Yes	Yes	Archival data	International Journal of Performability Engineering
A31	A.Crespo Marquez, J.A.Marcos Alberca and A. Crespo del Castillo	No	Yes	Yes	Yes	Yes	Archival data	Journal of Computers in Industry
A32	M. Munsamy, A. Telukdarie and M. Manenzhe	No	Yes	Yes	No	Yes	Archival data	5th International Conference on Industry 4.0 and Smart Manufacturing
A33	H. Meng, X. Liu, J. Xing and E. Zio.	No	Yes	Yes	No	Yes	Archival data	Journal of Reliability Engineering and System Safety
A34	K. Ortegona, L.F. Nies and J.W. Sutherland.	No	Yes	No	No	No	Archival data	21st CIRP Conference on Life Cycle Engineering
A35	V. Kothari	No	Yes	Yes	Yes	Yes	Archival data	M.Eng Thesis
A36	P. Iyer	No	Yes	Yes	Yes	Yes	Archival data	M.Eng Thesis

ID	Author(s)	Operating dynamics	Maintenance dynamics	Stock and Flow presented	SD Equations presented	Simulation	Source of data	Type of publication
A37	W. Ledet. and M. Paich	No	Yes	Yes	No	No	N/A	Talk given at Goal/QPC TQM Conference
A38	W. J. Ledet	No	Yes	Yes	Yes	No	Archival data	Marshall Institute
A39	J-H. Thun.	No	Yes	Yes	No	Yes	N/A	System Dynamics Review
A40	R. Chumai	No	Yes	Yes	No	Yes	Survey and interviews	Proceedings of the 27th International Conference of the System Dynamics Society
A41	S. Gallego García and M. García.	No	Yes	No	No	Yes	N/A	Journal of Materials
A42	T. Böhm, K. Beck, A. Knaak, and B. Jaöger.	Yes	Yes	Yes	Yes	Yes	N/A	WIT Transactions on The Built Environment, Computers in Railways XI

THE IMPLEMENTATION OF CIRCULAR ECONOMY PRINCIPLES TO THE RAPID SAND-CASTING PROCESS

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ABSTRACT

The rapid sand-casting process, a form of additive manufacturing for creating sand moulds and cores, uses technologies like ExOne and Voxeljet with furfuryl alcohol-based binder-jetting. These methods are now mainstream in hybrid moulding processes. Like traditional casting methods, rapid sand casting generates waste sand. With its growing adoption, waste sand is expected to increase. This paper explores applying the circular economy framework to manage this waste sustainably through recycling, repurposing, and reusing. In addition, this experimental research opportunity using the Voxeljet VX1000 sand printer indicates that integrating circular economy principles can make rapid sand casting more environmentally and economically sustainable.

Keywords: additive manufacturing, circular economy, rapid sand casting, furfuryl alcohol-based binder jetting, Voxeljet VX 1000 sand printer, waste sand, recycling, sustainable solutions

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1 INTRODUCTION

1.1 Sand-Based Additive Manufacturing

Within the field of additive manufacturing, the counterpart to rapid sand casting is commonly known as sand-based additive manufacturing or simply sand printing [1]. Although not an exact replication of traditional sand casting, this approach employs analogous principles, utilizing sand as a fundamental material for object creation [1]. The process commences with the digital creation of the desired part using computer-aided design (CAD) software [1]. Using the CAD design, the sand-based additive manufacturing machine employs a binder material to selectively fuse sand particles, layer by layer. A printhead, or similar apparatus, deposits the binder onto each layer of sand, shaping it into the desired part. This sequential layering process is iterated until the part is fully formed. Following each layer deposition, there may be a curing or solidification phase to enhance the bond between the sand particles and the binder. Upon completion of printing, excess sand is typically removed, and the part may undergo further post-processing steps such as curing, heat treatment or surface finishing to achieve the desired properties and surface quality [1].

The integration of additive manufacturing technology into sand casting expedites the design and production process by eliminating the need for patternmaking and reducing the lead times associated with traditional methods [2]. Researchers have developed both simple and complex castings using 3D (Three-dimensional) printed sand molds and cores This technique also enables the production of complex geometries without the need for complex tooling; as well as creating parts that are cheaper than those made using traditional manufacturing methods [1]. In sand casting, where intricate shapes and custom designs are essential, additive manufacturing provides a versatile solution.

In a study conducted by Hawaldar, and Zhang, it was emphasized that 3D printing process proves to be more efficient than traditional sand casting in several areas, such as reducing sand and metal usage, allowing for greater design flexibility, and minimizing fettling work, especially when only a small number of molds are needed [3]. Conversely, for larger mold quantities, the conventional tooling method may be more advantageous. Moreover, the expenses associated with 3D printing technology and its operation currently exceed those of traditional methods [3].

By leveraging 3D-printing techniques, manufacturers can create complex geometries more efficiently than the conventional method [2]. This adaptability makes sand casting attractive for industries requiring low-volume production runs, such as aerospace, automotive and medical device manufacturing. Additionally, the cost efficiency and reduced lead times associated with additive manufacturing contribute to its growth [2]. Rapid prototyping and streamlined design iteration allow manufacturers to bring products to market faster, meeting evolving customer demands and promoting wider adoption of this integrated approach [2].

1.2 Sustainable Waste Management in Additive Manufacturing

Additive manufacturing, which is advancing rapidly within the metal manufacturing industry, may benefit from a proactive approach to addressing potential waste generation issues associated with its existing linear model to promote sustainability. In the process of rapid sand casting with additive manufacturing, waste is generated at several production stages, as depicted in Figure 1. The amount of waste sand produced varies depending on factors like nesting density and component surface area [4]. Disposal of chemically bonded sand poses challenges due to environmental regulations and irreversible chemical reactions [5]. In response, the concept of a circular economy has emerged offering a transformative approach rooted in regenerative design and resource optimization [6]. In this study, waste furan-bonded sand generated from three-dimensional printing with the Voxeljet VX 1000 printer was repurposed for the production of common cement bricks.

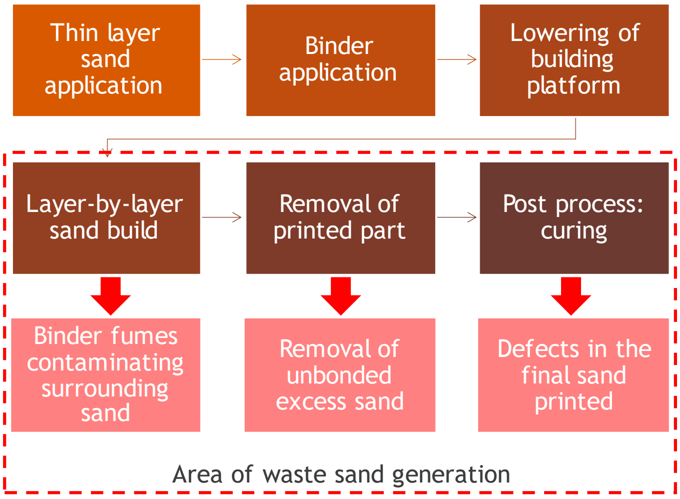


Figure 1: Waste sand generation in the sand-printing process [2], [7]

Before printing, the sand is prepared by coating it with sulphonic acid (catalyst) as such, the environmental friendliness is not known. The excess unbonded sand gets contaminated with fumes from the furfuryl alcohol resin during the AM process, which is well indicated in the change in colour as depicted in Figure 2.

Figure 2: Silica sand samples - waste sand from sand printing of furan-bonded sand cores (left), virgin silica sand (right)

The waste sand produced by the three-dimensional printing of sand parts is contaminated, although it has not come into contact with molten metal. Therefore, the physical characteristics of the sand grains are undamaged making the sand too valuable to dispose of. However, the residual binder in the waste sand remains a concern. Motlhabane et al. [8] investigated the properties of waste sand generated from the additive manufacturing of sand parts using the Voxeljet process. The investigation showed that waste sand generated from additive manufacturing has the potential to be reused for the production of sand parts using traditional methods of core and mould-making [8]. Figure 3 illustrates how waste sand from additive manufacturing and traditional foundry moulding operations is classified.

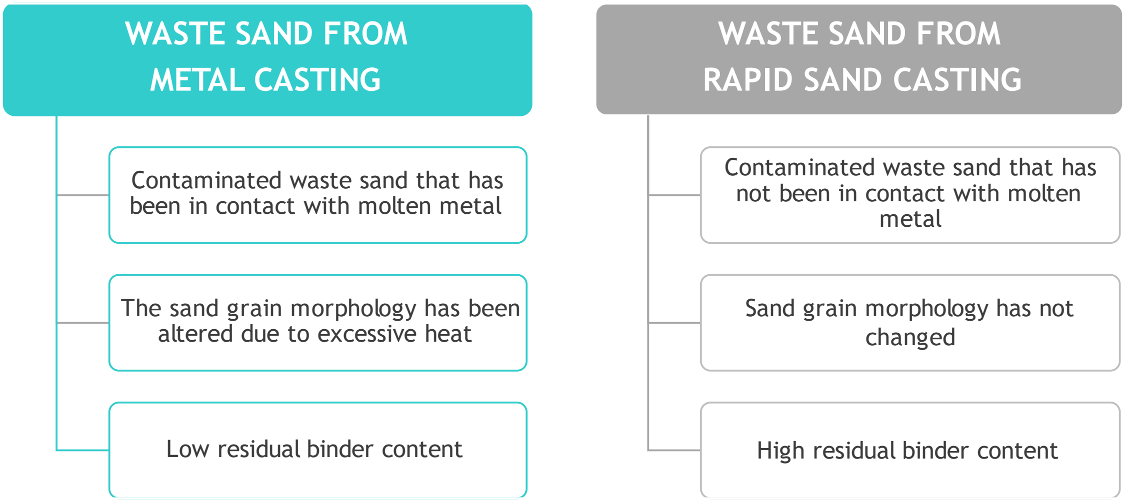
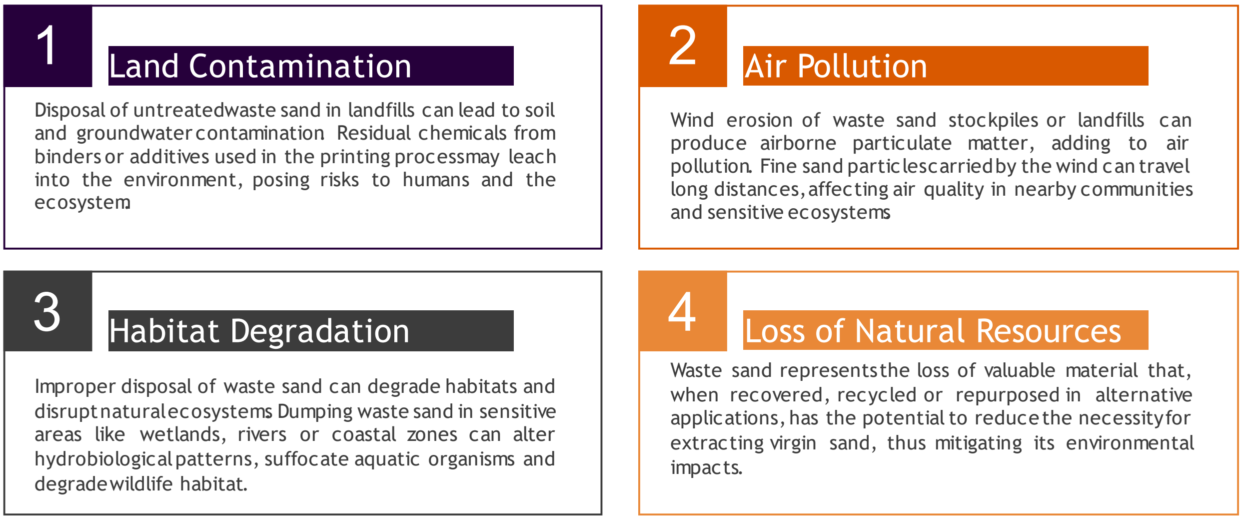


Figure 3: Characterisation of waste sand generated from the foundry and additive manufacturing processes [9]

The disposal of waste sand generated from sand printing or sand-based additive manufacturing can pose several environmental problems [10]. Figure 4 summarizes some of the key environmental concerns associated with this waste sand.



1 Land Contamination

Disposal of untreated waste sand in landfills can lead to soil and groundwater contamination. Residual chemicals from binders or additives used in the printing process may leach into the environment, posing risks to humans and the ecosystem.

2 Air Pollution

Wind erosion of waste sand stockpiles or landfills can produce airborne particulate matter, adding to air pollution. Fine sand particles carried by the wind can travel long distances, affecting air quality in nearby communities and sensitive ecosystems.

3 Habitat Degradation

Improper disposal of waste sand can degrade habitats and disrupt natural ecosystems. Dumping waste sand in sensitive areas like wetlands, rivers or coastal zones can alter hydrobiological patterns, suffocate aquatic organisms and degrade wildlife habitat.

4 Loss of Natural Resources

Waste sand represents the loss of valuable material that, when recovered, recycled or repurposed in alternative applications, has the potential to reduce the necessity for extracting virgin sand, thus mitigating its environmental impacts.

Figure 4: Environmental problems associated with the disposal of untreated waste sand, [10], [11], [12]

To address these environmental problems, it is essential to implement sustainable waste management practices for waste sand generated from sand printing or sand-based additive manufacturing [11]. This may include strategies such as the reclamation and recycling of waste sand for use in other applications, proper containment and treatment of contaminated waste, and regulatory measures to ensure compliance with environmental standards and regulations.

In addition, research and innovation in waste reduction, resource recovery and alternative materials can help minimize the environmental impact of waste sand [12]. Promoting the transition towards more sustainable manufacturing practices is crucial for mitigating the environmental consequences of waste sand and ensuring the long-term sustainability of manufacturing operations.

Previous research by Motlhabane et al. [9] looked at the viability of mechanically reclaiming the waste sand produced from the manufacturing of sand cores using the Voxeljet VX1000 printer. It was found that mechanical reclamation can eliminate the remaining binding agent in furan-bonded waste sand that is produced using this method [9]. The research also showed that the pH of the sands and the loss-on-ignition results suggested that mechanical reclamation using wet attrition is more efficient at eliminating the remaining binder in the sand than mechanical reclamation using dry attrition [9].

Efforts to mitigate waste in sand casting with additive manufacturing include optimizing design parameters to minimize material usage, exploring recyclable or reusable support structures and implementing efficient post-processing techniques to reduce material waste [2]. Continued research and development in additive manufacturing technologies and materials is essential for addressing waste management challenges and enhancing the sustainability of the sand-casting process [2].

While sand reclamation is a feasible recycling process, its limitations can still pose challenges. For example, while mechanical reclamation using wet attrition can effectively remove residual binders from sand better than dry attrition, the process may demand significant water usage. Additionally, the wastewater must be treated according to the safety and health regulations before being released into the local water system. After the removal of the acid, additional procedures, such as drying, should be applied to make certain the sand is suitable for reuse [4].

In a study, Motlhabane et al. [9] suggested that prolonged reclamation times must be implemented when reclaiming sand with a loss-on-ignition content greater than 0.50% [9]. It was further emphasized that precautions must be taken to avoid altering the grain shape, size, and distribution as this will affect the performance of the sand when coated with the binder system [9].

1.3 Industry Synergy Through Circular Economy

The circular economy concept emphasizes maintaining materials in circulation through reuse, recycling and regeneration, aiming to reduce resource use and waste generation [13]. Implementing circular economy principles in the foundry sector requires an understanding of pollutants in used sand and being able to explore reuse options. In addition, mutually beneficial relationships between industries, like foundries and concrete producers, demonstrate the potential for symbiotic or synergistic relationships between industries.

Manufacturing giants like Apple and Coca-Cola have already implemented the circular economy into their processes, and they are reaping advantages, such as creating new business opportunities, avoiding the purchase of virgin material, reducing dependency on imports and increasing resource security [14]. Properly aligning circular economy and sustainable development entails reorienting the focus towards resource access that enhances social well-being and environmental quality [14]. Given the increased urgency with which environmental challenges must be addressed, the circular economy is essential for advancing sustainable development.

Sustainability and the circular economy both arise from concerns about the excessive use of resources and the degradation of the environment brought on by risky human activities [15]. Economic sustainability's primary objective is the preservation of raw materials, both renewable and limited resources, that are necessary for economic activity [15]. The next section of the paper presents an implementation of the circular economy for the rapid sand-casting process adopted in this research study.

2 METHODOLOGY

For this study, the Vaal University of Technology's (VUT) additive manufacturing facility equipped with industrial-grade additive manufacturing technology was used as a case study on the repurposing of waste sand from 3D printing. The waste furan-bonded sand generated from the printing of sand parts by the Voxeljet VX1000 printer was repurposed for the production of common cement-type bricks. Before the bricks could be made, the waste sand was collected and characterized, and compared to virgin sand.

2.1 Collection and Characterization of Waste Furan Bonded Sand

2.1.1. Collection Process

The disposed waste Furan bonded sand was sourced from the VUT additive manufacturing facility. This sand is a byproduct of the three-dimensional printing of sand parts. The sand was systematically collected post-printing, ensuring no contamination occurred during the collection process. The collection aimed to gather a representative sample of the waste produced.

2.1.2. Initial Characterization

The collected waste sand samples were prepared for characterization. This involved drying the sand to remove any moisture and sieving it to achieve a uniform particle size distribution. Testing of the collected waste sand samples was run twice, that is, test 1 (T1) and test 2 (T2). Also, the virgin sand (precoated with sulphonic acid) was tested for comparison purposes.

The prepared sand samples underwent testing to determine their physical and chemical properties. These tests included:

- **Particle Size Distribution - AFS 1105-12-S:** Utilizing a sieve analysis, the range and distribution of the sand particle sizes were determined. 100 g of weighted sample material was screened through ten sieves with progressive opening sizes ranging from 1.180mm to 0.053mm. The percentage fines were calculated by summing up the percentage retained on sieves, 0.075mm, 0.053mm and pan, the AFS GFN (American Foundry Society Grain Fineness Number.) was determined as follows:

$$\boldsymbol{AFS\ GFN} = \frac{\boldsymbol{\%RETAINED*PRODUCT}}{\mathbf{100}} \qquad (1)$$

- **Chemical Composition Analysis:** An X-ray fluorescence (XRF) spectrometer (Phillips PW 2400) was used to identify the chemical makeup of the sand.
- **Grain morphology Analysis- AFS 1107-00-S:** The sand grains were examined with a stereomicroscope (Olympus SZ61), at magnifications ranging from 10x to 40x.
- **Loss on Ignition (LOI) - AFS 5100-12-S**The volatile matter lost will consist of combined water and carbon dioxide from carbonates. In a muffle furnace, 10 g of weighed sample material was exposed to 1000 °C for 4 hours. After 4 hours, the sample was removed from the muffle furnace and allowed to cool to room temperature, then weighed to obtain the Loss on Ignition content using the formula given in Equation (2).

$$Loss\ on\ ignition\ (\%) = [\frac{Weight\ loss}{Sample\ weight}] * 100 \qquad (2)$$

- **Sand pH - AFS 5113-00-S:** The pH was determined by mixing 25 g of weighed sample material with 100 ml of distilled water. After stirring for 5 minutes, the pH meter was used to measure the pH.

2.2 Repurposing Waste Sand for Brick Production

2.2.1. Formulation and Mixing

The characterized waste sand was mixed with standard cement and water to create a mixture suitable for brick production. Firstly, a control mix without waste sand was prepared at a laboratory scale to serve as a reference for comparison with the trial mixes. The fine sand in the trial mixes was replaced by 50% and 100% waste sand by mass. Rapid hardening cement, chosen for its finer particle size and larger surface area, was utilised to enhance the reaction rate with water, thereby increasing the rate of hydration and producing higher early strength. A mechanical mixer was used to ensure a homogeneous mixture. The mixing process was standardized to maintain consistency across all batches. Tables 1 and 2 present the fine sand blend ratios and the addition rates used in the preparation of the cement bricks, respectively.

Table 1: River sand blend ratios (%)

	Trial mix		
Sand type	**1**	**2**	**3**
River sand	100.00	50.00	0.00
Waste sand	0.00	50.00	100.00

Table 2: Brick-making addition rate - common cement bricks

Additive(s)	*Addition rate (%)*	*Amount (Kg)*
Cement (rapid hard cement)	12.50	1.125
Fine sand: River sand (0 - 1mm)	43.75	3.94
Coarse sand: Stone (1 - 3mm)	43.75	3.94
Total dry weight	**100.00**	**9.00**
Water addition against dry weight	+10.00	0.90

2.2.2. Moulding and Curing

The prepared mixtures were cast into moulds, vibrated, and levelled to form uniform ISO brick. The brick samples were subjected to air drying under consistent conditions, maintaining the same water-to-binder ratio used in conventional brickmaking. After a 72-hour drying period, the brick samples were demoulded and subsequently tested for their properties, see Figure 5 for summarised overview.

Figure 5: Brick making of common cement brick samples.

2.2.3. Testing of Brick Samples

- **Compressive strength test - ASTM C39/C39M:** This measures the ability of the brick to withstand axial loads. The test involves applying a compressive axial load to a standard specimen of the brick until failure.
- **Water absorption test - ASTM C140:** This indicates the porosity of the brick and its ability to withstand weathering. The test involves immersing the brick in water at 25°C for 24 hours. After immersion, the brick was dried of excess water and weighed to determine the water absorbed. The water absorption was calculated as the percentage increase in weight of the brick after immersion, see formula below.

$$\boldsymbol{Water\ Absorption}\ (\%) = \left[\frac{\boldsymbol{Weight\ loss}}{\boldsymbol{Sample\ weight}}\right] * \mathbf{100} \qquad (3)$$

- **Bulk density - ASTM C642:** Density testing provides information about the compactness of the brick. The test involves measuring the mass and dimensions of the brick. The density was calculated by dividing the mass of the brick by its volume, which is determined from its dimensions.
- **Visual inspection:** Inspecting the surface of the brick for defects such as cracks chips, spalling warping, colour variations and other imperfections.

2.2.4. Comparative Analysis

The results from the sand characterization tests were compared against the critical material attributes required for the following applications:

- Brick Making: Standards for structural integrity and durability.
- Foundry Core and Mould Making: Thermal stability, strength, and reusability.
- Sand Printing: Particle size distribution, bonding quality, and surface finish.

Each attribute was evaluated to determine the suitability of the waste sand for the intended applications. Based on the comparative analysis, the waste sand generated from the 3-printing application was categorized on the waste hierarchy.

With the methodology firmly established, the focus will shift to the critical evaluation of the findings. The subsequent sections present and discuss the results, providing insights into the practical implications and potential applications of our research.

3 RESULTS AND DISCUSSION

3.1 Waste Sand Classification

3.1.1. Sand Grain Distribution and Grain Morphology

Figure 6 shows the grain-size distribution of the waste sands, T1 and T2, and the virgin sand (precoated with sulphonic acid). The overall grain-size distribution of the waste sand was widely spread across sieve sizes 0.450 mm and 0.075 mm, while the virgin silica sand was narrowly spread across sieve sizes 0.150 mm and 0.106 mm. The waste sand grains were angular to sub-angular with medium sphericity, while that of virgin silica sand grains were observed to be angular to sub-angular with medium to low sphericity see figure 7.

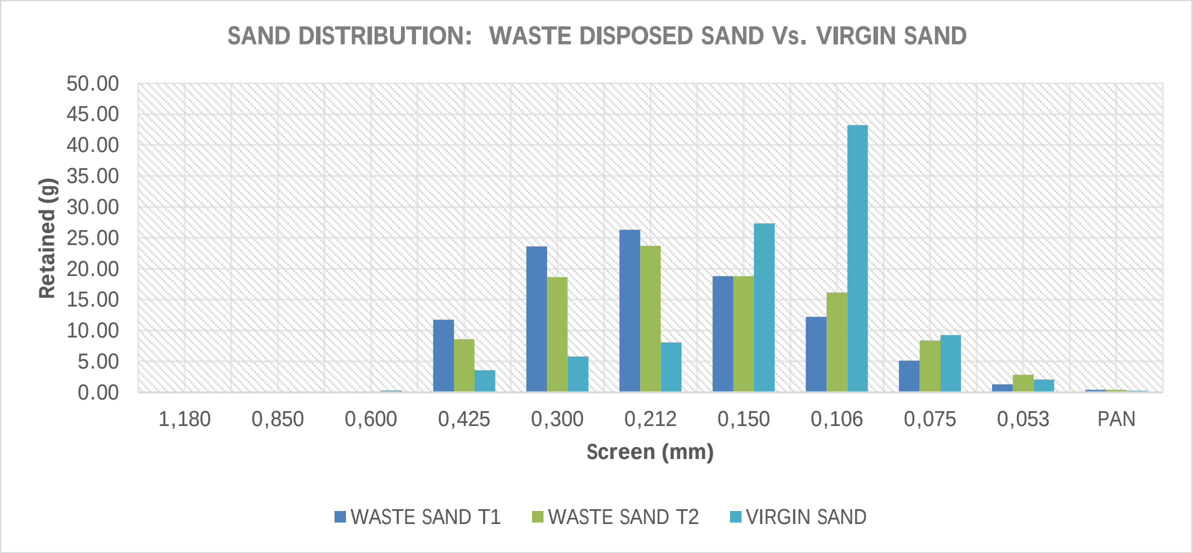


Figure 6: Grain-size distribution of the waste sands vs virgin sand.

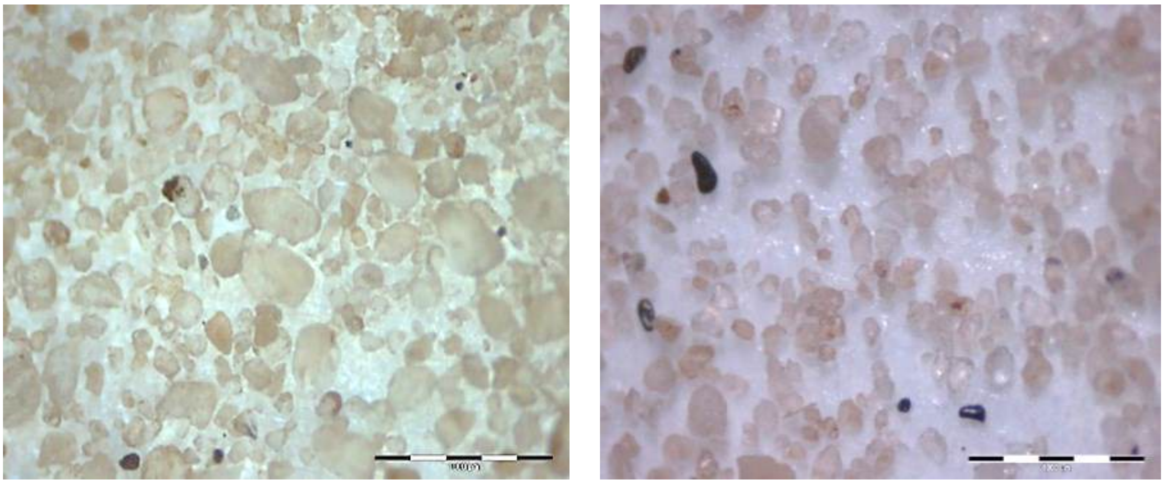


Figure 7: Microscopic imaging - waste sand grains (left), virgin silica sand grains (right).

Figure 8 shows the AFS GFN of the waste sand, The waste sand showed an average AFS GFN and percentage fines of 66.43 and 9.28%, respectively, which is lower than the 87.79 AFS GFN and 11.60% fines of the virgin silica sand. The printing process seems to reduce the fines of the sand, as observed in a previous study [8].

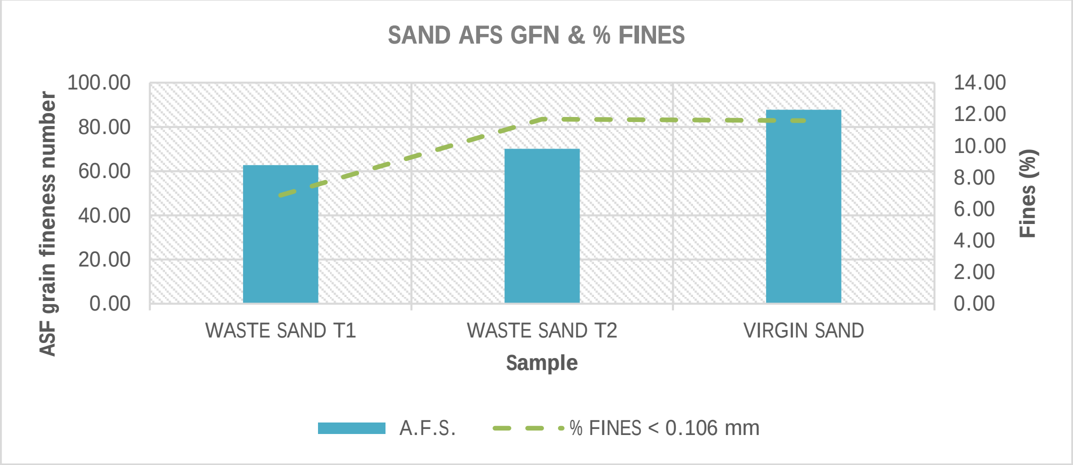


Figure 8: AFS grain fineness number and % fines of the waste sands and the virgin sand.

3.1.2. Sand Purity

The pH of the virgin silica sand was found to be 2.86, indicating the presence of sulfonic acid. The average pH of the collected waste sand was 3.22, suggesting that the sulfonic acid had been utilized. Both waste sands have identical LOI values of 0.52%, while the virgin sand has a slightly higher LOI of 0.57%. Although the difference is not significant, it is reasonable to hypothesize that the waste sand should have a higher LOI value. This discrepancy could be due to the storage and collection conditions of the waste sand, or the source and initial treatment of the virgin silica sand.

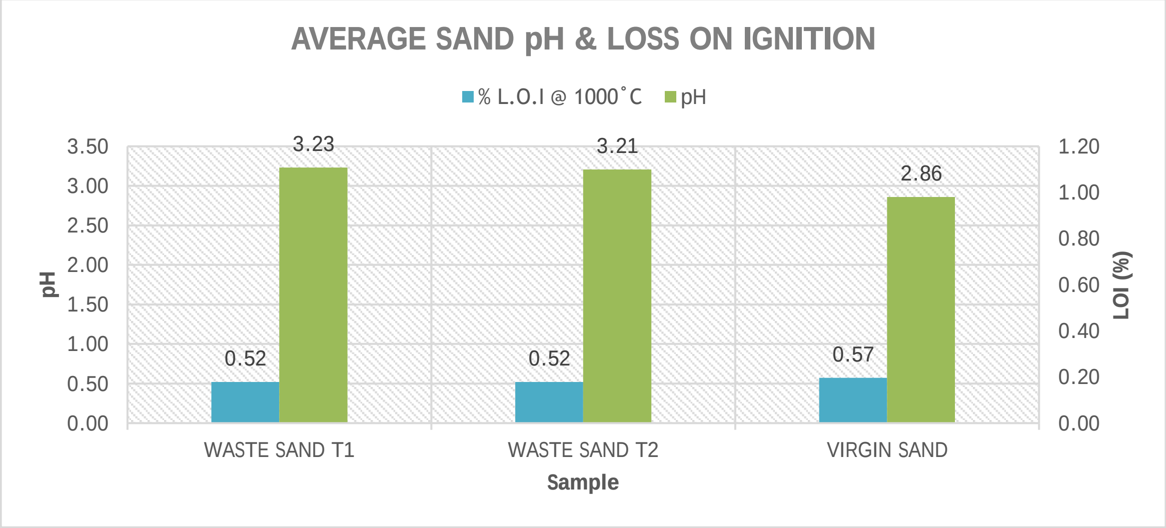


Figure 9: Sand pH and loss on ignition of the waste sands and virgin sand.

The waste sand's chemistry was optimal, except for the Fe_2O_3 content, which was found to be 0.39%, see table 3. While this is slightly high for the production of sand cores using traditional foundry and core making, for which the sand is required to have a Fe_2O_3 content of 0.30% [5], it remains relevant for the brick-making process.

In brick making, the acceptable Fe_2O_3 content can vary, but the slightly elevated level observed here does not significantly impact the overall quality and durability of the bricks. Fe_2O_3 can contribute to the density and hardness of bricks, therefore the waste sand, despite its marginally high higher Fe_2O_3 content, can still be efficiently utilized for the production of bricks, providing a sustainable use of the material.

Table 3: Chemical makeup of the waste sand (%)

Sample	SiO_2	Fe_2O_3	K_2O	Na_2O	Cr_2O_3	CaO
T1	97.07	0.39	0.04	0.01	0.32	0.02
T2	96.69	0.39	0.04	0.01	0.32	0.02

3.2 Brick Production Samples

3.2.1. Compression Strength and Bulk Density

The average cold crushing strength (CCS) of brick samples containing 50% and 100% waste sand was found to be 60.6 MPa and 58.7 MPa, respectively, see Figure 10. These values were higher than the average CCS of the initial brick samples, which consisted solely of river sand and no waste sand. Overall, the average CCS for all three brick-sample formulations ranged from 49.83 MPa to 60.6 MPa, with the samples containing waste sand (Trial mix 2 and 3) demonstrating the highest strength. These results indicate that the brick samples possessed exceptional strength capable of withstanding significant axial loads without failure.

According to masonry guidelines, the minimum requirement for a standard brick, when laid in Type-S or Type-M mortar, is 13.8 MPa [16]. The high strength observed in the samples can be attributed to the use of rapid hardening cement, known for its early strength development due to its fine particle size [17].

The bulk densities of the brick samples ranged from 2.02 to 2.06 g/cm³, which falls within the typical range of 1.8 to 2.2 g/cm³ [18]. This confirms that the samples have a high density appropriate for their high compressive strength.

The incorporation of waste sand generated from the sand printing of cores did not negatively affect the properties of the brick samples. Instead, the use of waste sand resulted in bricks with high compressive strength and density, making them suitable for construction applications requiring robust materials.

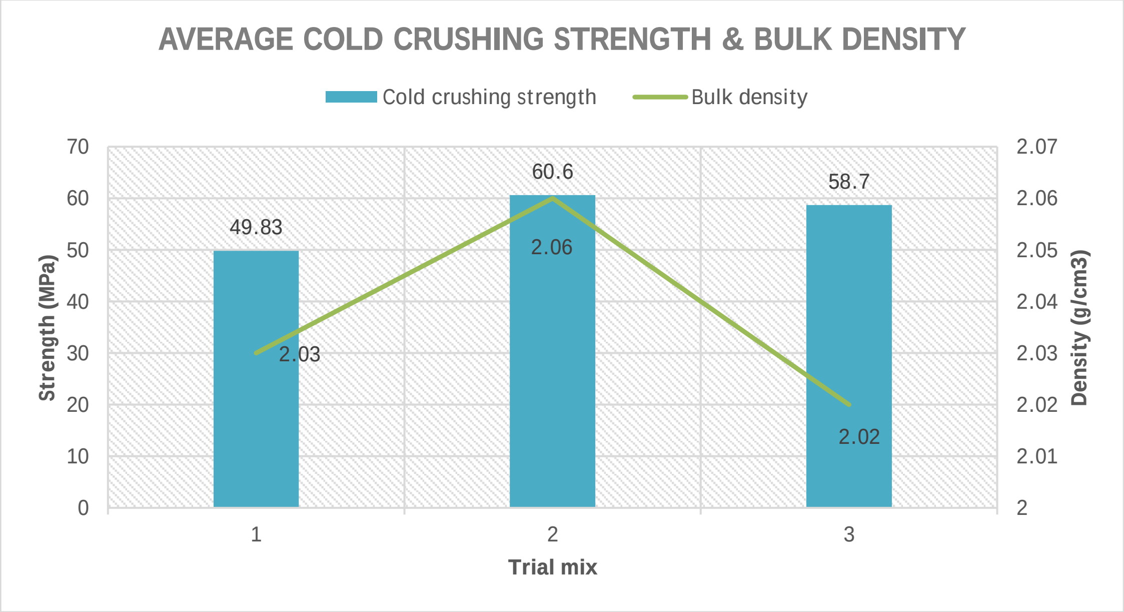


Figure 10: Compression strength and bulk density of common cement brick samples

3.2.2. Water Absorption

Brick density and water absorption are inversely related. A higher density in a brick sample indicates greater compactness with fewer voids or pores, resulting in reduced water absorption. As shown in Figure 11, trial mix 2 which showed a higher bulk density, has the lowest water absorption value at 4.62%. In contrast, trial mixes 1 and 3, which initially exhibited lower density levels, now show higher water absorption values, ranging from 4.91% to 5.09%.

The maximum amount of water absorption permitted for load-bearing concrete masonry units (CMUs) is specified by the ASTM C90 standards. CMUs usually have a maximum absorption of less than 15% [19]. Therefore, the water absorption results of 4.62% to 5.09% for the tested brick samples fall well within the required specifications for common cement bricks, indicating satisfactory performance. Low water absorption is desirable because it enhances durability, reduces efflorescence (white deposits caused by salt migration to the surface), and improves resistance to freeze-thaw cycles. Bricks with higher water absorption are more susceptible to damage from freezing and thawing, particularly in colder climates.

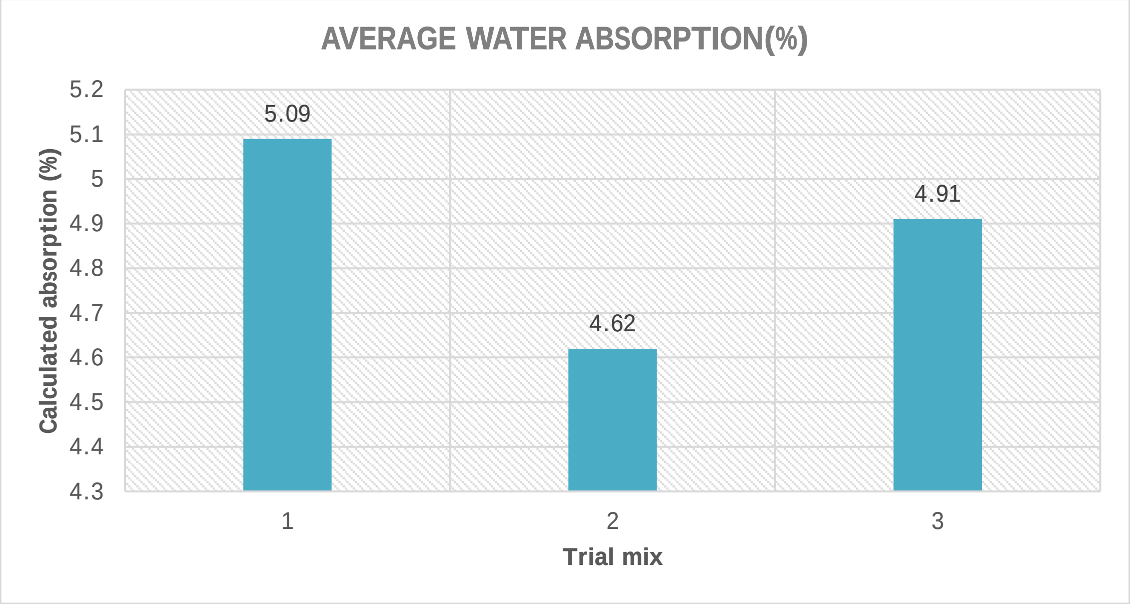


Figure 11: Water absorption of common cement brick samples

3.2.3. Visual Appearance

During and after the drying process, no apparent cracking was observed in any of the brick samples. However, visible porosity was noted across all three samples, with sample 3 exhibiting the least porosity. Additionally, no efflorescence was detected on the surface of any samples, See table 4.

The brick samples did not experience spalling or warping during the casting and demoulding processes, Maintaining a robust structure 24 hours after demoulding. Despite the darker appearance of the waste sand due to furan-resin contamination, all three brick samples exhibited a consistent grey colour throughout. Overall, these findings imply that the brick samples possess favourable characteristics, without the incorporation of waste sand having compromised their performance.

Table 4: Visual appearance of common cement brick samples

Sample 1	**Sample 2**	**Sample 3**
		
Porosity: High **Cracks/chips:** None **Spalling:** None **Warping:** None **Colour:** Grey	**Porosity:** High **Cracks/chips:** None **Spalling:** None **Warping:** None **Colour:** Grey	**Porosity:** Low to average **Cracks/chips:** None **Spalling:** None **Warping:** None **Colour:** Grey

3.3 Comparative Analysis - Waste Hierarchy

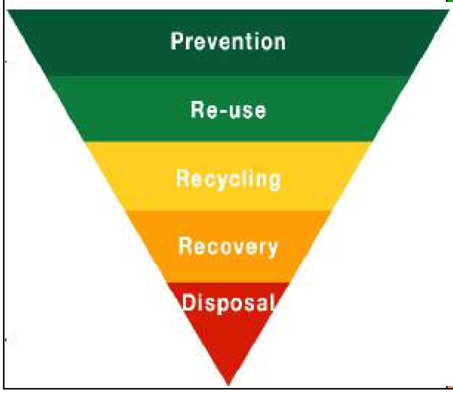
Table 5 compares the key material attributes of waste sand with the required attributes for brick making, foundry core and mould making, as well as sand printing. From the analysis of the waste sand, the AFS GFN was slightly above the required range for recycling, taking all three recycling routes into account. However, based on the moisture and loss-on-ignition content, as well as the grain morphology of the tested waste sand, repurposing it in the construction industry (without further treatment needed) is highly recommended.

Table 5: Key material attributes [20], [5], [21]

Route of recycling	AFS	Moisture	pH-value	LOI	Grain morphology
Construction	*50 to 60*	*< 1%*	-	*< 5.0%*	*Angular to sub-angular*
Foundry	*50 to 60*	*0.2 %*	-	*<0.5%*	*Rounded with medium to high sphericity*
Sand printing	*50 to 60*	*0.2 %*	-	-	*Rounded to sub-rounded*
Sand results					
Waste sand	66.43	0.63	3.22	0.52	*Angular to sub-angular, medium sphericity*

In Table 6, the tested waste sand is categorized based on the obtained results. It is also highly recommended to treat the waste sand before reuse in the production of sand cores using the traditional method, as well as three-dimensional printing.

Table 6: Waste hierarchy categorisation

Waste Hierarchy	Description	Area of Waste Reuse		
		Construction	Foundry	Sand Printing
	Obtaining new raw material			
	Preparing waste for reuse	✓		
	Waste separation and cleaning. Turning waste into new product		✓	✓
	Waste into energy			
	Hazardous waste sent to landfill			

4 CONCLUSION

The study demonstrated that the integration of circular economy principles into the rapid sand-casting process holds immense promise for ushering in a new era of sustainability and innovation in manufacturing. Through the adoption of circularity, sand-casting operations can transcend the limitations of the traditional linear model, forging a path towards resource efficiency, waste reduction and environmental stewardship.

Based on the analysis of sand test results, it is evident that waste furan silica sand produced during the sand printing of cores with the Voxeljet VX1000 printer can seamlessly find application in the construction industry for manufacturing standard cement bricks without requiring any additional treatment. The study also showed that incorporating waste sand from the sand printing process into brick production results in bricks with high compressive strength, density, and low water absorption, making them suitable for construction.

Despite having slightly higher Fe_2O_3 content and darker appearance, the waste sand did not negatively impact the brick properties. The bricks achieved compressive strengths ranging from 49.83 MPa to 60.6 MPa, exceeding the minimum requirement of 13.8 MPa for load-bearing masonry. Their bulk densities (2.02 to 2.06 g/cm^3) and low water absorption (4.62% to 5.09%) further indicate their robust quality and durability. On the other hand, it is advisable to consider treating the waste sand before employing it in the production of sand cores using traditional foundry core and mould-making methods, as well as in the three-dimensional printing of sand cores.

Future work will involve determining the optimal proportions of waste furan silica sand for repurposing, particularly in cement brick manufacturing. This research encourages the integration of circular economy principles in the growing field of rapid sand casting for metal casting. Additionally, a Life Cycle Assessment (LCA) will be used to evaluate the environmental impacts, enhancing our understanding of the benefits and potential drawbacks. This investigation will pave the way for sustainable waste management in sand casting and broader adoption of circular economy practices in industrial processes.

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OPTIMISING STORE OPERATIONS: ILLUMINATING INVENTORY MANAGEMENT FOR GLOBAL LEADERSHIP IN A MANUFACTURING ENVIRONMENT

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ABSTRACT

This research investigates store operations optimisation in a manufacturing environment with an emphasis on proficient inventory management to establish global leadership. The core objective is to ensure inventory availability while synchronously minimising tied-up stockholding capital. This study illuminates the complexities of inventory management within the context of store operations. Using a quantitative, non-experimental approach, primary data is gathered from a case study company through a structured survey questionnaire. The data is used to identify challenges within this company's store operations and to provide recommendations for improvement.

The inventory management challenges are mainly caused by inadequate staff training and technical knowledge. Therefore, training is the main recommendation to improve inventory management including the optimised use of the ERP/MRP systems. Alternative forecasting techniques including the Delphi method are recommended and using Lean Principles, in conjunction with ABC Analysis and 5S tools to enhance optimisation. Leadership support is crucial throughout this journey.

Keywords: Optimise stores, Inventory management, Inventory control, Stores operation, Manufacturing plant, Efficiency

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1 INTRODUCTION

Efficient inventory management is crucial in the manufacturing industry, serving as the cornerstone for optimising production processes. Manufacturing plants rely on the timely supply of inventory, including raw materials, components, sub-assemblies, and stock items, from storage facilities to production lines. Delays in the supply of parts can significantly disrupt production efficiency, causing daily inefficiencies and operational ineffectiveness. [1] highlights that there is a fundamental relationship between materials handling and production flow, and an imbalance can cause numerous challenges. The authors argue that the delay in material supply is one of the most vital factors that lead to project delays. Company XYZ experiences many of these inventory management challenges that are known to the manufacturing industry, especially inefficient inventory management.

Company XYZ is a South African manufacturing firm specializing in manufacturing industrial vehicles. The company has a footprint internationally and locally with its diverse range of products. Furthermore, the company is focused on operational excellence and efficiency as part of its plan to remain viable in an unpredictable market and establish global leadership.

Since Company XYZ operates in a niche market, retaining customers is crucial for revenue generation. Challenges such as inefficient store operations disrupt production flow, leading to delays and incorrect part supply, which compromise the manufacturing schedule and result in delayed deliveries. This causes customer dissatisfaction, contract penalties, and loss of business to competitors, weakening the company’s competitive position. Although not the only factor, inefficient store operations significantly contribute to these issues.

This study addresses the inefficient store operations at Company XYZ and their detrimental effect on inventory management. This operational inefficiency results in delayed production schedules and late deliveries, negatively affecting customer orders and the company's revenue streams. The main focus of this research is to identify methods and tools to optimise the stores’ operation at Company XYZ. These methods and tools are required to enhance inventory management practices and to improve the company’s overall business performance. Objectives include analysing current store processes, identifying improvement areas, determining factors influencing optimised inventory supply, and recommending appropriate inventory management methods and tools. The research question guiding this study is: How can inventory management principles, techniques, and tools be applied or adjusted to improve store operations at Company XYZ and similar organisations?

2 LITERATURE REVIEW AND THEORETICAL FRAMEWORK

This literature study is on aspects of store management with a focus on inventory control. This is followed by a discussion of all the major inventory management challenges and how they relate to the challenges of Company XYZ.

2.1 Inventory and Inventory Control

Inventory refers to the stock held by a company, including raw materials, components, sub-assemblies, and stock items. To ensure that production flows efficiently in a manufacturing plant, the inventory requires efficient management by the appointed employees. Kros, Falasca and Nadler [2] emphasise the importance of inventory management for operational efficiency and cost-effectiveness, while Ugboya [3] highlights that poor inventory management can severely challenge a manufacturing plant’s productivity.

Inventory control or management is defined as the process of controlling the stock amount held in several forms within the organisation, from receiving to issuance to the production line [4]. Sharif [5], describes the inventory management process as providing necessary services regarding quality, quantity, and order fill rate to avoid overstocking or bottlenecks while minimising costs. Additionally, Akindipe [6] concurs, noting the critical role of material management in enhancing manufacturing plant performance. Company XYZ requires efficient inventory control to ensure streamlined production processes. However, the company is experiencing various challenges in this regard as discussed in the following section.

2.2 General Inventory Control Challenges at Company XYZ

Company XYZ faces several inventory management challenges that are common in the manufacturing industry. These include inaccurate inventory levels, processing time delays, and unqualified or untrained staff.

Inaccurate Inventory Levels: Frequent discrepancies between actual stock and recorded inventory levels disrupt production flow, causing delays and inefficiencies. Factors contributing to these inaccuracies include incorrect supply of parts from suppliers, mislabelling, and misplacement. Atali et al. [7] and Hamlett [8] identify misplacement and mislabelling as significant causes of inventory discrepancies.

Processing Time and Time Delay: Delays in processing received inventory create discrepancies between physical stock and system records, leading to perceived shortages. Akindipe [6] stresses the importance of timely system updates and disciplined documentation to maintain reliable data.

Unqualified and Untrained Staff: Inefficiencies in inventory management at Company XYZ are exacerbated by unqualified and inadequately trained staff. Ahmad and Zabri [9] and Ogbo and Ukpere [10] highlight the necessity of skilled personnel for effective inventory management.

The literature study revealed that manufacturing plants are experiencing various challenges that limit optimal productivity, including inefficient inventory management. Several studies have examined inventory management and its effect on the organisation's efficiency, including the study of Sunday and Ejechi [11], which states that poor inventory management can lead to loss of sales and customers. Company XYZ has lost several customers because of these challenges.

Other challenges include the disruption of the supply chain. Generally, a supply chain team's goal is to balance inventory supply and demand [11], and any unplanned disruption can influence that balance. The disruption can be caused by endeavours such as inaccuracy in forecasting quantities, variability in stock lead time, and supply delays. However, these challenges faced by various manufacturing plants can be addressed by assessing the cause and finding methods to improve on the challenge through optimisation methods. According to Živičnjak, Rogić and Bajor [12], every measurable process can be optimised by applying the appropriate optimisation methods.

2.3 The relationship between inventory management and staff skills/knowledge

Various researchers [13,14,15] have found that relevant knowledge is crucial in effective inventory management. These authors found that a detailed understanding of inventory management adds value to inventory control planning, reducing waste, and good inventory control. Furthermore, numerous authors [16,17] found that staff knowledge enhances performance in a specific role [18]. After researching over 500 inventory control specialists from various countries, found that staff can perform optimally with the required knowledge. A complex inventory management system requires understanding, knowledge, and skills [19]. Therefore, this relationship will be investigated in this study.

2.4 Stores Optimisation Methods

Stores optimisation methods are techniques that can be applied to improve the functional operation of the store. Lean inventory management, the philosophy aimed at minimising waste, is one method that has been recommended as an aid to inefficient inventory management by numerous researchers [20, 21, 22]. Various studies have applied Lean

Principles including [23] to a boiler component manufacturing plant and Tasdemir and Hiziroglu [24] to a wood manufacturing plant, demonstrating its versatility.

Other optimisation methods, such as Just-in-time inventory management, and ABC analysis, are a few of the tools that commonly surfaced throughout the research process. Therefore, the following tools were analysed throughout this study:

- *Lean Inventory Management including Just-in-time inventory management and value stream mapping* [25,26].
- *5S Tools* [27].
- *ABC Analysis with safety stock optimisation* [28, 29].
- *MRP and ERP systems* [30, 31]

Inventory control techniques play a crucial role in inventory management and help compile inventory management and control policies, which will contribute to more effective store operations. These techniques were kept in mind throughout this research. The techniques include, determining stock levels, determining the safety stock required and economic order quantity.

The literature review establishes a link between Company XYZ’s inventory management challenges and broader industry issues. It highlights common causes of inefficiencies and identifies optimisation methods that can be applied to improve store operations. The findings from this review will inform the research methodology and provide a basis for recommending effective inventory management practices.

3 RESEARCH METHOD

This section structures the methodology of the study. A quantitative approach was utilised to analyse the study’s collected data, deemed suitable for addressing the research question through survey data rather than experiments.

3.1 Research Approach and Design

A quantitative research approach with a non-experimental and descriptive design was applied. This method was selected as it suits the survey data collection method used to investigate the primary research question. The descriptive study method aims to find associations among study variables to answer the research question [32].

3.2 Methods for Data Collection

The data collection tool for this research study was a survey questionnaire, chosen for its simplicity, cost-effectiveness, and ability to gather accurate data [33]. The questionnaire consisted of six sections covering participant information, educational background, job experience, inventory management skills, inventory check-in procedures, and inventory management challenges. The participants for the study were identified through a sampling process.

The sampling process involves selecting a group of participants that best characterise the study’s target population [34]. In this research study, the identified population was the store staff at Company XYZ which consisted of 41 employees. The sample population was 83% of the stores’ staff, from which the data was collected. The survey was conducted between June 2023 and July 2023, following ethical clearance. Participation was voluntary, with informed consent obtained from each participant.

Data Collection Approach

Two types of data were used: secondary data from existing literature and primary data from the survey. The literature review aimed to understand inventory management principles, techniques, and tools, while primary data provided insights from employees handling inventory. Data were collected, summarised, processed, and analysed to answer the research question. Survey data were stored securely on a password-protected computer, ensuring participant confidentiality.

Data Analysis

Data analysis is described as a method of investigating, organising, and structuring patterns in the data so that interpretations can be made [35] to answer the research question. In this study, the collected data follows four steps of preparation: (1) Data validation by checking for incomplete survey questionnaires and obvious outliers that are likely to skew the data and lead to incorrect conclusions, (2) allocation of numerical values to close-ended responses to make the data analysis easier as well as (3) cleaning and (4) checking for discrepancies [36]. Furthermore, Microsoft Excel is used to conduct the four steps. Once the data is in a usable form, descriptive statistics are used to portray the findings in a simple manner [37].

Descriptive statistics helped identify central tendencies and summarise data visually, highlighting patterns and outliers. Techniques like frequency distribution, cross-tabulation, and histograms were utilised[37].

Validity and Quality of the Data

Ensuring data validity and quality is essential for accurate and reliable conclusions. The survey questionnaire was carefully designed to align with research objectives, and questions were presented in English, the primary communication mode among participants. Participants were encouraged to seek clarification to ensure they understood the questions fully. Sampling errors can occur if the sample misrepresents the population. To minimise this, the sample size was maximised to accurately represent the population. Non-sampling errors, such as measurement, interview, systematic, non-response, and response refusal errors, were also considered. Addressing these errors is crucial for data accuracy and research reliability.

3.3 Ethical Considerations and Risks

Ethical considerations are considered one of the most significant parts of research. According to Bryman and Bell [38], Jayant [39], and numerous other authors, research participants should not be exposed to any form of harm during the research process. Therefore, care has been taken to ensure that the research survey questionnaire used to collect primary data does not include any form of offensive language or belligerent and discriminatory questions. Participants must consent before participating in the study and are treated with respect and dignity throughout the research. Participation is voluntary, and any potential participant identified as part of the sample population has the right to decline. Furthermore, participants have the right to withdraw from the study at any point without any complications.

All potential participants are supplied with sufficient information about the research and the value of their participation. Each participant signs a consent form before the data collection process commences. All communication related to the project is done honestly and transparently without the intent to deceive or exaggerate any part of the research that might influence a participant’s response. The privacy of the participants remains hidden and protected, and their confidentiality is ensured by not mentioning any names or information that can lead the reader to a specific participant. Furthermore, the participant information is linked to a participant number, which is visible on the survey questionnaire (instead of their names). Only the researcher has access to the list that links the participant number to the personal information, and the list is password-protected. Any risk is minimised by applying sound research design and avoiding unnecessary risks. The participant’s details and completed questionnaires are always stored on a password-protected computer.

4 RESULTS

A total of 34 survey questionnaires were distributed (83% of employees participating) which is considered an acceptable response rate by Holtom et al. [40] and Cleave [41]. The survey gathered data on participants' educational levels, job experience, and skills to determine their impact on inventory management at Company XYZ.

4.1 Participant Educational Levels and Skills

Section 2 of the questionnaire requested information on the participants' educational level, job experience, and skill level. These questions were deemed relevant to determine if there is a relationship between the educational level of the employees and the current level of operation in stores. According to the data, 67% of the participants have an educational level of secondary school or below, while 33% indicated they have a certificate in a field relevant to store management, inventory management, or stock handling. None of the participants have a diploma or degree in this field.

It is expected that the years of work experience will positively impact the stores' operation. However, this is not the case in this study. More than half (53%) of the participants have been working in store environments for more than six years while 13% have more than ten years of work experience. Only 13% of the participants have less than 3 years of experience. Kotur and Anbazhagan [42] found that employees with more experience tend to exhibit a higher level of performance. Even though more than half of the staff has a great number of years in stores, there is still a gap in their efficiency, which is impacting the operational flow of production. This gap indicates that the training the employees have received was insufficient and that there is a dire need for a higher level of training. Consequently, the employee's experience alone is not enough to ensure efficient store operation. Effective inventory management requires keeping up with the latest industry standards and trends such as lean tools. However, apart from the years of experience, the employee's skills might also impact their performance.

4.2 Inventory Management Skills

According to the data, 53% of participants have received some form of formal internal training in stores or inventory management, while 27% have not received any training and had to learn on the job. Additionally, 20% of the participants have received their education from certified short courses presented by accredited academic institutions. The high percentage of self-taught employees may contribute to the inefficient store management challenges because these participants learned from observing what other employees do. There was no formal training involved. Even though practical knowledge can be gained with this type of training, there might be misguidance from the mentor and a lack of understanding of the theoretical principles behind formal education of store operations. Furthermore, their exposure to different inventory management tools is limited which limits their overall understanding of improving the current systems. Employees are capacitated to better execute inventory management through training [43].

Even though 53% of the participants indicated that they have received store management training, the training could be outdated or at a lower level than required. Training management is a continuous and dynamic process because the concepts are evolving with time, and companies need to ensure that employees are kept up to date. Therefore, section 3 of the survey questionnaire focuses on the participants' inventory management skills to gauge their exposure level. Figure 2 summarises the results.

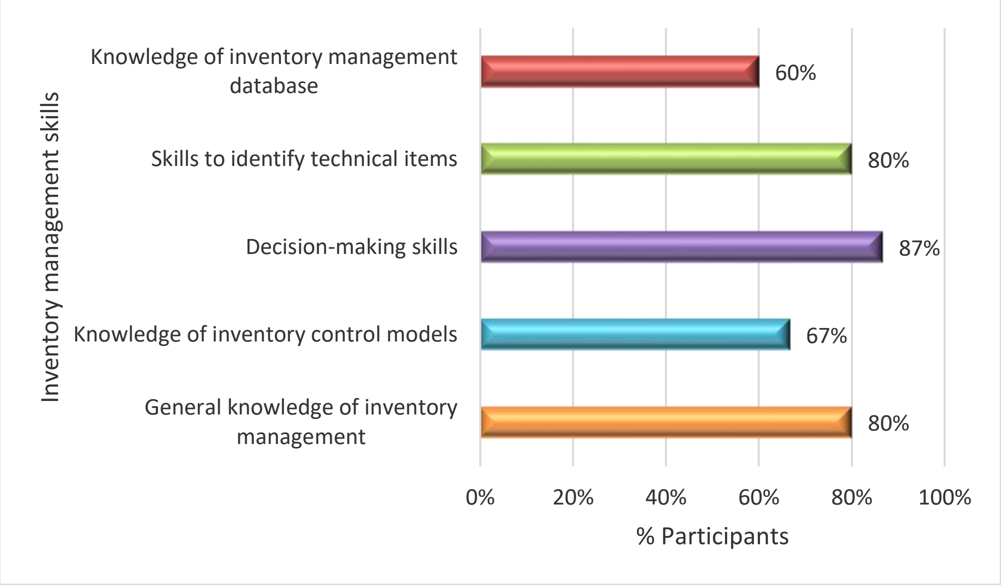

Figure 2: Inventory Management Skills of Participants

A total of 60% of participants indicated that they are competent in using the inventory management database, with 67% knowing inventory control models. However, their general knowledge of inventory management is higher at 80%, while 80% of participants also indicated that they struggle to identify technical items.

The lack of knowledge in using the inventory management database may be linked to a gap in training and a need for standard operating procedures. These procedures must be a guide for employees to use the database efficiently. Similarly, the inability to identify technical items is of great concern. Furthermore, 67% of participants know inventory control models, but the level is unknown.

4.3 Inventory Management Skills

About 73% of participants indicated that they are familiar with the ERP system, while 80% indicated that they are familiar with the MRP system even though the two systems are integrated. It was expected that all participants would be familiar with the in-house software used to control inventory as this is the only tool used. This might be another indication of a lack of exposure and training. The participant's knowledge of the other methods was low, which indicates that the employees are not aligned with the latest industry trends. To get the participant's input on possible causes, section 5 of the survey questionnaire was specifically developed to get insight into how the participants operate in this area. The section requests information on the checks done when stock is received.

According to the data, 100% of the participants indicated that they check the parts against the description on the delivery note and that they ensure that the correct quantity is captured on the system. However, only 93% check that the correct quantity is received. Furthermore, only 73% compare the supplier part code to the one captured on the company ERP system, which could be a good indication of whether the correct part was delivered.

Employees may have not received the proper training to receive parts or have become content because they have not experienced any major impact. The employees may not fully understand the impact of how their methods can hinder the internal flow of processes and continue without being educated on the topic. However, this can also be caused by staff shortages and overloading employees, but the causes are unknown at this point.

Employees share their experiences in section 6, where they are required to share their challenges concerning store and inventory management. Various issues were presented, and the results are summarised in Figure 3.

Figure 3: Various Store Management Challenges

According to the collected data, 73% of employees indicated that there is a criterion in place to ensure that suitable people are employed for store management and that sufficient methods are in place to measure their efficiency. However, only 47% were aware of the inventory management procedure, which is the written procedure used by store employees. Furthermore, the participants identified inefficient storage space and poor management support as the greatest challenges (73%). This is followed by a lack of familiarity with technical items and inadequate staff at 67%. Additionally, incorrect quantities received, incorrect inventory marking, abnormal demand, and unplanned purchases were found challenging by 60% of the participants. Only 20% indicated that inefficient moving and lifting equipment is a challenge, which indicates that the required equipment is in place.

It was evident that the participants perceived their inventory management skills at an acceptable level to contribute to running a store efficiently. However, they had little knowledge of other inventory control models. They faced other challenges that made it difficult to effectively manage the inventory, such as inefficient storage space, poor management support, a lack of familiarity with technical items, and inadequate staff.

Based on the findings from the survey, recommendations are made in the following section. These recommendations are not carved in stone and can be adapted to suit the company persona. However, the recommendations are a good starting point to address the gaps that were identified throughout this study.

5 CONCLUSIONS AND RECOMMENDATIONS

Effective store operation practices provide a competitive advantage for businesses, including manufacturing plants. This research identified significant gaps in inventory management at Company XYZ, primarily due to insufficient training and technical knowledge among staff. The following recommendations aim to address these gaps, offering valuable insights not only for Company XYZ but also for similar companies seeking to enhance their inventory management practices and overall operational efficiency. Recommendations

The following are recommendations that can be followed to improve inventory management at Company XYZ and similar organisations.

Inventory Management Tools

Forecasting techniques, such as the Delphi method, expert opinion, and consumer market surveys, should be considered, instead of just using legacy data. This recommendation is made because the legacy data is deemed unreliable in this constantly changing environment. Once the forecasting is more reliable, Lean principles in conjunction with other tools such as ABC Analysis can be implemented to improve stock holding. This should be monitored and updated regularly and should not be treated as a fixed and static implementation. The 5S tool can also be implemented in conjunction with the Lean approach to ensure that the storage facility is neat and that the space is optimised for keeping the critical stock. The company should investigate why employees find the space insufficient, as this will contribute to optimising storage. Furthermore, consider removing dead stock to clear space or expand if funds and space are available. Another option is to reorganise the store's layout to optimise the space utilisation, which will require in-depth planning.

Once the store is efficiently stocked with the implementation of ABC and 5S, applying the Lean manufacturing approach will likely improve overall production performance because the supply will be steadier. The level of lean must be based on the forecasting results and not just from a financial perspective. There must be a balance to avoid stock runouts. In seasons where demand is likely to pick up, ABC Analysis will require a re-analysis to adjust the stock levels.

Even though there is an ERP and MRP system in place, it is not being utilised to its full capacity. Therefore, the employees must receive the proper training to use the system, as this will greatly contribute to efficient inventory management. The current system already has a level of advanced technology built into it with the barcode and QR code scanning of stock with the cellular phone application. The main focus would be to ensure that these functions are used correctly.

Training

Store employees need to be evaluated and trained according to their needs. There is a lack of system knowledge and technical knowledge. The first recommended step is to ensure that all store employees are trained to use the ERP and MRP systems efficiently. This is to ensure that they have the required system knowledge.

To improve the employee's technical knowledge, basic training can be provided to identify the common items, and further knowledge can be developed on the job. An option would be to appoint someone who has a higher level of technical knowledge to support the stores' staff in identifying technical items to support the on-the-job training approach. Furthermore, the stores' employees must be encouraged to take ownership and implement continuous improvement. This will require a higher level of support from management and leadership.

Management and Leadership Support

Management needs to lead by example to implement Lean and any other tools. Employees who see management's involvement in the approach will likely feel more encouraged to follow. This should encourage an innovative culture and a continuous improvement attitude. Furthermore, management must acknowledge those employees who go the extra mile and celebrate any successes to create that feeling of accomplishment. It will also be up to management to evaluate the stores' staff and arrange the necessary training to ensure that the employees operate efficiently, supporting store optimisation. Additionally, they will have to continue to monitor the employee's progress and give feedback regularly.

Standard Operating Procedures (SOP)

Revisit the current procedures that are in place and update them to be more relevant. Employees must also be made aware of the procedures and understand the document's content. The SOP can include receiving procedures, storing, picking of stock, issuing the stock, and any other function relevant to store management. This is to ensure consistent and efficient operations amongst staff.

Employee responsibilities must be clearly stated in the procedure. Their key performance indicators (KPI) can also be specified in the SOP so that employees are aware of what is being tracked, and there must be feedback on their performance. The employees must celebrate when KPIs are reached to cultivate a feeling of accomplishment and collaboration amongst the team members.

Supplier Collaboration

According to Gutierrez et al. [44], better relationships with suppliers can help supply chains become more resilient. There are five dimensions to the supplier collaboration index, as shown in Figure 4.

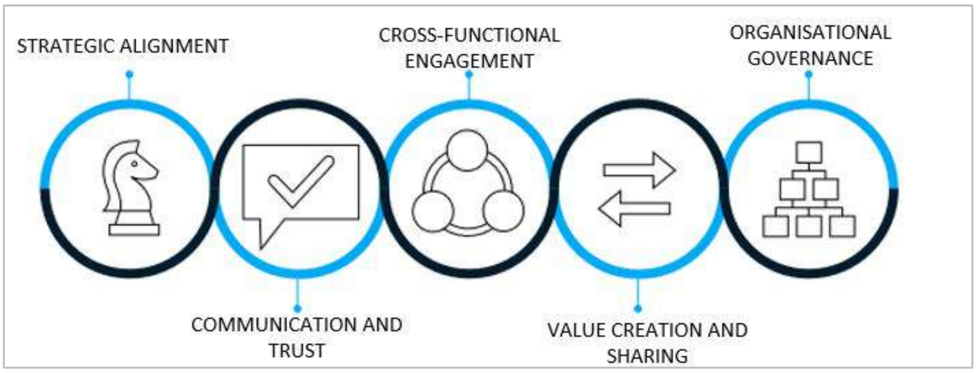

Figure 4: Supplier Collaboration Index

The strategic alignment is where the scope of collaboration is agreed on. Communication and trust are self-explanatory, but the tools and supporting mechanisms are identified in this dimension. The cross-level engagement dimension is where the required level of engagement is determined. The value creation and sharing dimension is where the parties involved ensure that the value sharing is fair and that all parties benefit from the collaboration. During the organisational government dimension, metrics are agreed upon to measure and track performance as well as the incentive structure. By identifying the most crucial suppliers and building that collaborative relationship by implementing the supplier collaboration index, the company can reduce product costs and lead time of deliveries and be the first to explore new designs.

By implementing these recommendations, Company XYZ should be off to a good start in improving inventory and store management. However, due to the nature of the company, these implementations should constantly be monitored and adapted to suit the company's needs.

5.1 Study Contributions and Limitations

This study greatly contributes to the field of inventory management by addressing challenges faced by manufacturing companies. Through a comprehensive investigation of these areas, the research strives to offer practical insights and actionable recommendations that can aid businesses in effectively managing their inventory to reduce costs, mitigate risks, and enhance inventory management efficiency. The implementation of Lean practices was evaluated, as well as technology adaption in the field of inventory management. Furthermore, Green, and Sustainable inventory management were briefly discussed to create awareness of the emerging mind shift amongst companies.

While this research aims to contribute valued insights into inventory management practices within a manufacturing plant, there are inherent limitations. First, due to practical constraints, the study cannot account for all variables influencing inventory management, which might result in an oversimplification of the complexities involved in the study. Secondly, since the study only considered a specific manufacturing plant, generalising the findings may not be feasible. Furthermore, while efforts were made to gather accurate data, the potential for data inaccuracies could affect the vigour of the study's conclusions. Regardless of these limitations, the research aims to provide a valuable understanding of the inventory management practices of this specific manufacturing plant, contributing to the broader discourse on effective inventory control strategies.

5.2 The Future of Inventory Management

Technological innovations, data-driven decision-making, and drastic changes in consumer behaviour drive the future of inventory management [45]. As industries, including manufacturing, continue embracing automation and digitalisation, traditional inventory management models and tools will likely be replaced or subsidised by more agile approaches.

Artificial Intelligence (AI) and Machine Learning (ML) are commonly mentioned digitalisation tools[46,47]. These tools are set to play a crucial role in shaping the future of inventory management as they enable businesses to predict demand patterns at high-level accuracy. As Sharma [48] states, AI applications in inventory management help with cost reduction and demand predictions, creating a balance between supply and demand. This could lead to improved demand forecasting and result in reduced stock-outs. Technology such as AI-powered algorithms is likely to improve replenishment strategies as it adapts to fluctuations in demand and supply based on real-time data.

The upsurge of the Internet of Things (IoT) devices is transforming inventory management by providing real-time visibility into inventory management operations such as the supply chain [49]. Consequently, proactive monitoring of inventory levels is made possible, including the immediate identification of ineffectiveness and potential bottlenecks. It is expected that with the maturity of IoT technologies, businesses will be able to achieve new levels of traceability and JIT inventory management. According to Mashayekhy et al. [50], IoT can significantly impact the supply chain through effective resource usage and transparency of supply chain operations while increasing agility based on real-time data. Additionally, Blockchain technology has become known for enhancing transparency and security within supply chains. This technology creates immutable transaction records and accurately tracks inventory movements, which enables Blockchain to mitigate business risks [51]. E-commerce and shifting consumer preferences are driving the need for flexible operational strategies. Additionally, sustainability concerns are influencing the future of inventory management and are pushing businesses to explore eco-friendly practices, including circular supply chains and sustainable sourcing. These sustainable methods implicate how inventory is managed to reduce waste and the environmental impact [52].

The future of inventory management is undergoing a paradigm shift driven by technological innovation, data-driven insights, and a holistic view of supply chain dynamics. AI, IoT, Blockchain, E-commerce, and changing market dynamics are influencing the business landscape, where real-time visibility, accurate predictions, and adaptive strategies will become essential for businesses to remain competitive. Strategically adapting to these changes and embracing emerging technologies will be vital to experiencing the full potential of inventory management in the future. Therefore, this topic articulates the need for future research in inventory management.

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A CASE STUDY ON THE INTEGRATION OF PROJECT MANAGEMENT AND SYSTEM ENGINEERING IN A HIGH TECHNOLOGY COMPANY

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ABSTRACT

For a project to be delivered on time, within budget and meeting the technical requirements, the project and technical management processes must dovetail into one another on many levels, like a precision clock. The importance of this need is illustrated by the cooperation between INCOSE and PMI in establishing a workgroup to investigate this topic further. This paper aims to present the first part of a case study within a high-technology company that focuses on identifying a suitable project management framework that can be integrated with the applicable technical processes over the complete lifecycle of a project. This case study aims to identify a tailored approach for three business lines within the company that are all based on the same project management framework and technical processes. This case study will be expanded by evaluating the organisation's performance using the innovative approach.

Keywords: Project Management, System Engineering, PM-SE Integration

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1 INTRODUCTION

1.1 Background

Project execution is often managed in an environment wider than just the project itself. Different stakeholders, technologies, and regulatory requirements need to be successfully managed and integrated into the overall project execution process to achieve the desired outcome [1]. Understanding and integrating this wider environment into a cohesive single entity is one of the critical elements to achieving the goals of the project and, ultimately, the goals of the company or organisation [1].

Projects can be considered to fall into two categories. The first category is that of complicated projects, and the second category is that of complex projects. In general, the level of complexity within a system relates to the number of elements within the system, the number of interconnections between the elements, the type of interconnections (linear or non-linear), and the number of feedback loops present in the system. In the context of a project, the complexity can, in a comparable manner, be related to the size and value of the project, the number of individual items to be delivered, and the number of organisations and stakeholders involved in the project.

A project can be classified as complicated when the relationship between the various elements within the system is based on fixed relationships. These fixed relationships allow reasonable predictions of the time, cost, and technical resources required to execute the project [2]. Similarly, a project can be classified as complex when the relationship between the various elements within the system is not fixed or known. This typically happens when unpredictable items such as new technology development are required during the project's execution.

Another aspect that contributes to the complexity of a project is that it constitutes a social-technical system. A social-technical system is formed when two interdependent systems, the social and the technical, interact within a single environment [3], [4]. The social part is due to the human nature of all the various stakeholders involved in the project. The technical part revolves around the technical problem that has to be solved by the project, including the different processes, tasks and technologies that may be involved [5]. A perfect technical solution for a socio-technical problem may not deliver a successful solution to the actual need. The effect of the socio-technical environment can result in a change in priorities, preferred technical solutions, and how and where these solutions are implemented [6]. This phenomenon is referred to as the socio-technical gap and is illustrated in Figure 1 [6].

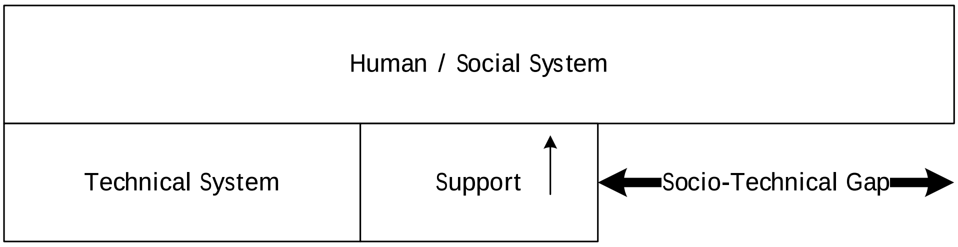

Figure 1: The socio-technical gap (redrawn from [6])

The systems that form part of the socio-technical system can further be classified as a closed system where the environment does not cross the system boundary or an open system where the environment can directly interact with the system. All social systems, i.e., where people are involved, can be classified as an open system [7]. The behaviour of a complex system is driven by the behaviour of the individual elements and how these elements interact with one another. To understand the whole, both the individual elements as well as the interactions between these elements need to be understood [8].

By way of an example, building a new house can be considered to fall into the regime of a complicated project. In contrast, the development and launch of the first Starliner capsule can most definitely be classified as a complex project. A complex approach to executing a project will be needed where a complex system is encountered. It is typical for complex problems (and, by extension, complex projects) to show a certain degree of self-organisation. The net result of this self-organisation is that new, emergent behaviour can cause havoc during the execution of a project.

To counter the anticipated or experienced project complexity, the project manager will need a robust project management approach that also includes a mechanism to deal with technical complexity. Jackson [9] defines this technical complexity as occurring when one:

> *"… seeks to design a complex system to achieve a predefined purpose by organising the various components and subsystems (of machines, material, money, and people in the most efficient way."* [8, p. 171].

Complex systems and complex problems can be addressed by applying a systems thinking methodology. Possible systems thinking methodologies that can be considered when encountering technical complexity within a project environment include Operation Research, System Analysis and Systems Engineering [9]. Thus, an approach that integrates the project management and systems engineering domains should provide a better outcome during the execution of complex projects.

1.2 Case study problem description

The organisation within which this study is conducted engages in the conceptualisation, design, manufacturing and rollout of complex, high-technology products, solutions and systems. Historically, the organisation allocated the roles of the project manager, contract manager and systems engineer to a single individual. Project teams were also allocated full-time to the individual projects or business lines. This type of model worked well for smaller projects. Still, it introduced several inefficiencies, including under / over-utilisation of resources, project silos and a lack of sharing of lessons learnt - resulting in the reinvention of the wheel across projects.

A decision was made by the management of the company that the complete project execution approach was to be overhauled and improved. The one prominent area of improvement that was found was to create an organisational split between the project management and the system engineering functions. The project management functions were allocated to the individual business lines, and the project support functions were assigned to a central project management office (PMO). The PMO is also tasked with governance of the projects to ensure that they align with the selected project management approach or methodology. The systems engineers, technicians, and installation teams were allocated to a central engineering function from which they were assigned to the individual projects in a matrix-style function. The main aim of this move was to ensure that scarce resources are fully allocated and can focus on the key roles they must play within the project.

Once this was accomplished and the organisation settled down within the new structures, it became apparent that role separation between the project management and systems engineering sides of the project execution equation was still not fully defined and precise. The systems engineers quickly returned to their previous roles and took on some project management or supporting functions (such as procurement activities). This leads to frustration on both sides, with the project managers feeling they are not kept appraised of what is happening in the project and the systems engineers feeling overworked and not receiving sufficient support.

An intervention was defined (as reported in this paper) whereby an integrated project management approach is to be determined that clarifies the roles of the individuals involved in the project and provides them with guidelines and boundaries of where their responsibilities start and end. The selected or defined project management approach must also fully support the implementation of the complete system life cycle and the systems engineering process.

A secondary goal of the optimisation exercise is to align the organisation's support functions, such as configuration management, supply chain management, etc., to support the overall project execution process fully.

1.3 Research approach

This paper is written as a case study and addresses the definition of the problem scenario that requires the pragmatic integration of the project management and systems engineering environments. After defining the problem scenario, a review and analysis of what has been reported in the literature as possible ways forward are investigated. A preferred solution is then identified that can be rolled out in the organisation.

The layout of the paper follows a typical case study approach [10]:

- Section 1 - Introduction (This section)
- Section 2 - Theoretical basis
- Section 3 - Ideal implementation of a harmonised project management and systems engineering structure
- Section 4 - Conclusion and recommendations

During the implementation phase, the actual outcome will be compared with the desired outcome, and corrective action will be identified and implemented to try and move closer to the desired outcome. The intention is to capture the results of the overall exercise report on them in a future paper.

2 THEORETICAL BASIS

2.1 Projects and Project Management

PMBOK [1] defines a project as:

> *" … a temporary endeavour undertaken to create a unique product, service or result."* [1, p. 5].

A project can thus be considered to consist of a series of activities and tasks that must (a) be completed within specification, (b) within a specific time frame as defined by the start and end date, (c) has limited funding available, and (d) consumes resources such as money, people and equipment [7]. A project can only be completed when all the project objectives have been met or, in a worst-case scenario, the project is terminated due to failing to meet the goals. Although a project is a temporary endeavour, the intended outcome of the project is a unique product, service or result that may need to last for many years and may require support activities to keep operating [1].

Project management can be defined as the planning, organising, directing and controlling of company resources for a short-term objective that has been determined to complete specific project goals and objectives [7].

For any project to succeed, it must achieve its cost, time, and technical performance targets. In a complex or high-technology environment, this technical performance falls within the domain of the systems engineer or the systems engineering manager [11].

With the different aspects of time, cost and technical performance so tightly interconnected, it is only logical that the project manager has a direct influence on the technical performance or technology aspects of the project in the same way that the systems engineer has a direct impact on the time and cost aspects. This is illustrated by an example where the systems engineer identifies equipment crucial to achieving the project's performance requirements. Still, this piece of equipment may cause the project to exceed the available budget or may add a delay in the final delivery of the project. Similarly, the project manager can directly influence the technical performance of the project by refusing to allocate sufficient funding or time to incorporate the correct piece of equipment that will enable the project to meet its technical specifications.

In addition to the three core aspects of cost, schedule and technical performance that the project manager must keep in balance, Kerzner [7] adds a fourth dimension, good customer relations. This last aspect is a shared responsibility between the project manager and the systems engineer since both interact with the customer and other stakeholders.

Numerous project management methodologies can be used to manage a project, with some performing better than others under different circumstances. A selection of these methodologies is listed in Table 1.

Table 1: Different project management methodologies

Nr	**Methodology**	**Nr**	**Methodology**
1	Waterfall	9	Critical Chain Project Management (CCPM)
2	Agile	10	New Product Introduction (NPI)
3	Scrum	11	Packaged enabled reengineering (PER)
4	Kanban	12	Outcome Mapping
5	Scrumban	13	Six Sigma
6	eXtreme Programming (XP)	14	PMI’s PMBOK
7	Adaptive project framework (APF)	15	PRINCE2
8	Lean	16	Rapid application development (RAD)
9	Critical Path Method (CPM)		

Many of these methodologies are adaptions of one another or may only apply to specific types of projects (e.g. such as software development projects). The one thing that is, however, missing from these project management methodologies is a straightforward way how to manage the complex, technical side of the project. Gabb and Sommer [12], for instance, remarked on the use of the PRINCE2 project management methodology within complex technical projects, that while the methodology provides comprehensive processes, products and techniques that can be used in managing a project, it lacks techniques to address the technical project issues in any detail. In the same line, the systems engineering processes (As defined in the INCOSE Systems Engineering Handbook [2]) define the technical management processes that are required but do not address the project management aspects sufficiently [12].

The project manager has the overall responsibility for the project, very much like the chief executive officer (CEO) has overall responsibility for the running and performance of a company and can be said to be running “a business within a business”. The project manager relies heavily on the company processes and supports organisations. The project manager authorises the defined work packages, distributes the budget, monitors the progress, and is the primary interface with all of the stakeholders [11]. Gabb and Sommer [12] identified different roles for the project manager, as is shown in Table 2.

Table 2: The different roles of the Project Manager [12]

Facilitator and coordinator between the project and the:	• Customer or user of the product, i.e., stakeholders, • Subcontractors performing engineering work on the program, • Supporting organisations within the company hierarchy, • Company senior management.
Enforcer of controls and processes	• Program review processes, • Quality control procedures, • Configuration management, • Schedule management, • Risk management, • Data management, • Financial controls.
Managing customer expectations	• Avoiding overly optimistic projections, • Effective stakeholder management.
The final judge	• Adjudication of disputes within the team, • The "buck stops here."
Team builder	• Everyone on a common goal and on the same page, • Effective use of rewards and recognition.

The project manager's objective is to assist the project team and buffer them from distractions caused by external issues and questions. The project manager should be the route of appeal for organisational conflicts and the single point of contact for all matters relating to team performance [11].

2.2 Systems Engineering

The INCOSE Systems Engineering Handbook [2] defines systems engineering as:

> *"… a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods."* [2, p. 1].

The high-level focus of the systems engineering function is to:

1. Establish, balance, and integrate stakeholders' goals, purpose, and success criteria, and define actual or anticipated stakeholder needs, operational concepts, and required functionality, starting early in the development cycle.
2. Establish an appropriate life cycle model, process approach and governance structures, considering the levels of complexity, uncertainty, change, and variety.
3. Generate and evaluate alternative solution concepts and architectures.
4. Baseline and model requirements and selected solution architecture for each project stage.
5. Perform design synthesis and system verification and validation. [2]

The systems engineering process, as defined by INCOSE, is a methodology that can be used to facilitate, guide, and provide the leadership required to integrate all the relevant disciplines and speciality groups necessary to form an appropriately structured development process that proceeds from concept to development, production, utilisation, support, and eventual retirement [2]. This systems engineering process considers both the business and technical needs with the ultimate goal of providing a quality solution that meets the needs of users and other stakeholders, is fit for the intended purpose in real-world operation, and avoids or minimises adverse unintended consequences [2].

The overall goal of the systems engineering activities is to manage risk, including the risk of not delivering what the acquirer wants and needs, the risk of late delivery, the risk of excess cost, and the risk of negative unintended consequences [2]. The systems engineer defines what the end item or product (project deliverable) must achieve to satisfy the end user's requirements and is, as such, responsible for the created system [11].

The systems engineer works within the overall project environment and reports to the project manager within the project structure. The systems engineer is responsible for taking a holistic and balanced view of the problem. Once the problem domain is clear, the systems engineer shifts focus to the solution domain by defining a system life cycle approach that will support the successful execution and completion of the project. The systems engineer is ultimately responsible for providing a solution to the problem situation that is fit for purpose [2].

The systems engineer can fulfil many roles within the project environment. Sheard [13] identified different roles that the systems engineer may fulfil during a project. These roles are summarised in Table 3. While a systems engineer is referenced here, the identified roles may be assigned to or more individuals, depending on the size and complexity of the project.

One of the crucial roles that the systems engineer on the project must fulfil is the day-to-day interface between the project manager and the project technical or engineering team. The systems engineer is considered the technical leader within the project organisation and has the authority to speak for and commit the systems engineering team [11].

Table 3: Systems Engineering Roles [13]

Nr	**Role**
1	Requirements owner
2	System Designer
3	System Analyst
4	Verification and Validation Engineer
5	Logistics or Operations Engineer
6	Interface Engineer
7	Customer Interface Engineer
8	(Project) Technical Manager
9	Information Manager
10	Process Engineer
11	Coordinator

Nr	Role
12	Other Systems Engineering tasks (Classified Add's Systems Engineer)

3 IDEAL IMPLEMENTATION OF A HARMONISED PROJECT MANAGEMENT AND SYSTEMS ENGINEERING STRUCTURE

The challenge of integrating project management and system engineering within a harmonised structure is not new, and various articles have been published on the subject. The topic has also been recognised by both INCOSE and the Project Management Institute (PMI), and a joint working group has been established to investigate the subject. Despite all of the focus placed on the topic, the project management roles and systems engineering roles are still viewed very much as individual disciplines by industry, academia and industry societies [14].

To improve on the current situation, Dasher [11] identified that some of the main obstacles in defining a suitable forward are firstly to create a shared understanding of the roles and responsibilities of the different parties involved in the project execution process and, secondly define a consistent terminology that is used within the project [11].

Certain of the various roles and responsibilities of the project manager and systems engineer have been summarised in Table 2 and Table 3. These roles must be embedded within the selected project structure and evaluated to see if they work or need optimisation. Similarly, common terminology must be established (e.g., project versus project life cycle vs. systems development life cycle) and embedded in the applicable process descriptions.

3.1 The overlap between the roles of the project manager and the systems engineer

As previously mentioned, one of the challenges in rolling out the new way of working is that the systems engineers may fall back into their bad habits by trying to fulfil all possible roles. The identified approach to address this challenge explicitly focuses on the systems engineering management or project technical management role that falls between the systems engineering and project management roles. Forsberg et al. [15] define this overlap as managing the project business, budget and technical baselines with the primary objective of aligning these baselines. Van Gemert [16] defined the activities within this overlapping region as belonging to the systems engineering or technical management role [11]. These systems engineering management role is shown in more detail in Figure 2.

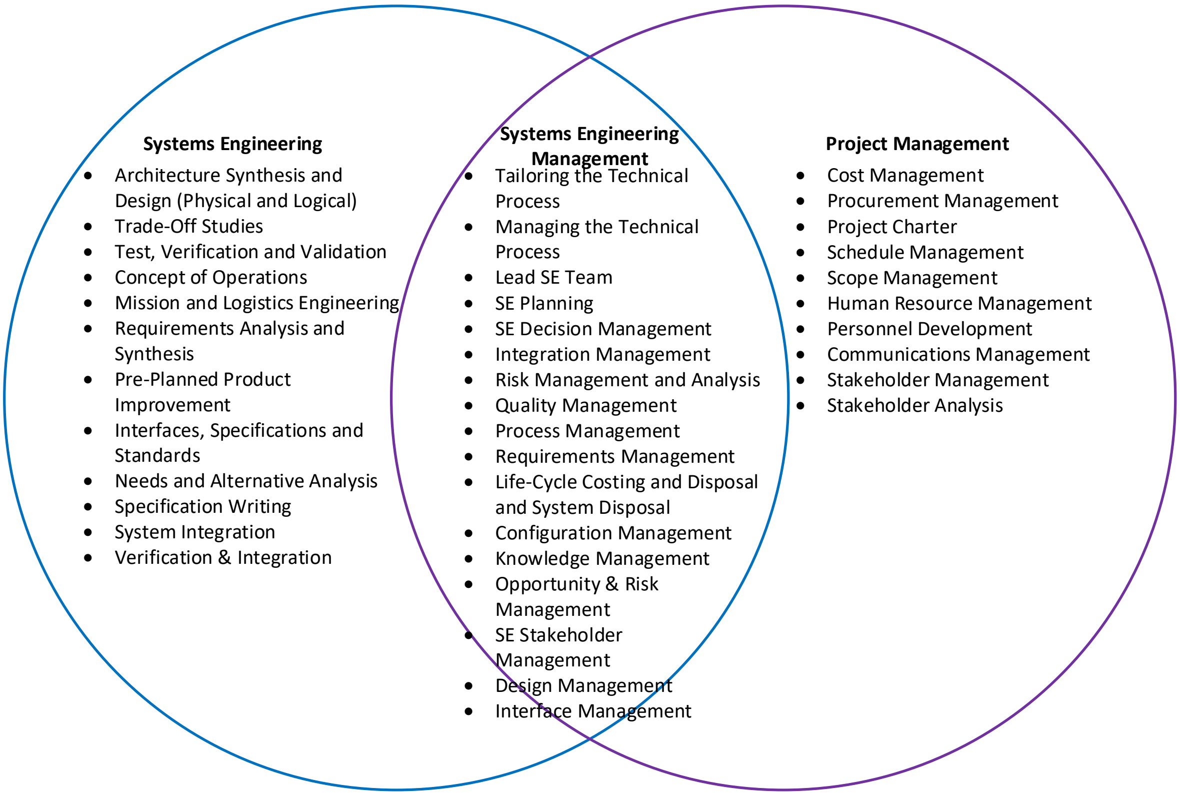

Figure 2: The intersection between Project Management and System Engineering Roles [16]

3.2 Generic project team and team roles

A clear definition of the generic roles and responsibilities of the different team members will be vital to a project's success and how the team works together [11]. A logical starting point is to start with the project structure and identify all the role players from there. While different project management methodologies were identified in Table 1, they all have a similar structure based on the roles shown in Table 4. It has also been identified earlier that a multi-disciplinary team should support the project manager that the systems engineering function will typically lead [11]. Depending on the size and complexity of the project, the systems engineering function can be subdivided into two separate disciplines: that of the technical knowledge domain, in which the systems engineer operates, and of the systems engineering management domain that the project technical manager may typically fulfil [11]. The generic structure of the larger team is shown in Figure 3.

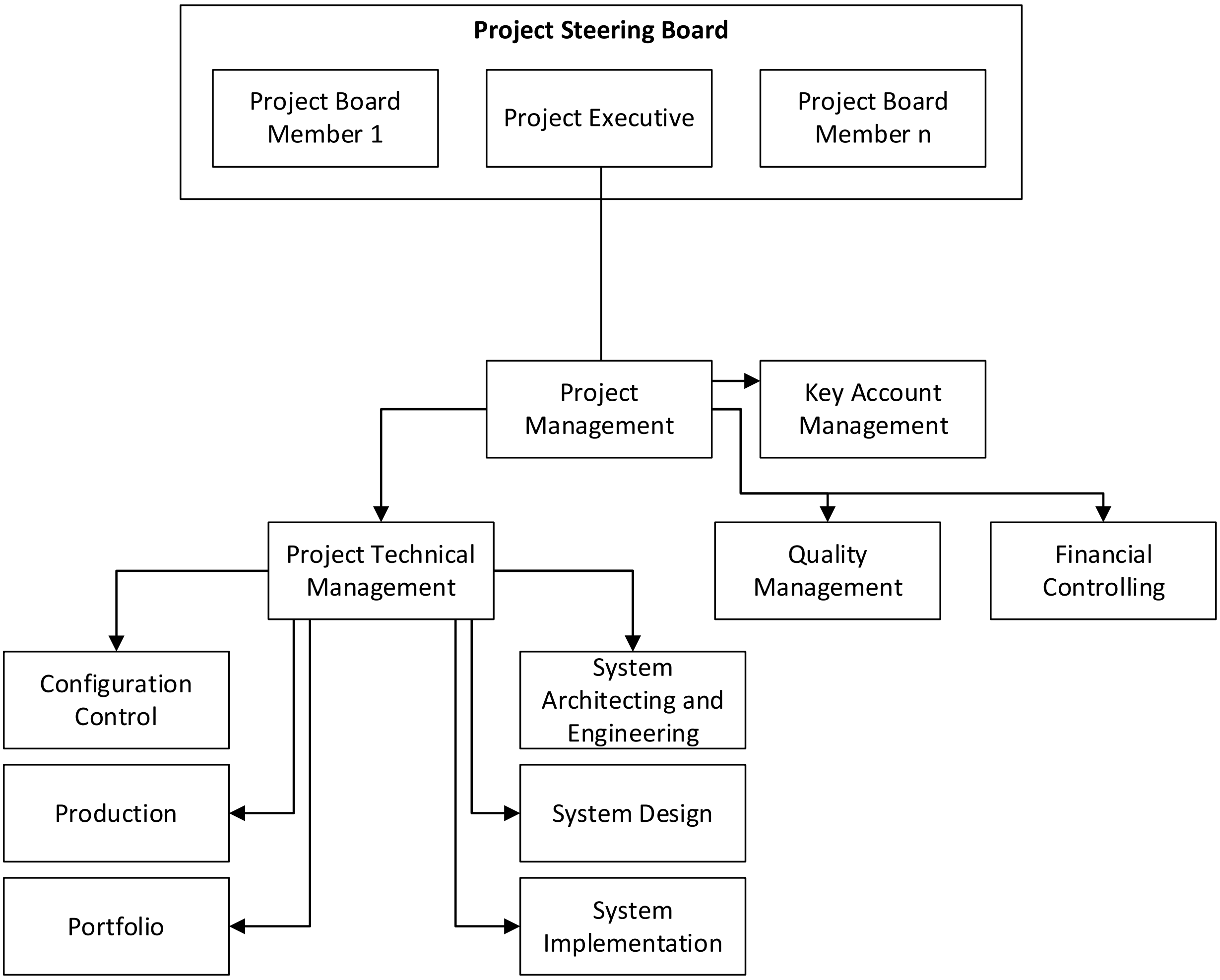

Figure 3: Typical Project Team Setup

A generic high-level project management team can now be identified, as is shown in Table 4 with the understanding that this team will have other team members reporting to them in the overall project structure.

Some literature references describe the role of the project manager and the systems engineer as being "joined at the hip," where neither can function without the other [11]. An alternative view is to view the interaction of the project manager and systems engineer as running on parallel paths, with each role focusing on its responsibilities but intersecting periodically at events such as review gates, where the project execution process is again synchronised and harmonised.

Table 4: Generic Project Management Team Roles

Nr	Project Team Roles
1	Project Steering Boards, including the Project Executive
2	Project Manager
3	Project Technical Manager
4	Project Quality Assurance Team

Nr	Project Team Roles
5	Change Authority
6	Project Support Functions

3.3 A generic project life cycle

The systems engineering process is based on a logical and orderly progression of different project stages, separated by quality or review gates such as the systems requirements review (SRR), Preliminary Design Review (PDR), etc. [2].

In an ideal environment, the generic project lifecycle should incorporate these requirements in the project execution process. These review gates are also vital tools for managing risk in the project process.

One conceivable way of defining such a combined project and systems development lifecycle is shown in Figure 4. The project life cycle is loosely based on the Prince2 project management methodology [17], which includes working in stages and managing stage boundaries. These stages and stage boundaries are fundamental to this project management methodology. They can also be directly aligned with the logical stages and quality or review gate inherent in the systems engineering process. The generic activities associated with these distinct stages are described in the following sections.

3.3.1 Project Initiation Phase Activities

a. Classify the project in terms of size and complexity to assist with tailoring the project process and identifying the project team.
b. Appoint Project Manager.
c. Conduct project initiation meetings.
d. Identify critical stakeholders.
e. Nominate next-level project management team.
f. Create project charter.
g. Create a baseline project on the ERP system (Financial and Configuration Management).
h. Review and conclude Initiation Phase activities (Stage or Phase Boundary)

3.3.2 Project Planning Phase Activities

a. Conduct project kick-off meeting.
b. Prepare a risk management approach and identify any known risks.

3.3.3 Project Execution, Monitor and Control Phase Activities

a. Initiate “Execution, Monitor and Control” Activities.
b. Evaluate production readiness.
c. Evaluate support services readiness.
d. Integrated change control.
e. Manage quality.
f. Manage costs.
g. Manage reporting.
h. Manage schedule.
i. Manage Communication
j. Manage Scope
k. Manage Risks
l. Review and conclude “Execute, monitor and control.”

Within the overall project execution, monitoring and control phase activities, the following detailed activities will be included:

3.3.3.1 Concept Definition Phase

a. Business or mission analysis.
b. Stakeholder needs and requirements definition.
c. Stage gate - system requirement review (SRR).

3.3.3.2 System Definition Phase

a. System requirements definition.
b. Interim stage gate - preliminary design review (PDR).
c. System architecture definition.
d. Design definition.
e. System analysis.
f. Stage gate - critical design review (CDR).

3.3.3.3 System Realisation Phase

a. Implementation.
b. Optional stage gate - integration readiness review.
c. Integration.
d. Interim stage gate - verification readiness review.
e. Verification.
f. Stage gate - post verification review.

3.3.3.4 System Deployment and Use Phase

a. Transition.
b. Interim stage gate - validation readiness review.
c. Validation.
d. Stage gate - post validation review.
e. Operation.
f. Maintenance.
g. Disposal.

3.3.4 Project Closure Phase

a. Initiate project closure activities.
b. Archive project artefacts.
c. Close project activities.
d. Capture Lessons Learnt.
e. Hand-over project to in-service support.
f. Review and conclude “Project Closure”.

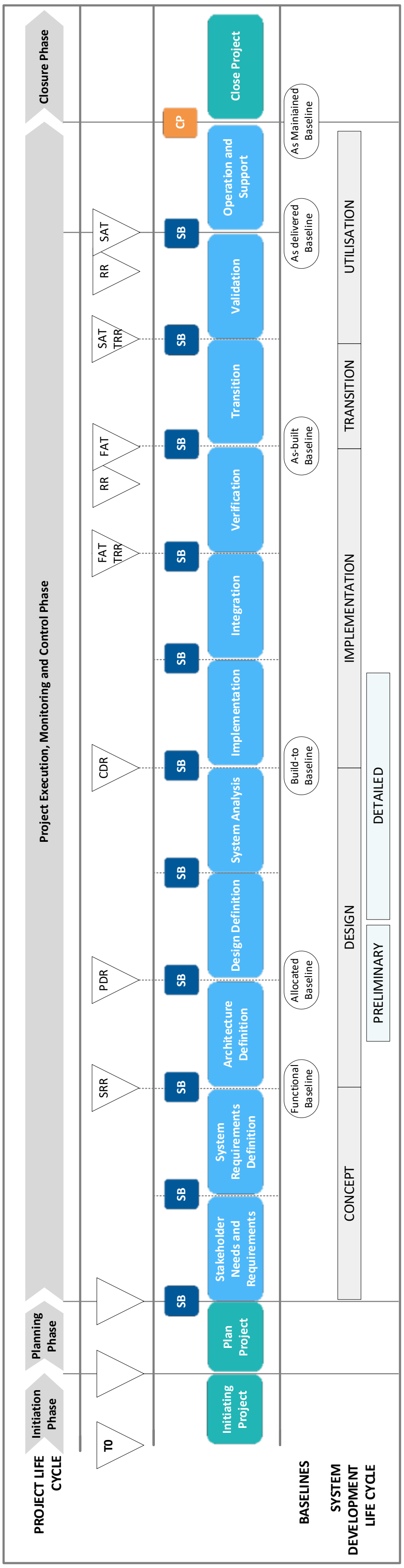

Figure 4: Combined Project and System Development Life Cycle

4 CONCLUSION AND RECOMMENDATIONS

The need for a systems engineering approach to delivering complex projects is undeniable. This approach must be paired with a suitable project management approach to leverage the total value that project management and systems engineering bring during project execution. While this need to integrate and harmonise the project management approach with a suitable technical management approach also forms the subject of a combined PMI and INCOSE work group, many challenges must be solved before this approach becomes an accepted way of working. This paper aimed to identify the salient requirements from both a project management perspective and a systems engineering or technical management perspective that must be accounted for in a harmonised approach.

A generic project life cycle was defined based on the Prince2^{TM} project management methodology overlayed over the systems development life cycle elements. This combined process view is considered unique as it leverages the identified project management methodology's inherent stage gate/boundary characteristics to support the various phases of the systems engineering process.

The following steps in this research journey will be to implement this generic process within the organisation and evaluate its effectiveness in projects that involve complex, high-technology solutions. The results of this evaluation process and optimisation activities will be reported in a future paper.

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A QUALITATIVE ASSESSMENT OF THE RAPID SAND CASTING PROCESS USING THE RESSOURCE EFFICIENCY CLEANER PRODUCTION FRAMEWORK.

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ABSTRACT

The rapid sand casting process for producing sand cores and moulds is gaining worldwide prominence in the foundry industry. As this process is growing and being applied on a larger scale, users and customers are querying its sustainability and environmental safety. Examples of process challenges include production and disposal of solid waste, high electricity usage and emissions of harmful gases. This paper investigated the employees of one rapid sand casting operation in South Africa to ascertain if they were aware of and trained in the principles of resource efficiency and cleaner production (RECP). The study focused on the operators, designers, engineers and administrators in running the Voxeljet VX 1000 sand printer at the local Rapid Sand Casting Operations. A qualitative research methodology was adopted, which included responses to a tailor-made questionnaire based on the key performance areas of RECP. The research revealed that knowledge of resource efficiency was only held by top management and was not passed down to the employees. None of the staff were aware of the RECP strategies and their benefits. This study aimed to improve the rapid sand casting process to achieve the United Nations' sustainable development goals.

Keywords: Rapid sand casting, Resource efficiency, Cleaner production, Additive manufacturing, Metal Casting, Sustainable development Goals.

1 INTRODUCTION

Rapid sand casting (RSC) is a 3D printing technique for the direct manufacturing of sand moulds and cores used in metal casting (1). Rapid sand casting is one type in the binder jetting category of 3D printing. Binder jetting is a process of utilizing a liquid-based binding agent to selectively bond powder particles, layer by layer (2). The RSC process begins with the dispersion of a layer of sand, precoated with a catalyst, on the print bed. This is followed by selective deposition of the bonding material, known as the binder, on the sand bed in accordance with the computer-aided design (CAD) of the final 3D part. As the second layer of the powder material is spread, the printing plate automatically drops and this is repeated until the printing process is complete. RSC printed parts require post-processing, known as sintering, to strengthen the parts, since they are fragile in their green state (2).

RSC is known for its advantages such as the reduction of the lead time in the design process of mould production. The RSC process offers the easy integration of cores and gating systems into the mould, and the production of complex internal geometries. The RSC process also enables the production of optimized mould designs weighing up to 33% less than traditional moulds, while still meeting engineering requirements and specifications (3). Most RSC studies have been focused on productivity and the quality of the part produced. We are currently in an era when resource efficiency and cleaner production are encouraged to minimise negative effects on the climate. As metal casting is one of the industries with the highest levels of pollution, it is being pressured to reduce its pollution levels by introducing more environmentally friendly processes. Adoption of advanced technologies, such as RSC in metal casting, has positive effects such as reduced emissions of greenhouse gases and reduced waste generation.

Resource efficiency and cleaner production (RECP) is an environmental management strategy that increases competitiveness by improving productivity and efficiency while adopting precautionary environmental strategies when implementing processes, products and services (4). It optimises the productive use of natural resources while applying environmentally sustainable methods to mitigate damage (5). The goal is to enable economic growth without causing environmental deprivation, while still meeting the needs of human capital (6). It is believed that the application of RECP will restrict the extent of pollution and waste generation, thus reducing their risks to humans and the environment (7). It encourages the elimination of waste before it is even generated, the efficient use of resources and the overall reduction of pollution.

Like the rest of the world, South Africa’s most concerning environmental issues include air pollution, global warming and extreme weather events, high waste generation and climate change. These environmental issues impose threats to people’s health and livelihoods (8). The metal casting industry is one of the top industries required to comply with RECP methods so as to reduce its operational costs and conform to sustainable development goals. RSC is considered an environmentally friendly sand moulding process as it can advance and encourage economically practical and socially required growth alternatives, while still protecting the environment. One way to effectively implement RECP strategies is through awareness-raising. This paper introduces the RECP concept into the RSC processes. The level of awareness and preparedness of employees involved in the RSC operations is investigated and categorised according to their roles in the organisation.

2 LITERATURE REVIEW

Resource efficiency and cleaner production (RECP) was initiated with the cooperation of the United Nations Industrial Development Organizations (UNIDO) and the UN Environment Programme (UNEP) to advance sustainable development in developing countries. The main aim of RECP is to reduce waste and emissions through the strategic management of water, energy, and environmental and financial resources. The focus of RECP is to enhance the means of meeting human needs while maintaining ecological carrying capacity (9). The RECP strategy relies on the continual application of precautionary environmental practices to processes, products and services to minimise risks to the environment and humankind, and for the beneficial use of natural resources and the reduction of waste generation (9).

The application of RECP in manufacturing results in the efficient use of resources (raw materials, energy, water, etc.) to add economic value. Considering that natural resources are becoming scarcer and more expensive, manufacturing companies are required to prioritise resource efficiency to continue being competitive and move toward green manufacturing (10). Studies show that new manufacturing technologies will significantly help reach the target of a low carbon economy while maintaining the same and improved productivity (11). Rapid sand casting forms part of the range of new 4IR technologies available to the foundry industry.

The application of RSC technology to the production of sand moulds, for casting parts and products, optimises the consumption of materials through design optimisation of both part and mould/core, hence reducing energy consumption and use of metal. This metal saving results in the reduction, by at least two-thirds, of the CO_2 emissions produced by traditional casting (9). RSC reduces the metal-to-rand ratio to a maximum of 1:1 as opposed to 1:3 in traditional sand moulding. RSC reduces the amount of resin/binder consumed during mould production as the binder is only sprayed on exact locations (12). If the maximum mould density produced by Voxeljet VX500 is 1.738, then the specific energy consumption of printing mould and core is 1.08 MJ/kg (12).

The total sand weights (wm) of moulds and cores produced using RSC, compared to traditional mould making, were found to be 301 kg and 90 kg, respectively. The core weights were 7.7 kg and 3.3 kg, respectively; and the mould weights were 34 kg and 23 kg, respectively (13). The specific energy consumption for producing one mould was calculated to be 52.08 MJ for traditional moulding and 110.36 MJ for the RSC process. Nevertheless, it was concluded that RSC is the best option for single part production. For mass production, traditional moulding is more beneficial (13). The carbon dioxide emissions for RSC and traditional moulding processes were calculated to be 9.96 $kgCO_2$ and 4.70 $kgCO_2$, respectively (13).

The RSC process consumes lower amounts of resources (metal and moulding materials), whereas traditional moulding consumes relatively more quantities (14). About 29.02% and 10.35% of energy is saved by RSC and traditional moulding, respectively indicating that RSC process has more energy savings. Also, the application of new technologies has the potential to transform foundries from a labour-intensive to technology-intensive industry more dependent on equipment which helps the industry to venture into the current Forth Industrial Revolutions (4IR) which is known for its improved international competitiveness benefit.

3 METHODOLOGY

The methods of this study are summarised in Figure 1. The case study of this research was the Voxeljet VX1000 RSC process of the local Rapid Sand Casting Operations. The research approach applied in this study was a face-to-face interview of staff members involved with the Voxeljet VX1000 sand printing operations. The procedure began by conducting a pre-assessment of the RSC to identify the RECP key performance indicators of the process. Questionnaire design was based on critical points identified in the literature, and on process pre-assessment (see Table 1). The station manager, administrator, additive manufacturing team leader, technicians, operators and interns were interviewed and their responses were recorded. Ethical considerations of this study included voluntary participation and anonymity. Responses of staff members at different levels were analysed to understand the culture and to find and compare similarities between the different levels.

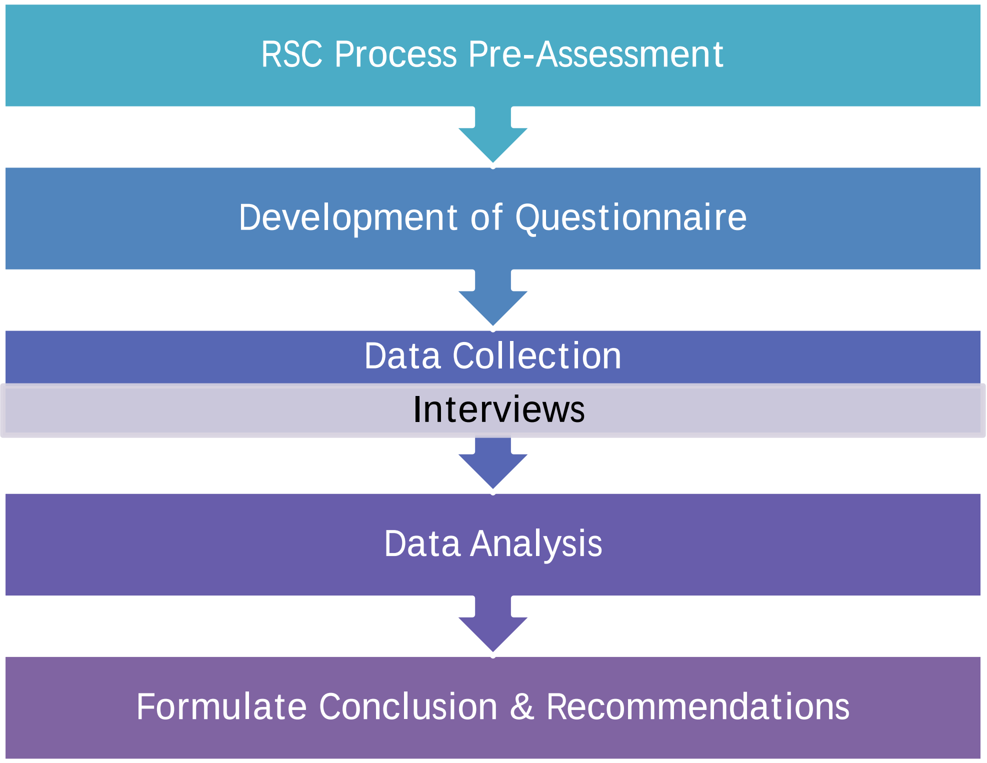

Figure 1: Research methodology

3.1 RSC process pre-assessment

The RECP key performance indicators (KPIs) play a significant role in evaluating and enhancing sustainability and monitoring the environmental performance of the process. The KPIs of the RECP process are classified into two categories, i.e. input and output indicators as described below:

A. Input Indicators

- Materials productivity - indicating the efficiency of the use of raw materials consumed in the process.
- Energy productivity - measures how efficiently energy is used during production.
- Water productivity - evaluates the efficiency of the water usage.

B. Output Indicators

- Solid waste emissions - quantifies the amount of solid waste produced in the process.
- Air emissions - indicates the amounts of pollutants released into the atmosphere.
- Wastewater - evaluates the impact of waste water discharge.

The above KPIs were utilised to locate specific RECP KPIs for the RSC process.

4 RESULTS AND DISCUSSIONS

4.1 RSC Process (RECP KPIs)

RSC is the process of fabricating sand moulds and cores using 3D printing technology. The input and output indicators of the process are identified in Figure 2. This process does not use water as an input, therefore there is no waste water in the process. Currently, no recycling protocol is being applied during the entire process, and the process does not have any protocol to monitor environmental performance.

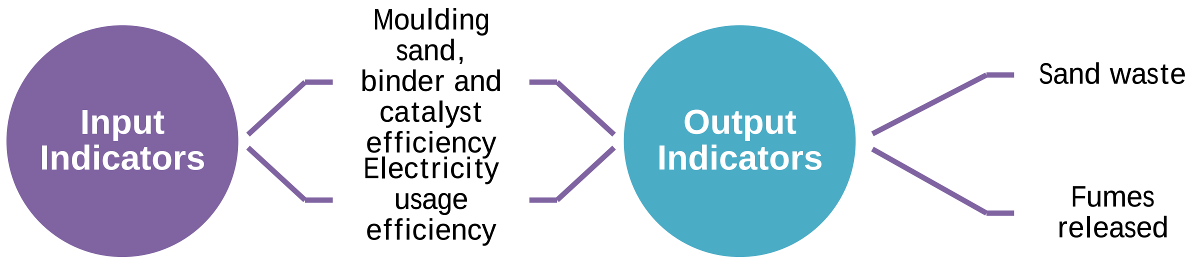

Figure 2: RECP KPIs for the RSC process

4.2 Operational interventions

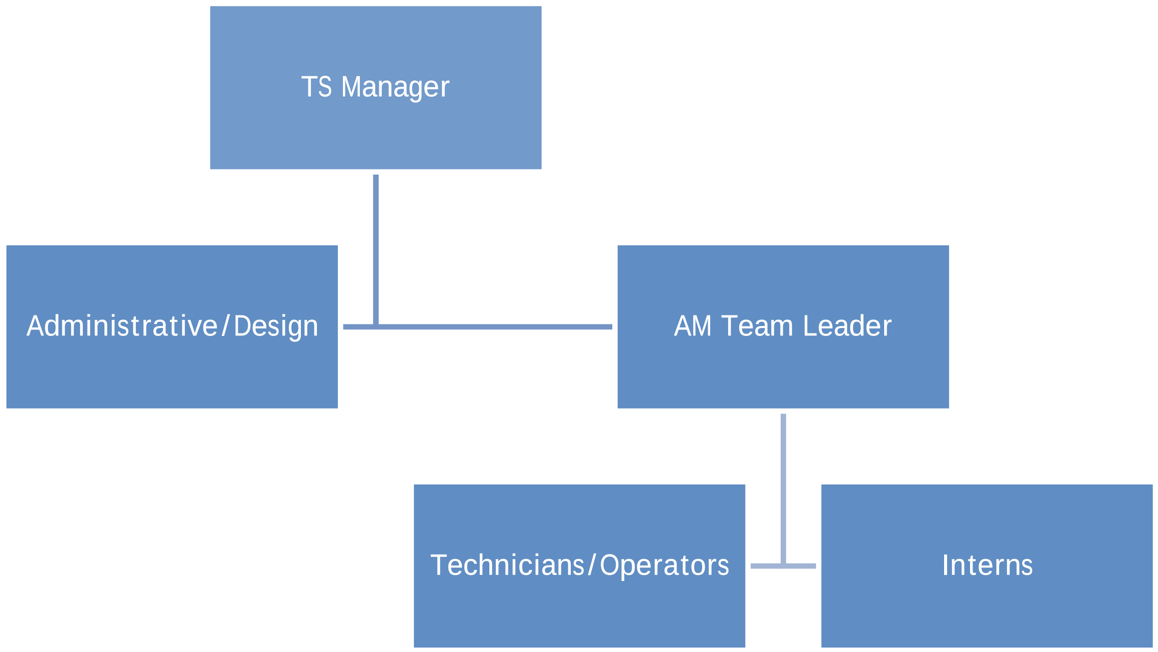

Figure 3: TSMPT RSC process organogram

The operational organogram of the staff who manage the RSC process at the Technology Station for Material and Processing Technologies, appears to be a simple hierarchical structure with three levels and with the AM team leader having two subordinates. The RSC operations at TSMPT have a narrow span of control. The benefits of a low span of control includes better control, good productivity, more effective communication and improved room for decision-making by management (15). The limitations of a narrow span of control have minor to no effects on this process, for the following reasons:

- **Low morale,** which means that when managers are micromanaging, the staff become demoralised. In this case study managers are not micromanaging.
- **Greater cost** becomes a limitation when a company have more managers to supervise fewer staff, thus incurring unnecessary costs. This is also not applicable in this case study as can be observed in Figure 3.
- **Slower communication and coordination** usually results from a hierarchical structure consisting of many levels. Communication is normally found to be better controlled in a smaller, flatter structure. This structure has three levels which does not hinder the rate of communication from top management to staff.

4.3 Interview Results

This case study is focused on a specialized industry hence only a specific set of individuals suits the nature of the research study depending on the experience they have in the field of RSC in South Africa. A total of 5 employees participated in the survey: 1 manager, 1 designer, 1 technician/operator, and 2 interns. Their responses were summarized and statistically analysed to ensure anonymity.

Table 1: Research questions and responses of participants

Research question	Manager's response	Designer's Response	Technician/Operator's Response	Interns' Responses
Briefly explain the history of the RSC process.	"The world has evolved from traditional mould making to 3D printing technology. Traditional methods still play a major role in foundries, but 3D technology, despite its limitations in size and precision, stands out for its accuracy and reliability."	No Response	"Sand casting is an ancient method used for decades to produce metal pieces. Rapid sand casting is versatile, allowing for complex shapes and sophisticated geometries without specialized tooling."	No Response
What is your understanding of RECP?	"Increasing production and creating a cleaner or safer environment and creating preventive measures to ensure no pollution to the environment and staff."	No response	"I have never heard of it before, so I do not understand it."	No response
Do you know about electricity consumption? And what is your take on it?	"High because of machine usage and high voltage, lastly aircons high consumptions because of maintaining temperature in labs."	"I do not know the exact amount of electricity being used But from observation, I can tell it is a lot depending on how many parts are being printed and the volume of the build."	"Our machines consume a lot of electricity. Not only for operating the machine but also for maintaining a controlled environment. The air conditioners always need to be on to control the print environment."	"I cannot tell whether it is high or consumed efficiently."
What are some environmental considerations of the process?	"Containing and decreasing fumes and disposing of waste silica sand."	"Disposal of sand. Our sand is mixed with acid so we must implement proper disposal procedures."	"The biggest environmental consideration is amount of the waste generated during this process. This is because we do not have an effective and environmentally safe way of discarding and reusing the waste sand."	"Energy consumption, air pollution, and sand consumption."
Do you think this process is better that the original foundry moulding?	"Yes."	"In terms of speed, accuracy and continual use of a mould, yes"	"Yes, because not only does this method save time but it also saves costs and allows more complex designs."	"Yes."

Do you have any policies for governing the rapid sand-casting process?	"Yes."	"Regular maintenance of machine Accurate and proper upkeep before all print jobs Ensuring that the sand is completely dry before loading the machine for a new job."	"Yes."	"Yes."
How would you describe the overall material consumption of the rapid sand-casting process?	"Manageable and aligned to the volume of parts. Buying locally has reduced significantly the cost and material usage."	"Relatively neutral because we often recycle the sand depending on the client's needs."	"Our overall material consumption is good. Since the localisation of material, we have managed to save on sand costs and freight costs."	"Yes."
Does the process produce any fumes during manufacturing? If yes, what types of fumes are produced?	"Yes, carcinogen."	"Yes. Fumes are emitted when mixing the silica sand and acid."	"Yes, carcinogen."	"No."
How do you deal with sand waste?	"Discard and use waste companies for safely disposing it."	"We can recycle the sand if the quality of the sand isn't compromised too much, but if it is, we dispose of it."	"We do not have an environmentally friendly method of discarding sand. We currently use two methods: o Store waste sand in containers in the storage containers. o Discard it outside in a stockpile."	"Discard on the dumping sites."

4.4 Discussion

The survey results reveal several key insights into the awareness and implementation of Resource Efficiency and Cleaner Production (RECP) principles at TSMPT's RSC operations.

4.4.1 Awareness of RECP:

Only 20% of respondents are aware of RECP strategies and their importance. This indicates a significant gap in knowledge among other employees, suggesting the need for comprehensive training and awareness programs.

4.4.2 Electricity Consumption:

100% of respondents acknowledge high electricity consumption, particularly due to the operation of machines and the use of air conditioners to maintain a controlled environment. This highlights the need for energy efficiency measures and monitoring.

4.4.3 *Environmental Considerations:*

Waste management is identified as a significant challenge, with no effective methods for discarding or reusing waste sand. The disposal of sand mixed with acid and the generation of carcinogenic fumes are also concerns that need addressing.

4.4.4 *Comparison with Traditional Moulding:*

The RSC process is viewed favourably compared to traditional methods, with benefits in cost savings, accuracy, and the ability to create complex designs. This positive perception supports the continued adoption of RSC technology.

4.4.5 *Policies and Procedures:*

While policies exist for machine maintenance and operation, there is a lack of comprehensive procedures for environmental performance monitoring and waste management. This gap underscores the need for robust policy development and implementation.

4.4.6 *Material Consumption:*

Local sourcing of sand has improved material consumption efficiency and reduced costs. However, the lack of recycling protocols indicates room for further improvement.

5 CONCLUSIONS

This study aimed to investigate the awareness and preparedness of employees in one rapid sand-casting operation in South Africa. The case study was conducted in a local Technology Station having a binder-jetting additive manufacturing operation. The analysis indicates that only the manager showed RECP awareness and preparedness. The knowledge of resource efficiency was only held by top management and was not passed down to the employees. None of the staff were aware of the RECP strategies and their benefits.

The study recommendations emphasise on the necessity of enhancing awareness and training on RECP strategies across all employee categories to achieve a more sustainable and environmentally friendly RSC process. Addressing the identified challenges in waste management, energy consumption, and environmental impact is crucial for aligning with sustainable development goals and improving overall process efficiency. Future studies should involve conducting an RECP assessment of the entire process, a quantitative analysis and the development of an RECP framework for the rapid sand casting process.

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INVESTIGATING THE DEFORMATION OF THE RIGHT-HAND SIDE BOX OUTER OF AN AUTOMOTIVE MANUFACTURER USING LEAN SIX SIGMA DMAIC METHODOLOGY

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ABSTRACT

The objective of the study is to investigate why is it only the right-hand side of the vehicle that is producing defects while the opposite side is defect free. Theoretically in stamping operations the dies of the left-hand side and right-hand side are manufactured “mirror made”, meaning what is happening on the left must also happen on the right. On average about 10% of every press run of the right hand(RH) side box outer contributes to scrap and rework in this instance. A qualitative research methodology using a case study was adopted to collect data of all the process anomalies related to the stamping process. Lean Six Sigma DMAIC methodology was used to complete the research study. The resultant information and data alludes to conclusive evidence that proper quality assurance protocols were neglected in the finalisation of the stamping dies.

Keywords: Lean six sigma; industrial engineering; performance management

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1 INTRODUCTION

The organisation's stamping plant currently manufactures structural and skin panel parts for the new product A and product B. The plant currently runs 3 shifts of 8 hours and the shifts are as follows 06h00-14h00, 14h00-22h00 and 22h00-06h00. The target for each shift is to press 3500 parts and the press tools that is installed uses the latest technology. The press has a capacity to produce up to 16 SPM (Stroke per minute) parts/pieces. The stamping plant currently manages 62 dies for the different vehicle body parts. The press planner rotates the dies on evaluation of stock levels and the economic order quantity (EOQ) to fulfil the demand. The new product A and new product B have an agreement to share some of the parts in their vehicles. This means that the shared dies must be scheduled more than others or have a large, planned quantity because Product A and Product B are built simultaneously.

A particular die is currently a challenge whenever it is used which led to this research being initiated. The die of right-hand side box outer of the vehicle produces a high level of scrap and rework. It is estimated that if the plan is to run 2000 parts is it estimated that over 250 parts will contribute to scrap and rework. The reason for this is because the die is not manufactured the same with the left-hand die, as the left-hand die gives zero defects. This leads to the organisation's business unit failing to meet the required operational targets. A defect that is omitted or undetected and found at a dealer destroys reputation of the organisation and the product. It lowers the profit margin and increased cost of production that leads to financial distress.

2 LITERATURE REVIEW

Stamping or the pressing process is a single process operation where every stroke of the press produces a final product or parts. The pressing process is associated by many operations such as bending, drawing, piercing, flanging as well as coining. The stamping die is the main process tool that is used to produce high-volume sheet of metal parts.

Lean Six Sigma (DMAIC) methodology was found to be the most suitable for the purpose of the study. It is defined as a structured process improvement and problem-solving methodology for the existing problem. Press settings/parameters play an important role in the quality specification as differ material specifications with different material elongation is utilised. The speed, amount of lubricant and temperature impact the quality of the product produced.

Lean Six Sigma represents a comprehensive quality improvement methodology that merges Lean Manufacturing and Six Sigma principles where these two methodologies complement each other. When integrating Lean Manufacturing and Six Sigma principles, organisations can attain significant operational and financial benefits. Employing the principles of lean management simplifies waste reduction, shortens lead times, and enhances process efficiency within an organisation.

With the application of statistical concepts, process variation is easily detected. Inherent errors in a process would be highlighted where the risk of scrap is prevented. Six Sigma is focused on the reduction of variation where the capability of the process is measured at sigma levels. In view of its very nature, six sigma methodology is based on a series of interconnected phases that controls inputs and outputs of the system. It is robust in nature using quantitative analysis as the primary means of defect identification.

Lean six sigma is based on fundamental principles of continuous improvement and provides organisations with the opportunity to reduce material flows, non-conforming products, costs, material losses, defective parts, warranty costs, dis-satisfied customers, unproductive times, process capability, productive capacity, and improved delivery performance.

3 METHODOLOGY

A qualitative research methodology using a case study analysis was applied in this study. According to [10] qualitative research is a research approach that aims to explore and understand the social phenomenon by analysing non-numerical data, such as words, images and observations. In this research, direct observation of the process in question was the primary means of data collection. Informal discussions were held with the operators on the stamping process.

Data collection techniques- Informal discussions where one on one conversations between the researcher and the participant took place. The researcher asked open-ended questions to understand the participant's experiences, perspective, and feelings related to the research topic. Observations involved observing and recording the behaviour and interactions of participants in their natural environment.

The Lean Six Sigma DMAIC methodology is used to achieve the aim of the study. The steps are explained as follows:

The Define Stage - is where the problem is identified, and plan how is going to be fixed by providing a framework for the entire improvement process. Draft a precise in scope and out of scope parameters for the process improvement.

The Measure stage - This is where the baseline measurement methods chosen and can be quantifiable and be compared to result and post improvement outcomes. It is data driven.

The Analyse stage - is where the analysis of the problem occurs. Solutions are identified that will genuinely target and address the identified problem.

The Improve Stage - This is where the improvement is implemented and measured to determine the variance in the improvement.

Control stage. In this stage there is standardization of the process, checking the progress of the improvement and ensuring that it does not deteriorate.

4 RESULTS AND DISCUSSION

4.1 Define phase

In the case of this study, the problem is defined. Various personnel are appointed by a project coordinator and the scope of the project is demarcated. It is by relevant personnel that will formally authorise the existence of the project and provide the project owner with the authority to apply organisational resources to project activities. This document describes the reasons why the project is initiated and the project boundaries. It is way to set boundaries on the project and define exactly what goals, deadlines and project deliverables are expected.

There is a communication plan that identifies how information will be communicated to stakeholders throughout the project. It also determines who will be receiving the communication, how those people will receive it, when they'll receive it, and how often they should expect to receive that information.

Work breakdown structure (WBS)

It is a helpful diagram for project coordinators or managers as it allows to break down the project scope and visualize all the tasks required to complete the project. All the steps of the project work are outlined in the work breakdown structure chart which makes it an essential project planning tool.

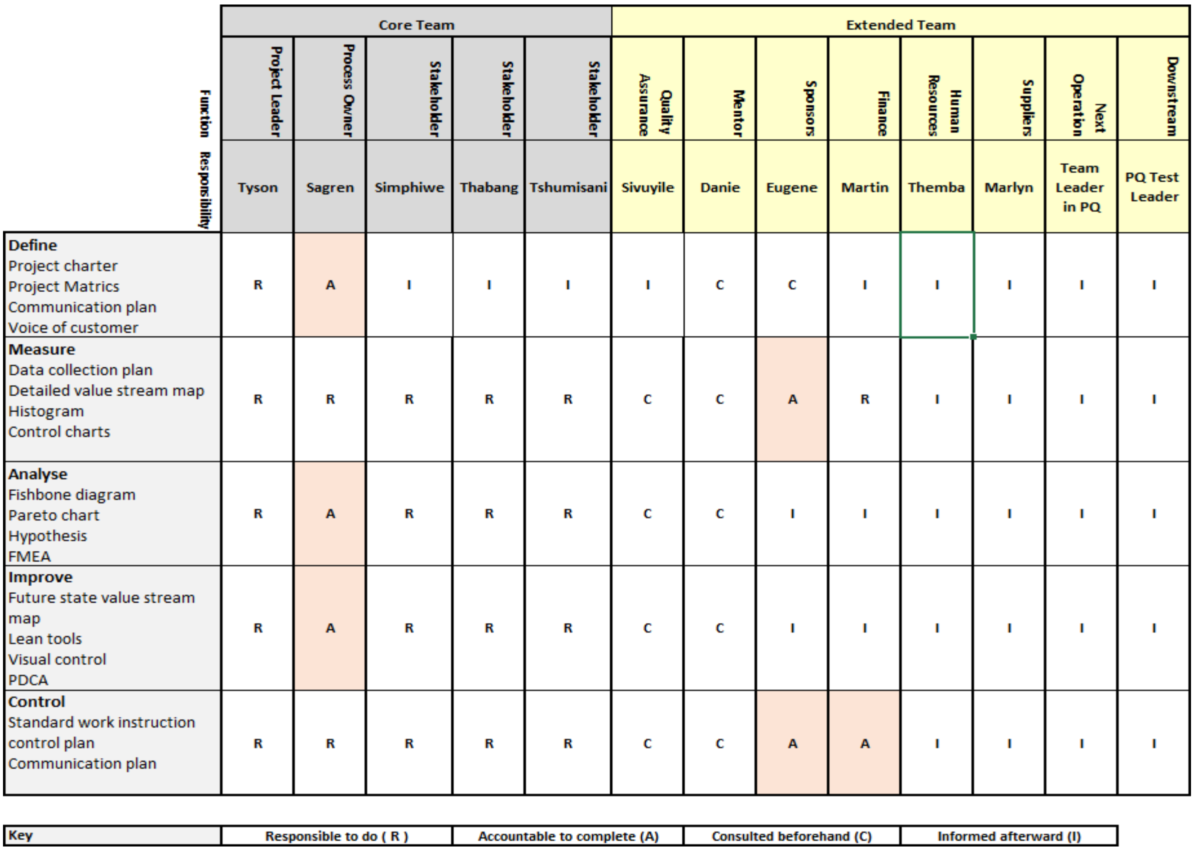
Voice of Customer (VoC)

It is a structured process of directly soliciting and gathering the specifically stated needs, wants, expectations and performance experiences of the customer about the products or services that you provide.

RACI Matrix Identified

RACI matrix is a roles and responsibility matrix, which stands for Responsible, Accountable, Consulted and Informed. The RACI matrix guides the researcher to build from the work breakdown structure (WBS) and provide a room to use deliverables to assign roles and responsibility to each identified stakeholder.

Table 1: RACI table for roles and responsibilities



Function Responsibility	Core Team					Extended Team							
	Project Leader	Process Owner	Stakeholder	Stakeholder	Stakeholder	Quality Assurance	Mentor	Sponsors	Finance	Human Resources	Suppliers	Next Operation	Downstream
	Tyson	Sagren	Simphiwe	Thabang	Tshumisani	Sivuyile	Danie	Eugene	Martin	Themba	Marlyn	Team Leader in PQ	PQ Test Leader
Define Project charter Project Matrics Communication plan Voice of customer	R	A	I	I	I	I	C	C	I	I	I	I	I
Measure Data collection plan Detailed value stream map Histogram Control charts	R	R	R	R	R	C	C	A	R	I	I	I	I
Analyse Fishbone diagram Pareto chart Hypothesis FMEA	R	A	R	R	R	C	C	I	I	I	I	I	I
Improve Future state value stream map Lean tools Visual control PDCA	R	A	R	R	R	C	C	I	I	I	I	I	I
Control Standard work instruction control plan Communication plan	R	R	R	R	R	C	C	A	A	I	I	I	I

Key	Responsible to do (R)	Accountable to complete (A)	Consulted beforehand (C)	Informed afterward (I)

Measure Phase

The measure phase is about understanding the extent of the problem. In this research it about understanding why there are challenges with one side (RHS) box of the vehicle.

Data collection plan

This a well thought approach to collecting both baseline data as well as data that can provide clues to the root cause. The plan includes where to collect data, how to collect it, when to collect and who will do the collecting. Below is the data collection plan table.

Table 2: Data collection plan

<table>
<tr><th colspan="2">Data</th><th colspan="4">Operational Definition and Procedures</th></tr>
<tr><th>What</th><th>Measure Type/ Data Type</th><th>How Measured[1] ?</th><th>Related Conditions To Record[2]</th><th>Sampling Notes</th><th>How/where Recorded (attach Form)</th></tr>
<tr><td>Right hand box outer tool die producing defective partsand excessive rework</td><td>Interview Survey answers and every production run recordings</td><td>Scrap & rework trends</td><td>Quantitative data-scrap & rework amount</td><td>Baseline trend before research vs trend with ongoing research trend</td><td>Recorded on OnTrackMIS</td></tr>
<tr><td colspan="3">How will you ensure consistency and stability?
• By putting control measures into place: ensure that the run is properly managed while the research is still ongoing to find solutions
NOTES
[1] Include the unit of measurement where appropriate. Be sure to test and monitor any measurement procedures/ instruments.</td><td colspan="3">What is your plan for starting data collection? (Attach details if necessary.)
• Interviews with tool makers (peopleworking with die on daily basis)
• Base line data vs ongoing project research data
How will the data be displayed? (Sketch on additional sheet)
• It will be displayed through diagrams and power point</td></tr>
</table>

Developed process flow chart for the organisation stamping section

The organisation stamping process flow with decision making points activities demonstrates how a quality product is made after every press run. The procedure for the process flow is as follows:

The production quality standard is to be set at the beginning of each production cycle following a die set and/or changeover a part release of the line or in the event of a breakdown resulting in re-setting of a die(s). It is re-verified at a minimum of once per press and/or production run and at the end of the production cycle in the form of a " Last Hit Panel". The re-verification of the current part to the PQS for the production cycle is to be done on a new sample and in accordance with the process control plan.

Production and Quality Inspection Personnel

The part is taken from the beginning of the production cycle for the Production Quality Standard (PQS) approval. It is checked against specified requirements (e,g Control Plan Requirements, Reference Sample, Gauge information, Last Hit, Product Audit (PA) standards.

Below is how the process flow buy off outlined.

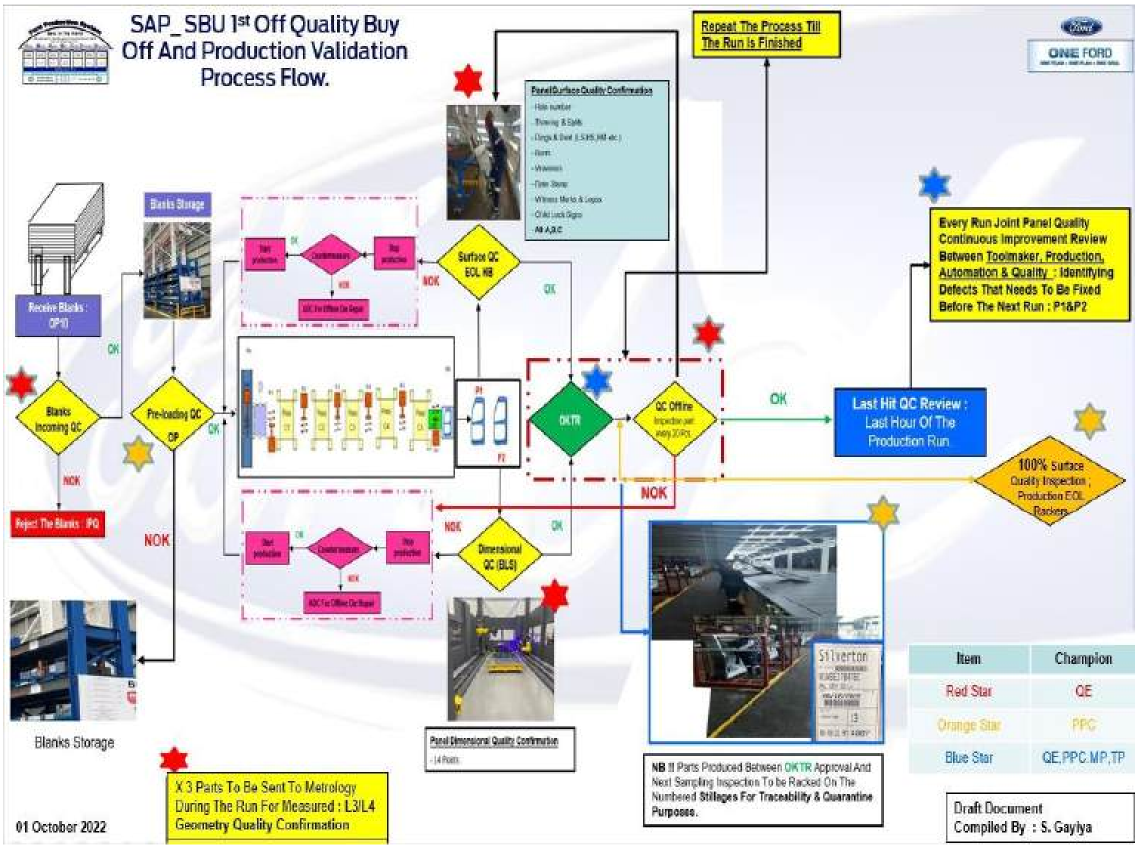


Figure 1: Flow process chart

X Bar chart and R Bar chart of a tool

Below is the X chart which shows the measured flow of material on both left and right dies of box outers. The chart clearly shows that the process is unstable. Tool A represents the right-hand die for the box outer which is the problematic die that gives scrap and rework. The chart for tool A shows that there is instability in the process. Below is the X chart by tool.

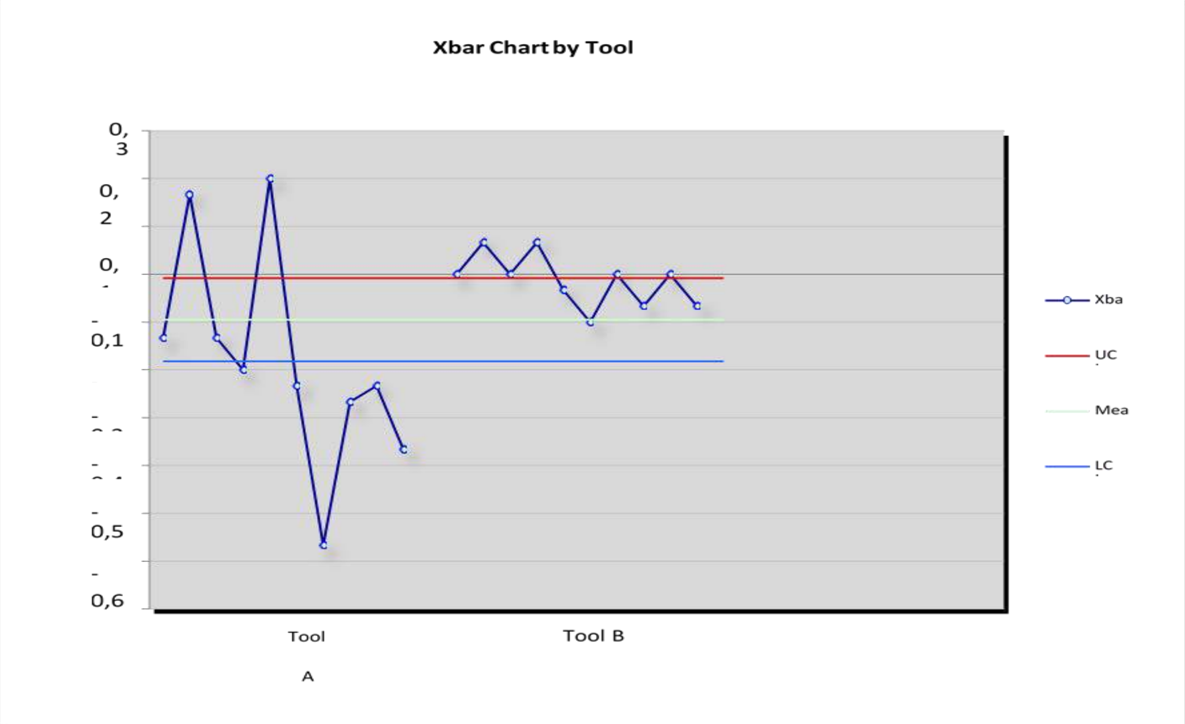


Figure 2: X Chart by tool

R-chart shows how the range of the subgroup’s changes over time. It is also used to monitor the effects of process improvement theories. If the subgroup size is constant, then the centre line on the R chart is the average of the subgroup ranges. If the subgroup sizer differs, then the value of the centre line depends on the subgroup size, because larger subgroup tends to have larger ranges.

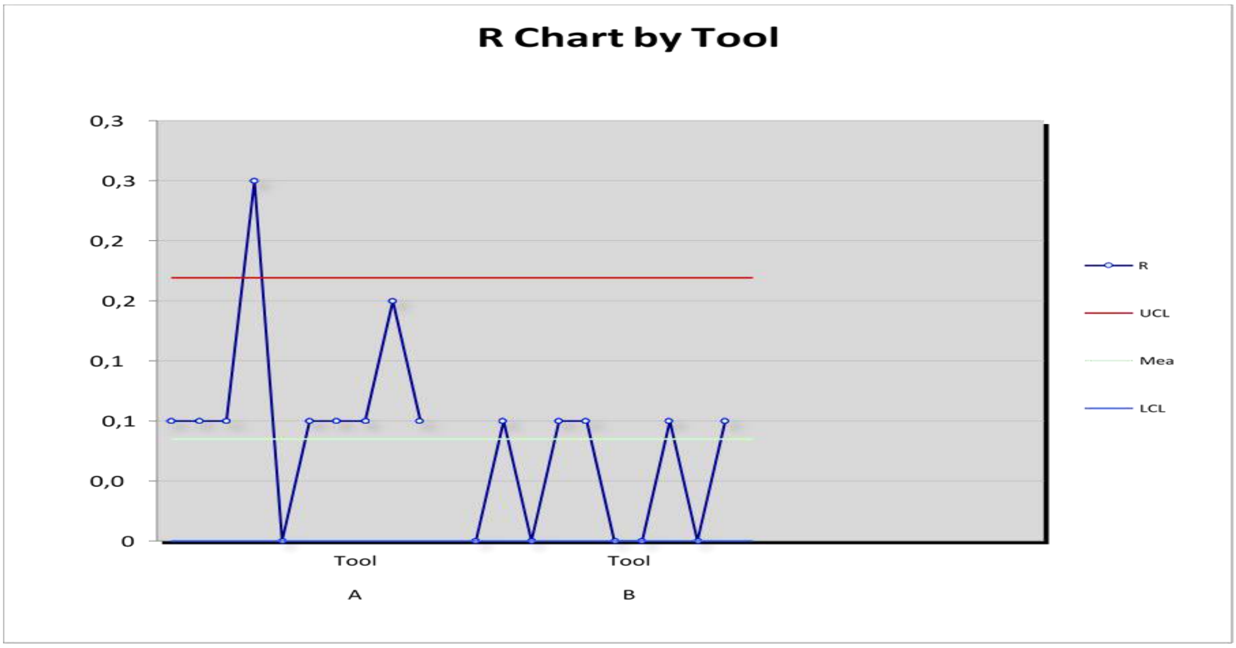


Figure 3: R Bar Chart by tool

Table 3: The study recorded the following scrap and rework

Production date	Scrap	Rework	Total
16/01	18	39	57
24/01	13	23	36
30/01	21	20	41
07/02	44	38	81
16/02	3	1	4
21/02	2	3	4
28/02	4	2	6
08/03	1	0	1
15/03	1	0	1

The above table presents the combined numbers of scrap and rework quantities per run date of right-hand box. It is evident that there is a problem with box as the scrap and rework rate is too high. It is important to note that managers should recognise the importance of creating resources and time so that employees can in parallel with their daily duties be allowed to pursue the new ideas as well as to be encouraged to challenge conventions and assumptions regarding the situation.

Analyse Phase

Analyse phase is the third step in DMAIC process, which is a method for solving problems and developing strategies. In this phase data is analysed to determine the probable causes of failure in the process.

Brainstorming

This is the method used to generate ideas and sharing knowledge to solve the problem of the right-hand die that produces excessive scrap and reworks. In this event, ideas are gathered and written on a board. The ideas were divided into four categories with a tool called the pay-off matrix which is as follows:

- Good solutions-means solutions that will have high impact applying low effort.
- Quick wins- means solutions that will have a low impact applying low effort.
- Big system change-means solutions that will have high impact applying high effort
- Why bother-means solutions that will have a low impact applying high effort

The group of people which was involved in this event to solve the issue includes:

- Tool makers: responsible for die repair and maintenance
- Die specialists: responsible for changes that needs to be done on the die
- Rackers: responsible racking parts at the end online
- Quality Engineers: responsible for geometry and part surface
- Quality inspectors: responsible to monitor and check parts at end of line
- Process engineers: responsible for the setup of parameters on the dies

Below are the solutions that came up with the team while doing the brainstorming and they are divided according to the pay-off matrix.

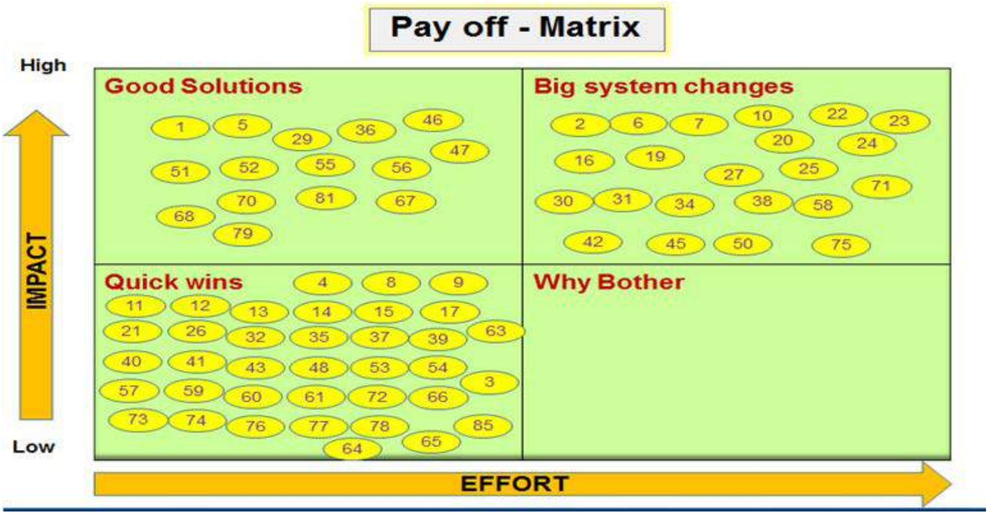


Figure 4: Pay-off Matrix for the problem

The numbers that are shown above in small circles inside the quadrants represents the solutions that the team gave during brainstorming session. The team came up with over 85 ideas on how this problem can be solved. Some of the ideas when doing analysis, fell under the category of Why Bother. If the team decides that an idea or solution fell under why bother it reveals that there is no need to look at the idea.

Analysis of Die A and Die B

Theoretically when manufacturing two dies of opposites sides they must be the same because they are mirror made. This means that when they are both in production, they will give the same results. The die of left-hand is designed in the correct manner while the die of right-hand side is not designed in the correct manner, as they do not give the same results.

Figure 5: Left-hand Dye

The left-hand side die has two draw beads that are close to each which allows the flow of material to be fluent and uniform during the press run. Draw beads of a die are used to control the flow of sheet blank metal into the cavity during stretch-draw forming of panels. The purpose of draw bead is to prevent the following:

- wrinkling in formed panels
- reduce the blank holder force
- minimize the blank size needed to make a part
- force to keep tools closed during the drawing process

Poor design of a draw bead can lead to producing defective panels which is what is being experienced in this study.

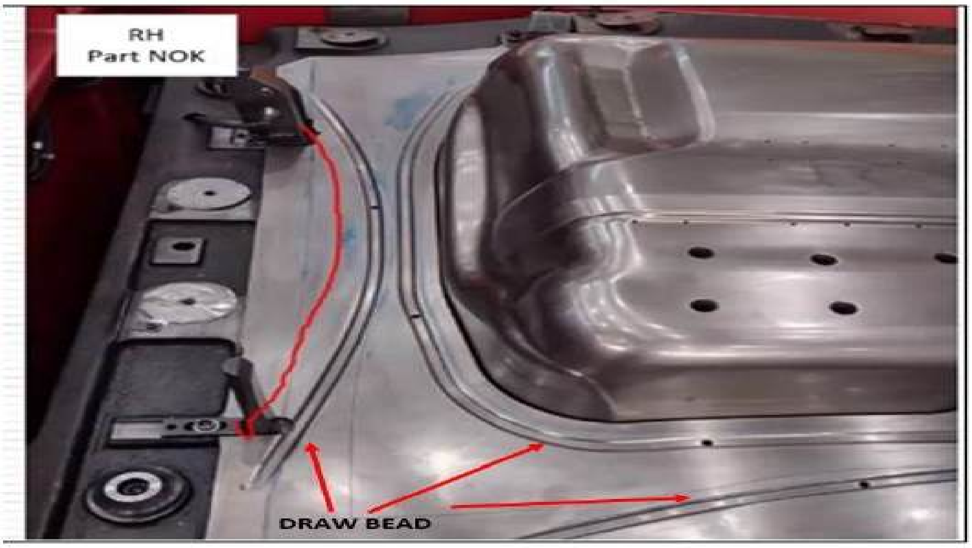


Figure 6: **Right-hand Dye**

Improve phase

Improve phase is the fourth step of DMAIC process, this is the phase where the team starts finding solutions to the root cause of the problem discovered in the first three phases. It is said to be the most creative stage of the cycle since it does not involve much statistical analysis. People try to come up with creative ideas to find solutions to the problem.

Its focus is to remove variations in the process by applying feasible solutions to the root causes of the problem. After the solutions are identified and are implemented to reduce variations an improve target performance are executed. The activities in the improve phase include:

-Identifying specific inputs that are affecting the outputs of the process

-Creating solutions to eliminate the main causes of the problem

-Verifying the solutions and critical inputs

-Optimizing critical inputs and assessing the implemented solutions

Improvement plan

In this research project there are three factors involved which are dies, process of stamping and technology. All these factors have discrepancies within them, and they need to be improved.

This research is based on the right-hand side box outer of the vehicle as it produces defects. The way forward for this problem is to optimise the die and put it on the same level as left-hand side box outer. The figure shows the current state versus the future state.

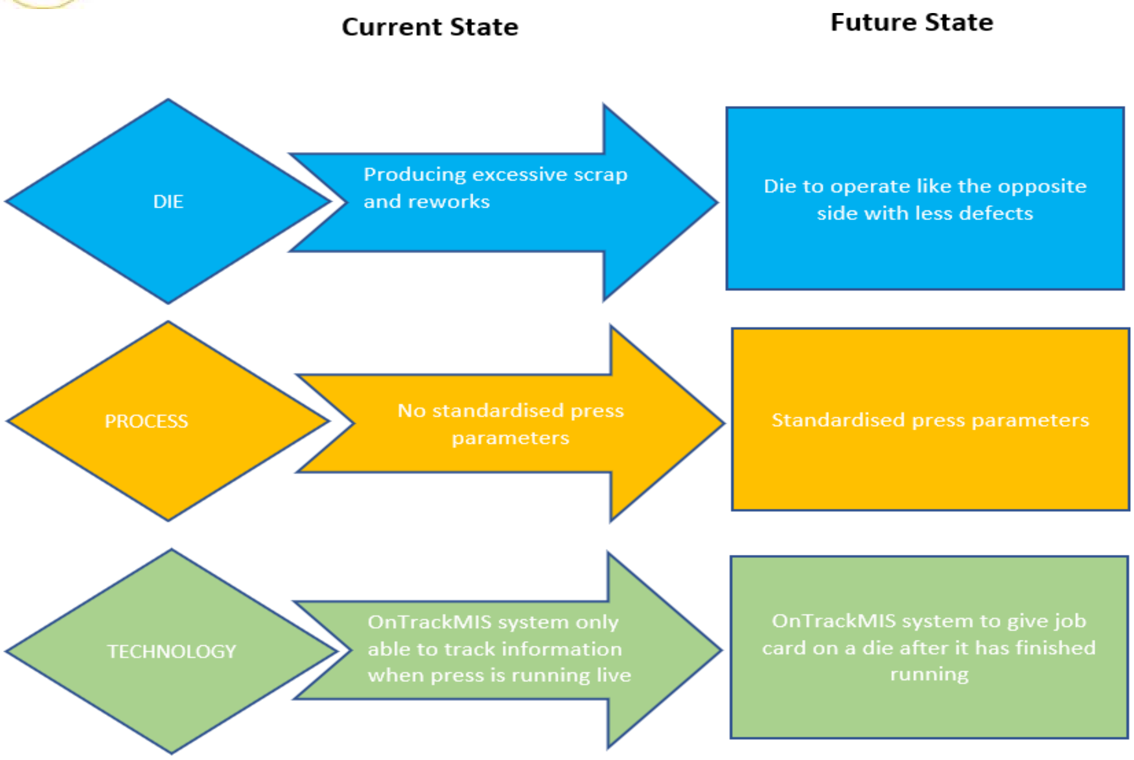


Figure 6: Current state vs Future state

5 DISCUSSION OF FINDINGS

The bar graph clearly shows the inconsistency of the press die (right hand box outer). On the 7th of February 2023 a record of 81 parts were scraped which is the highest number recorded of scrap at the organisations stamping plant. Furthermore, the bar graph shows that every scheduled press run there was always parts that were being scraped for right-hand box outer. The data gathered for both charts was taken from the roamer arm system used to measure the material flow of the dies.

Comparison on the figures show that the right-hand die was not designed the same way as the die of the opposite side. From the conceptual stage the die of right-hand side was poorly designed. The tool is supposed to be designed as a mirror made for both side but in this situation, it was found that there was no mirror made design. Hence there was a lot of deviation when comparing the two dies.

On the figures clearly the draw bead that hold the material to flow are far from each other, making it difficult to have a better flow. The die was supposed to be exactly like figures as shown that the draw beads are closer to each other making the flow of material better.

Plan effectiveness

The below figure shows that after the rectification of the die there was significant improvement in reducing the scrap cost of the box outer. The measures and control that were implemented reduced that scrap rate to a negligible number.

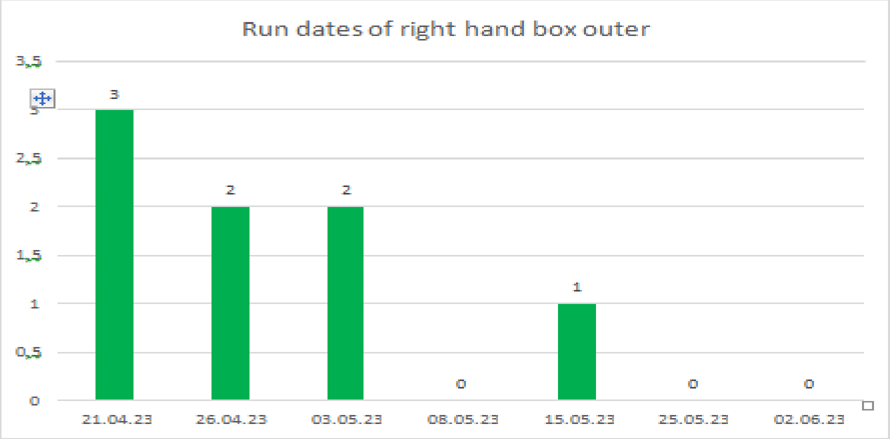


Figure 7: Improvement in the scrap rate

The figure shows a great reduction in the amount of scrap that was generated from the correction of the die. The projected savings of the project amounted to R382 800,00 which was being lost to scrap.

6 RECOMMENDATION AND CONCLUSION

The use of DMAIC methodology was of great importance in assisting to resolve the right-hand side box of the vehicle. It leverages on an analytical approach to make fool-proof and data driven changes. The methodology follows a top-down approach, and it allows equal participation as the process is easily understandable.

This methodology helps in building the team coordination and communication which directly affects overall performance and creates a vibrant team that is eager to solve problems in the organisation. The brainstorming event where all stakeholders participated was one of the highlights of the research study. People were giving different ideas on how to best solve this problem. It is evident enough to conclude that the design of the die on right-hand side box outer was poorly designed from the conceptual stage.

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IMPLEMENTING RISK BASED INSPECTION AND MAINTENANCE IN THE POWER INDUSTRY

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ABSTRACT

The equipment's failure rate in the power plant industry is a significant problem that causes several downtimes and maintenance costs. This research evaluated the advantages and limitations of implementing Risk Based Inspection and Maintenance (RBIM) in the power plant industry. RBIM aims to highlight critical factors necessary for the implementation of maintenance by considering equipment failure risks. The study used a mixed methods approach involving case studies, a literature review, interviews, and analyzing data from some power plants. The findings highlighted the positive impact of RBIM on efficiency and effectiveness, emphasizing the potential for cost reduction and improved risk assessment accuracy. Key recommendations include transparency in reporting, early problem detection, and data-driven decision-making.

Keywords: risk management; industrial engineering; performance management

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1 INTRODUCTION

Asset management involves risk assessment, and its main idea is to assist businesses in taking a comprehensive view of their performance [1]. This comprehensive view covers the technical or commercial aspects of risk and the context in which they occur [1]. In the power plant sector, Risk Based Inspection and Maintenance (RBIM) objectives are often related to enhancing productivity, safety, asset effectiveness, and capacity utilization. Power plants are large-scale capital projects with the broad goal of energy security. The current energy supplier faces severe challenges in managing increasing operational, safety, economic, and legal requirements in severe global shortages of expertise and resources [2]. According to Simshauser and Wild [3], current power plants often operate at maximum design capacity and sometimes beyond to meet current electricity demand. Risk-based inspection gives users flexibility in terms of time management and optimization techniques. Risk-based inspection is a method that combines reliability techniques and risk assessment strategies to achieve an optimal maintenance schedule. Today, risk-based inspections are quickly becoming a popular tool that is reported to offer enormous benefits to factories and other facilities [4]. Previous studies have reported significant benefits, including improved plant availability, reduced failure rates, reduced failure risk, and reduced direct inspection costs.

2 LITERATURE REVIEW

Risk-based assessment develops cost-effective inspection plans and ensures regulatory and corporate requirements compliance. RBI has found extensive application in the chemical and oil and gas industries.

2.1 The Goal Of Risk-Based Inspection

The primary goal of the risk assessment process is to prioritize equipment for inspection based on failure rates. This enables organizations to concentrate their inspection efforts on high-risk equipment while avoiding excessive inspection of low-risk equipment. The failure rate is quantified as the product of the Probability of Failure (PoF) and the Consequence of Failure (CoF). PoF assessment considers various factors influencing equipment failure rates, such as degraded mechanisms, degradation rate, operational conditions, equipment design, past inspection effectiveness, and equipment age [5]. Common degradation mechanisms in risk-based inspection assessment encompass general or localized thinning, stress corrosion, cracking corrosion under insulation, brittle fracture, embrittlement, and fatigue. CoF evaluation considers factors affecting the severity of hazards in the event of a hydrocarbon release, including the substance within the equipment and process conditions.

Consequently, risk-based inspection considers four categories of consequences: personal safety and health impact, environmental impact, product losses, and facility repair costs. The results of PoF and CoF assessments are combined and depicted in a risk matrix to communicate the risk assessment outcomes. As a result, higher-risk equipment receives greater inspection priority, necessitating more frequent and stringent inspection techniques to mitigate the risk of failure. Risk acceptance levels are typically employed to determine whether inspection planning can reduce the equipment failure rate to an acceptable level. In essence, inspection does not directly address performance degradation mechanisms but instead reduces uncertainty about equipment health as organizations act appropriately based on inspection results [6].

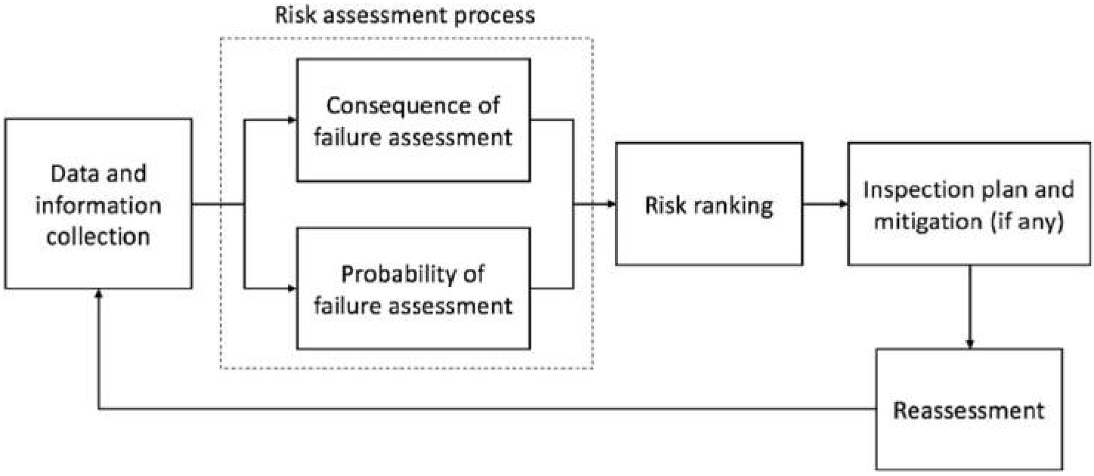

Figure 1: Generic RBI methodology

Activities related to risk mitigation are only necessary when the inspection efforts fail to effectively reduce the equipment's rate of failure (RoF). This scenario typically occurs when the equipment has a low Probability of Failure (POF) and a high consequence of Failure (CoF) [7]. Since inspections can only lower the POF, it becomes imperative to implement mitigation measures, such as establishing an integrity operating window or upgrading hazard detection systems, to reduce equipment failure rates. In many processing systems, a significant portion of the overall risk is concentrated in a relatively small percentage of the equipment. Therefore, a screening assessment is performed before a detailed examination to identify equipment significantly contributing to the system's failure rate. This allows for a thorough evaluation focusing solely on high-risk items [8].

Risk-Based Inspection (RBI) involves assessing the likelihood and potential impact of failure to optimize inspections based on risk understanding. The conventional approach of conducting routine plant inspections at fixed time intervals by competent individuals is widely recognized as having several drawbacks [9]. This approach can be overly cautious and miss opportunities to benefit from positive operational experiences. Legislation focusing on goal setting has encouraged a shift towards risk-based strategies prioritizing inspection resources on higher-risk plant components. Prioritising the prevention of failures in such components leads to the most significant benefits [9].

RBI is a process that seeks to strengthen and guide planned plant inspections. Failing to carry out these inspections as intended poses challenges to realizing the benefits of RBI [9]. RBI acknowledges that it is not prudent to invest significant resources in frequently inspecting something improbable to fail or would have minimal financial or safety consequences [11].

Several studies have explored the application of machine learning techniques in the oil and gas industry's inspection and diagnostics field. Models based on data analysis were developed to assist oil and gas pipeline operators in evaluating pipeline conditions and planning inspections, maintenance, and refurbishments [12]. These models considered various pipeline characteristics such as age, diameter, coating condition, metal loss, crossings, free spans, operating pressure, and cathodic protection. The model output provided an overall pipeline condition rating from 0 (worst and critical) to 10 (perfect and excellent), with an average validity score exceeding 96%. [13] improved these models using a neural network (NN) instead of regression analysis as the learning algorithm, resulting in an improved average validity score of 97.4% [13].

Risk-Based Inspection (RBI) is a strategic methodology for assessing and managing risks associated with the reliability of pressure systems. Its objective is to reduce or eliminate these risks to an acceptable level. As described by Millar, RBI serves as a framework for prioritizing and managing inspection activities to ensure cost-effectiveness while adhering to applicable regulations, industry standards, and company criteria [13].

The RBI assessment's outcomes encompass the following elements:

- Prioritization of high-risk components: Establish a sequence for inspecting components at high risk, followed by those at medium-high risk before they reach a critical stage. Keep a watchful eye on medium and low-risk components, scheduling inspections as they approach a high-risk threshold.
- Determination of inspection intervals: Evaluate the time it takes for an identified risk to realize and define the suitable inspection frequency prior to that point. Ensure the inspection intervals are not too close to the expected risk occurrence time, considering potential delays in the inspection process.
- Identification of anticipated damage mechanisms: Scrutinize component data, encompassing design specifications, operational records, and past failures, to pinpoint the expected forms of damage.
- Selection of the most effective inspection method: Opt for the inspection techniques best suited for detecting the anticipated damage mechanisms.
- Data prerequisites for continuous enhancement: Execute process audits to identify and rectify any deficiencies in the performed work to improve the process. Engage in benchmarking endeavors, gather insights from past experiences, and refine the RBI process accordingly.

Numerous organizations that have implemented RBI (Risk-Based Inspection) have reported surpassing their initial expectations in terms of improvements in reliability, safety, and financial outcomes [14]. Here are some suggested strategies for effectively implementing the RBI process:

i. Establish a well-structured and operational Document Management System to facilitate quicker data collection through easy document retrieval.

ii. Create a robust RBI assessment tool, like a spreadsheet or software, based on specific standards (e.g., API 580/581, RIMAP-CWA 15740, SANS 347, etc.). Ensure the tool's ability to receive regular updates as standards evolve.

iii. Verify the quality of data collection. After inputting data into the RBI tool, it's crucial to validate its accuracy, sourced from various places by a plant expert. They should confirm its practicality and correctness, ensuring it aligns with the plant's reality. This step is vital as precise plant data directly impacts the effectiveness of risk assessment and decision-making.

iv. Assemble a diverse Risk Assessment Team with highly qualified and experienced members capable of making well-informed decisions. Personnel safety relies on the team's judgments and relevant legislation.

Strategically determine inspection intervals to harmonize inspection schedules across all plant areas to prevent unnecessary plant shutdowns. Coordinating inspection schedules minimizes downtime, leading to enhanced plant productivity.

v. Essential documentation of inspection requirements, including design drawings indicating NDT inspection positions and any supporting documents that clarify instructions for the inspection team [14].

vi. Prioritize RBI scopes based on risk ranking for upcoming downtime inspections. Executing these inspections is critical because required risk mitigations cannot reduce risks without proper implementation.

vii. Ensure the competence of resources through continuous training for all personnel involved in the RBI process. This training can be formal classroom sessions or practical on-the-job training. Having multiple resources trained in RBI assessment to maintain skills is advisable.

viii. Conduct audits to evaluate the implementation process of RBI against RBI procedures, fostering ongoing process improvements.

Collaborate with other organizations that have adopted RBI through forums or similar platforms. Sharing lessons learned can significantly improve processes and prevent failures [15].

3 METHODOLOGY

For this study, the most suitable research design was a qualitative approach. Given the research topic's requirements, this choice stemmed from the necessity to collect and analyze qualitative data. It constituted a comprehensive framework enabling researchers to gather and scrutinize numerical and non-numerical data, offering a more thorough insight into the research problem.

The study is a case study focusing on one of the power station industries in South Africa. Statistical methodologies were subsequently employed to discern prevailing trends and patterns. The mixed-methods research design facilitated a holistic comprehension of the benefits and drawbacks of implementing Risk Based Inspection and Maintenance in power plant industries. It further enabled the triangulation of findings and data sources, enhancing the research's validity and reliability. The data verification process was emphasized to gather relevant data for this study. The data collected from 14 power stations in South Africa was presented and analysed, involving system engineers, metallurgists, maintenance personnel, and risk engineers from power stations.

The data presentation involved detailed information on the power stations, their capacities, commissioning years, and participants interviewed. The research employed an evaluation framework with 11 criteria to assess the effectiveness of RBI implementation, ranging from successful process implementation to audits and training assessment. Through interviews, audit findings, and analysis, the research evaluated the implementation of RBI, identified recurring audit findings, and assessed the effectiveness of the process across power stations.

The research also conducted cost analysis and simulation to assess RBI implementation's projected maintenance and downtime costs. An NDT supplier obtained quotes for maintenance scopes to enable cost comparison. The study involved factors like inspection intervals, downtime, and maintenance costs, demonstrating how RBI implementation influenced these costs.

Qualitative data were acquired through interviews, focus groups, and case studies, aiming to delve deeply into the perspectives and experiences of those involved in implementing Risk Based Inspection and Maintenance in power plant industries. Thematic analysis was applied to discern common themes and patterns.

In this regard, qualitative data will undergo content analysis to identify recurring themes and patterns, offering a deeper understanding of participants' perspectives, experiences, and attitudes toward Risk-Based Inspection and Maintenance. Conversely, quantitative data from closed-ended survey questions will undergo statistical techniques like descriptive statistics, correlation analysis, and regression analysis [16].

The study followed the research methodology that is summarised in Figure 2.

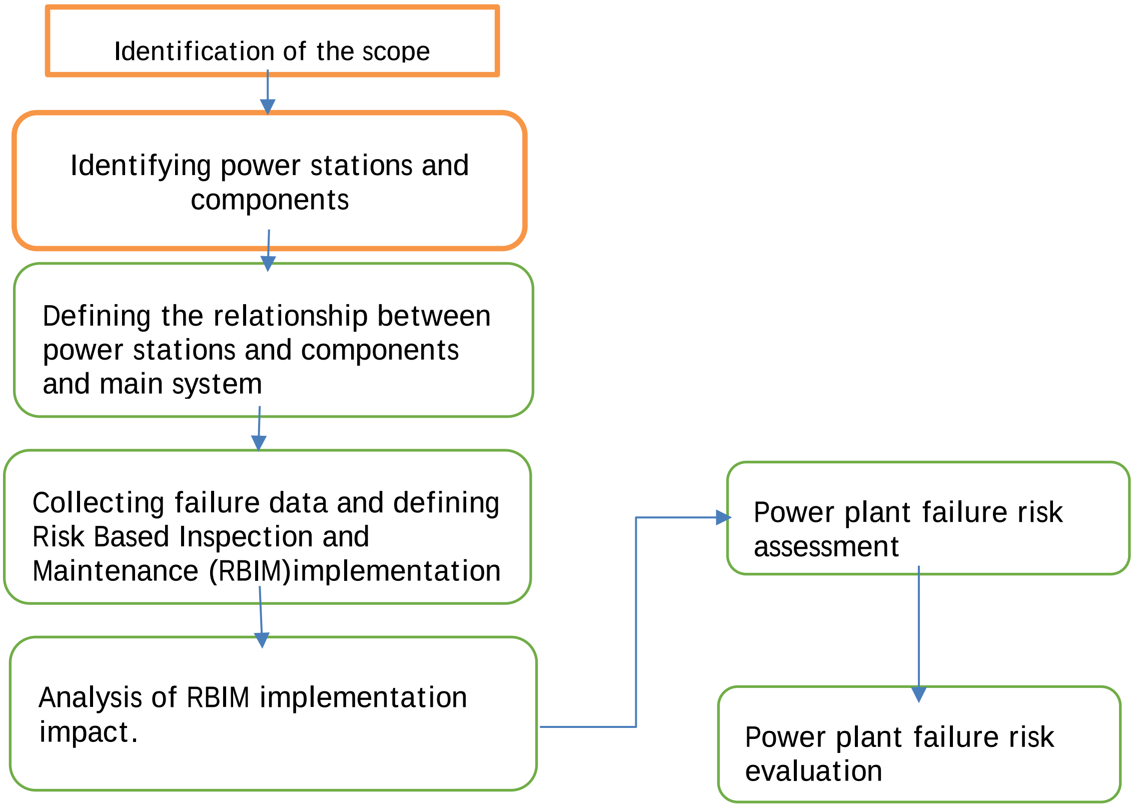

Figure 2. RBI critical methodology

The methodology showed the importance of the data's role in evaluating RBI's effectiveness in its implementation. The process flow details how the study was carried out and how it was supported to reach the study. Figure 2 provides a structure to achieve results and understand the implications of implementing RBI.

4 RESULTS AND DISCUSSION

The survey, which consisted of 11 benchmarks, as indicated in Table 1, was created to collect data and assess the effectiveness of the implementation of the RBI Process. Table 1 showcases benchmark results.

Table 1: Assessing effectiveness

Standards	Explanations	Evaluation
1	Successful Implementation of the RBI Process	Monitoring Schedule: Compare the completion dates of actual tasks with the target completion dates.
2	Optimizing RBI Scope	Comparison of pre-and post-outage scopes of work submitted for execution, assessing any scope reduction due to process improvement and better understanding.
3	Execution of RBI Scope during Outage	Inspection Report Analysis: Compare RBI scopes submitted for outage with executed scopes through inspection reports.

4	Validity of Certificates of Compliance (CoC)	Examine the SAP/CoC validity list from the AIA/Statutory Compliance list to identify any CoCs affected by RBI/Mini-RBI implementation.
5	Unexpected Failures in Pressurized Components (RBI Assessed)	Review of Issue Classification and Occurrence Management Meeting/Production Risk Management Meeting Minutes to identify any unforeseen failures in RBI-assessed components.
6	Realizing Maintenance Cost Reduction	Evaluation of RBI maintenance scope execution quotations/payment invoices to determine if there's a reduction in maintenance costs.
7	Resource Training Assessment	Comparison between planned and actual execution of the training plan to assess resource training effectiveness.
8	Oversight of Steering Committee	Assessment of adherence to Terms of Reference (TOR) to verify if meetings occur as planned and address escalated challenges.
9	Documentation of RBI Process	Examination of expiry dates and accessibility of all documents, ensuring validity and common accessibility for all RBI participants.
10	Internal Audits of RBI	Analysis of Audit Findings to ensure closure/addressing of all nonconformities and opportunities for improvements identified.
11	External Audits of RBI	Review of Audit Findings to ensure closure/addressing of all nonconformities and opportunities for improvements identified in external audits related to RBI.

The benchmark results provided a better understanding of the implementation of the Power Station RBI and its effectiveness. The Power Stations RBI and Overall RBI effectiveness results demonstrated a better performance that increases good maintenance of the maintenance program.

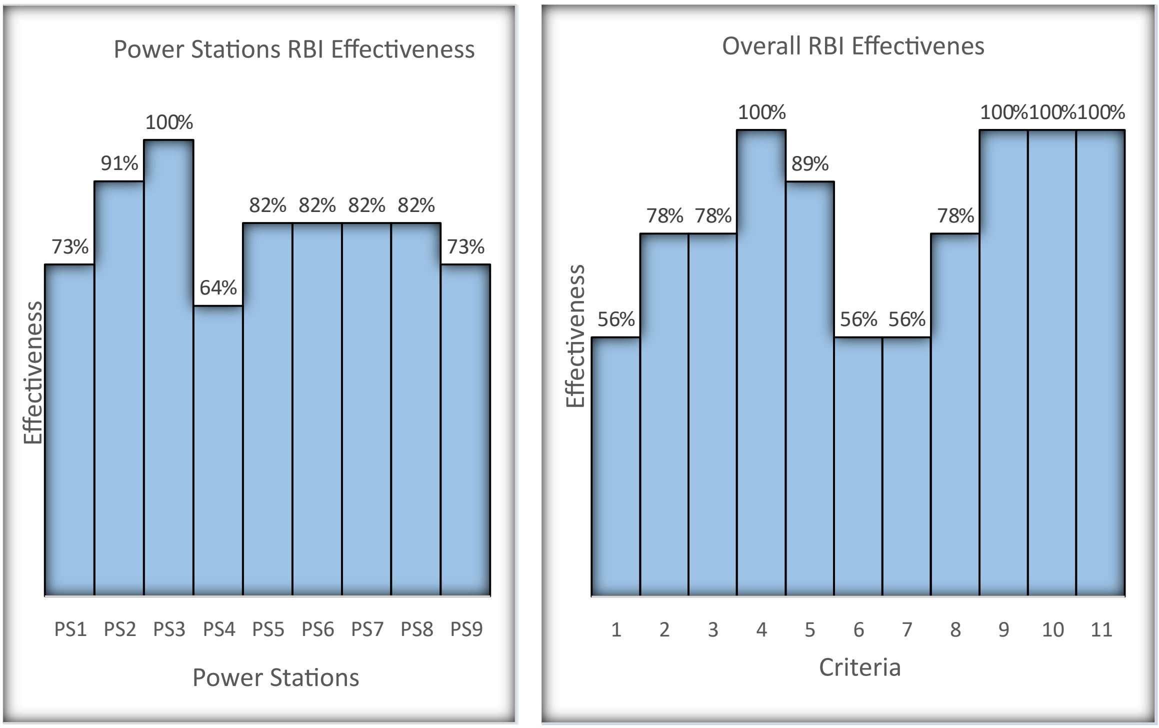

Figure 3. RBI effectiveness

The cumulative expenses associated with maintenance amounted to just 0.25% of the downtime costs for this power station during its previous RBI operation, and this figure decreased to 0.23% with the introduction of RBI. This finding is significant because it underscores the organization's potential for substantial financial improvement by minimizing power plant downtime. The study clearly illustrates that implementing RBI for power station one could lead to a remarkable 42.86% reduction in downtime-related expenses and a substantial 46.04% decrease in maintenance scope execution costs. The maintenance cost is reduced due to less time labor will spend maintaining power stations than power stations operating effectively.

The cumulative downtime costs reveal that significant production expenses are depleted due to frequent downtimes. Over 18 years before implementing RBI (Risk-Based Inspection), it was observed that approximately R 19.6 billion could be forfeited because of maintenance occurring every 36 months. This translates to an annual average loss of around R 1.1 billion, factoring in the initial downtime costs in year zero, which included seven outages totaling 910 days of downtime [17].

Audit findings revealed common issues such as deviations between RBI recommendations and executed inspections, data input errors, and lack of risk assessment updates. Interviews with risk engineers were conducted to evaluate the effectiveness of RBI implementation across power stations. The overall efficacy was ass per power station and per evaluation criterion. The results showed variations in effectiveness among power stations and criteria, highlighting areas of improvement and success [18].

The findings presented in this study underscore the significant impact of RBI (Risk-Based Inspection) implementation on efficiency and effectiveness within the context of the case study. The study's focus on Power Stations 1 and 2 demonstrates the tangible benefits of adopting RBI strategies.

Regarding efficiency results, the research highlighted that the traditional approach of quoting lump sum values by NDT service providers led to challenges in accurately assessing maintenance scope execution costs. By breaking down costs to the inspection technique level, direct comparisons of component scopes across outages became possible. This process facilitated scope reduction optimization, leading to substantial cost reductions.

For Power Station 1, implementing RBI resulted in considerable reductions in both downtime and maintenance costs. The analysis revealed potential savings of approximately R 8.4 billion in downtime and R 22.1 million in maintenance costs. Similarly, for Power Station 2, RBI implementation exhibited remarkable results, potentially saving R 7.7 billion in downtime and R 1.09 million in maintenance costs over the same timeframe.

Effectiveness results highlighted key fundamentals through audit findings and interviews. The incorporation of RBI scopes into the SAP system was identified as a crucial step in mitigating recurring findings. The results highlighted the role of SAP tools in streamlining scope submission, reducing duplication, and improving overall risk assessment accuracy. Additionally, the analysis showed varying levels of effectiveness across different power stations, with Power Station 3 demonstrating the highest effectiveness at 100% and Power Station 4 the lowest at 64%. These variations were attributed to factors such as SAP integration, data validation, and the presence of experienced stakeholders during risk assessment sessions [19].

The study’s comprehensive approach emphasised the organization-wide impact of RBI implementation. By incorporating lessons learned and improvements recommended from the assessment, the study concluded that audit findings and lessons learned significantly enhance the RBI implementation process. The findings highlight the potential of RBI strategies to dramatically enhance efficiency, reduce costs, and improve risk assessment accuracy within power plant maintenance operations.

The findings in this study presented a comprehensive understanding of RBI implementation, including its benefits, challenges, and impact on maintenance costs. The research identified areas for improvement in audit findings and provided insights into the varying effectiveness of RBI implementation across different power stations and criteria. This information can be a valuable resource for power plant industries aiming to optimize their maintenance strategies through Risk Based Inspection.

5 RECOMMENDATIONS AND CONCLUSION

Based on the findings presented and discussed in the study, several recommendations were formulated for implementing Risk Based Inspection (RBI) and maintenance in power plant industries. These recommendations are based on the benefits and shortcomings identified through data analysis, audit findings, and interviews.

5.1 Improved Incorporation of RBI Recommendations

The study found instances where RBI recommendations were not fully incorporated into the final maintenance scope. This can lead to additional maintenance inspections and tests after finalizing the scope. To address this, it is recommended that there be a better alignment between RBI recommendations and the final maintenance scope, ensuring that all identified components and tasks are correctly included. RBI optimizes resource allocation, enhances safety, and reduces downtime by placing critical elements in high-risk areas. Implementing RBI can have profound implications for the power sector’s performance in a country like South Africa, which has energy-intensive industries. For example, assessing boilers, pressure vessels, and piping systems using RBI can mitigate the risk of leaks, explosions, and other hazardous events, ensuring the safety of workers and surrounding communities [20].

5.2 Data Accuracy and Quality Control

Data input errors were identified as a recurring issue affecting the accuracy of RBI assessments. Organizations should implement stringent data quality control measures during the RBI process to mitigate this. Regular training and review of data input should be conducted to minimize errors that can lead to incorrect assessments. Implementing robust data accuracy and quality control measures requires a multifaceted approach. Advanced sensors and instrumentation technologies can aid real-time data collection with reduced human intervention, enhancing accuracy. Automation and integration of data management systems, combined with regular calibration and maintenance of equipment, can contribute to improved data consistency and reliability) [21]. Additionally, the adoption of international standards for data collection and reporting, such as ISO 9001, can help establish a structured quality control framework).

Ensuring data accuracy and quality control can yield significant benefits for power plant industries in South Africa. Accurate data facilitate informed decision-making, leading to optimized operational performance and reduced costs. Enhanced data quality supports compliance with environmental regulations, which are increasingly stringent globally [21]. Moreover, improved data accuracy contributes to grid stability, minimizes energy losses, and fosters a more sustainable energy sector, aligning with South Africa's commitment to renewable energy [22].

5.3 Enhanced Inspection Reporting

The study identified instances of poor inspection reporting, mainly when alarming results were obtained. It is recommended that inspection reports provide detailed measurements, analysis, and fit-for-service (FFS) calculations when results indicate potential issues. This transparency is crucial for informed decision-making. Enhanced inspection reporting aids in identifying potential equipment failures and safety hazards. Regular inspections allow for early detection of issues, preventing catastrophic failures that could lead to operational disruptions or accidents. Correctly reported inspections lead to timely maintenance and repairs, thus ensuring the reliability of power generation. Comprehensive inspection reports provide detailed insights into the condition of equipment. This information enables power plant operators to allocate resources efficiently by prioritizing maintenance tasks and replacement decisions. Optimized resource allocation leads to cost savings and improved overall operational efficiency.

The power plant industry is subject to stringent regulations to ensure environmental protection and worker safety. This data-driven approach enhances decision-making processes, leading to improved operational outcomes.

5.4 Risk-Based Approach for RBI Multilevel Assessment

The RBI level assessments are essential for power plant industries in South Africa due to their potential to mitigate operational risks while optimizing maintenance practices. Traditional time-based inspection approaches often result in unnecessary maintenance, leading to increased downtime and costs. A risk-based approach, however, allows plant operators to focus their efforts on critical equipment and components, ensuring that resources are allocated where they are most needed. This approach improves operational efficiency, helps achieve regulatory compliance, and reduces the likelihood of accidents.

Organizations should adopt a risk-based approach to determine the appropriate level of assessment and ensure that the necessary inspections are performed when warranted. The power plant industry is capital-intensive, and any approach contributing to cost reduction while maintaining operational integrity is precious. RBI-level assessments enable the optimization of inspection and maintenance activities. Instead of following a fixed schedule for all equipment, resources are allocated based on risk, ensuring that inspections and maintenance are performed where needed. This approach helps reduce unnecessary downtime and associated costs and avoid premature replacement of components still in serviceable condition [23].

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DEVELOPMENT OF BERTH PERFORMANCE MEASUREMENT SYSTEM: AN OVERALL EQUIPMENT EFFECTIVENESS PERSPECTIVE

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ABSTRACT

South African refineries manufacture and distribute various products to their customers. These products are distributed via railway, road by trucks, and coastal by ships. In 2020, PetroSA had mechanical faults, so Astron and ENGEN refineries had major fire incidents, and all three refineries were shut down, reducing product supply. In 2022, the SAPREF refinery was flooded during the April floods, and the refinery was also shut, which reduced product supply even further while demand remained constantly high, especially for diesel products. This reduction in product supply was mitigated by buying finished products from other international suppliers to meet South Africa’s product demand through the coastal infrastructure. This paper aims to measure terminal equipment effectiveness to establish equipment performance measurement in shipping operations using Overall Equipment Effectiveness principles.

Keywords: maintenance strategy; industrial engineering; performance management

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1 INTRODUCTION

For every production company, the objective is to produce goods at a profit, and this can only be achieved using an effective maintenance system that helps maximize equipment availability by minimizing equipment downtime due to undesirable stoppage, according to [1]. Overall equipment effectiveness (OEE) measures how well production process equipment is utilized against its total capacity during the periods when it is expected to run. According to [2], OEE is a tool for measuring production equipment's effectiveness and identifying the problem areas. This then leads to developing improvement plans to reduce the negative impact on scheduled production. The overall equipment effectiveness (OEE) is a critical measure that indicates the total effective equipment performance compared to the determined potential yield, which identifies blockages in the production process and sets new targets for improvement.

This paper presents the collection and analysis of data for shipping operations under actual working conditions that are representative of the current scenario. OEE of the system equipment will provide a valuable guide to aspects of the shipping operations and maintenance strategies. Moreover, stoppages are due to equipment failures, such as defective valves, pipe leaks, damaged hoses, and faulty instruments. FMEA was applied to identify the critical equipment that required further improvement through an effective maintenance strategy.

With the high import rates, there is an increase in berth equipment failures, causing berth operations to be stopped to restore equipment operation or to switch over to redundant equipment. This increases the ship's turnaround time and creates a risk of running out of products inland. When ships are delayed 24 hours from the allocated shipping time, there is a demurrage fine of 30000 USD/hour SAPREF must pay, which results in profit margin losses. The berth equipment has proactive maintenance activities; some are time-based, and some are condition-based, which should minimize the amount of equipment failure. However, random equipment failures still result in reduced capacity or complete stoppages and cause shipping delays. With high import rates, there is an increase in berth equipment failures, causing berth operations to be stopped.

2 LITERATURE REVIEW

a. Overall Equipment Effectiveness

Sahu el al. [3] suggests that OEE is a quantitative measure in a manufacturing plant for assessing and controlling production equipment effectiveness. It comprises three essential components: Availability, productivity, and quality. According to Kamath and Rodriques [4] availability considers any events that results in stoppage of planned production for a significant length of time (about several minutes or long enough to log as a trackable event). Performance rate takes into consideration speed losses vs what the equipment can do. Quality rate is a ratio of the excellent quality produced and total produced items and considers quality loss. The OEE is used to measure or/and to handle uncertainty when production is interrupted due to failures, temporary malfunction, set-ups, minor stoppages, idling, speed losses, and quality defects. The use of OEE, not only as an operational measure but also as an indicator of process improvement activities, remarks that OEE provides an excellent perspective on production improvement but should be balanced by other, more traditional operational measures, thereby retaining an overall perspective of the manufacturing environment. The main objective of the OEE is to reduce complex manufacturing problems quickly, aiding in improving the procedure with systematic measurements that are simple to obtain. OEE embraces the empowerment of production operators, establishing a sense of ownership in their daily operating equipment.

b. TPM

Jangaler and Ranganath [5] suggests that maintenance has a high impact on production costs and suggests that we assess maintenance problems that are significant enough to be resolved. Total Productive Maintenance (TPM) is a methodology focused on increasing the availability of existing equipment. Maintenance practices and tools comprise reactive, scheduled, and proactive maintenance (PM). Further detailed research found that reactive maintenance (CM) cost is about three times more than the same repair conducted in proactive maintenance [6]. TPM focuses on maximizing the OEE by involving everyone in the company. TPM is a stepwise strategy combining productive and preventive maintenance features with total employee engagement to maximize OEE [7]. OEE measurement is inspired by the TPM and OEE evaluation, critical machine performance tools that measure availability, performance, and quality rate. As an aggressive maintenance strategy, the TPM approach improves equipment performance by avoiding failure.

c. FMEA

FMEA is a proactive analysis performed before a failure occurs, requiring a team effort to identify and mitigate possible equipment failure. According to Munoz-Villamizar et al.[8], dealing with failures after they have occurred is an example of reactive maintenance. Once a failure mode is identified, it is possible to identify the impact of failure on the process and assess what can be done to minimize its effects when failure occurs [9].

Maintenance management strategy

Equipment maintenance must be done very carefully and promptly to avoid machine failure. The maintenance strategy that is applied on the ice cream production line is:

- **Breakdown maintenance**: this refers to the maintenance when the equipment fails or the equipment performance declines. In this type of maintenance, machines are serviced only when maintenance is drastically required. This concept has the disadvantage of unplanned stoppages, excessive damage, spare parts problems, high repair costs, excessive waiting and maintenance time, and high troubleshooting problems [12]. The main stages are stopping the machine, diagnosing the failure, finding spare parts, repairing the failure, controlling and re-opening. In this case, maintenance occurs after a failure, which means high cost, many person-hours, and long stoppage times for the line.

- **Preventive maintenance**: in this type of maintenance, a physical equipment checkup is performed to prevent equipment breakdown and increase equipment service life. The maintenance function is established in this phase, and time-based maintenance activities are generally accepted [8]. The preventive maintenance work includes equipment lubrication, cleaning, parts replacement, tightening, and adjustment of nuts and bolts.

- **Condition-based maintenance**: This technique is used to measure the physical condition of the equipment, such as temperature, noise, vibration, lubrication, and corrosion [13]. Maintenance initiatives are undertaken to restore the equipment to the desired condition when one of these indicators reaches a predetermined deterioration level. This means that equipment is taken out of service only when direct evidence exists that deterioration has taken place. Condition-based maintenance is premised on the same principle as preventive maintenance, although it employs a different criterion to determine the need for specific maintenance activities. This maintenance type tends to apply to the company's maintenance policy. It is considered by the technician to be the most suitable because it is more economical than preventive maintenance since preventive maintenance does not exhaust the life of spare parts, which translates into higher costs. Still, unnecessary maintenance work is drastically reduced, the personnel is freed from this work, and the production time and the availability of machines are increased.

3 METHODOLOGY

A qualitative research methodology was used to collect data from the birthing process. Data collected from equipment and shipping operations were necessary to determine the critical components of OEE (availability, performance, and quality). To assess berth performance, the study collected information from research participants. In-depth interview guides, observation guides, and interviewers were used to collect data. Observational data were collected through direct observation at the berths, documenting the operational processes, turnaround times, and equipment utilization. Secondary data were retrieved from port records, shipping logs, and performance reports to provide historical data on berth operations, vessel traffic, and cargo handling statistics. The population for this study includes all the stakeholders involved in berth operations at the target port, specifically berth operators, vessel crew members, port authorities, and management staff. Purposive Sampling was used to select participants with significant experience and involvement in berth operations, ensuring the data collected was relevant and insightful. The sample size was decided by the scope of the study and the need for strong data representation. Interviews were 20 in-depth interviews, including 5 port authority members, 5 berth operators, 5 shipping company representatives, and 5 logistics managers. Continuous observation over 2 months, covering peak and off-peak operational hours to ensure a comprehensive understanding of berth performance. Thematic analysis was used to categorize qualitative data into major themes and sub-themes, facilitating a deeper understanding of stakeholder perspectives on berth performance.

It was used to identify the related losses of the equipment to improve total asset performance and reliability. The losses that reduce the effectiveness of the equipment could be classified into six major categories below:

a. Equipment failure losses, contained failure modes that stop the regular operation of the equipment and reduce its production rate

b. Setup and adjustment losses, that is, time losses that occur when production of one item ends, and the equipment is adjusted to meet the requirements of another item

c. Losses of minor stoppage and idle: these occur when the production is interrupted by a temporary malfunction or when a machine is idle

d. Losses of reducing speed because of the drop in speed from the nominal speed of the equipment

e. Losses of the defect (or rework) in the process; and

f. Performance and material losses are reduced because of input and output weight differences.

It is a three-part equipment performance analysis tool based on availability, performance, and quality rate [10].

4 RESULTS AND DISCUSSION

Data collection and recording is a project developed in collaboration with the company. The company allowed the study to be conducted to find solutions that would benefit the company. Production managers, operators, and the technical and scheduling departments were all contacted frequently throughout this project to provide ongoing support. The shipping procedure is carried out in one or two successive daily shifts, depending on the production schedule. The business plan runs from January to December, with shipping activities occurring throughout the year based on demand. Scheduled maintenance windows are outlined in the business plan and incorporated into the yearly schedule. Engine lubrication of joints and cam locks, hydraulic oil system servicing, valve replacement, electrical flange insulation, and cleaning are examples of maintenance tasks [11].

The data for shipping activity was collected from the records of the company's maintenance department and the production supervisors during each shift. The data covered an entire period of six months. During this time, 356 failures were observed. In addition, they were recorded per shift: the total time of the shifts, total vacation time for adjustments/setups, equipment failure times, the line's net operating time, the number of acceptable products, and the number of defective products.

The inability of some refineries to continue operating means that inland product supply is dependent on imports via the docks, and terminal availability is essential to meeting product demand. The demand for berth operations is high due to the growth of imports, and berth equipment availability is improving. Data from the berth equipment failures will be gathered for this study to assess the berth performance. The effectiveness of process equipment would be measured using the Overall Equipment Effectiveness (OEE) to achieve this. The goods an online refinery produces are moved into IV storage tanks and pumped onto the ship using loading arms and product transfer pipes, which direct the product into the boat. With a refinery offline, the product is received from international companies, pumped from the ship through the loading arms, and processed pipes into the storage tanks where it is stored until required. Figure 1 below is the overview of the shipping operation.

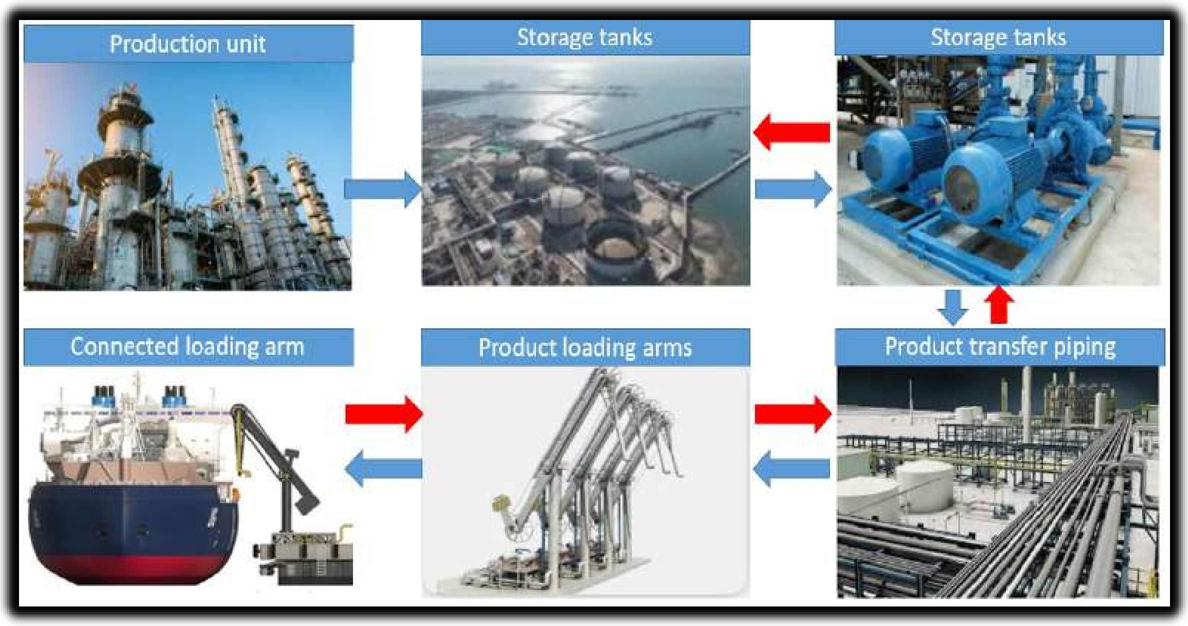

Figure 1: Overview of the shipping process

With the high import rates, there is an increase in berth equipment failures because of the intensive operation of the equipment. This causes berth operations to be stopped to restore equipment operation or to switch over to redundant equipment.

On ship arrival on the berth, the ship is connected to the shore through loading arms via a flanged assembly that ensures the integrity of the connection. Each berth has four loading arms: 3 for "white oils, "colorless oils, and 1 for fuel oils. KS valves are used to route a selected product to flow through. A tank is then lined up to receive or discharge a product. Once the shipping process starts, it continues until enough volumes have been moved, and then the ship is disconnected.

It was found that the OEE of the terminal equipment is currently 71%, which is 14% below the industry standard. The industry standard for manufacturing processes is 85% or higher. The most significant contributor to this score is equipment performance, which is 82%, which is the lowest of the three elements. These metrics can significantly impact the overall performance of the port, influencing operational efficiency, financial outcomes, customer satisfaction, and competitive positioning.

The inefficiencies in berth performance can lead to higher costs due to extended use of port facilities and equipment, additional fuel consumption, and increased labor hours.

The current Availability performance of 88% is achieved, which is above the current target and has been achieved most of the time. Availability for batch-operated plants is 95%. Therefore, it is recommended that the target of 85% be reviewed. Assessing the skewness of the availability data shows that the data is negatively skewed, and there is a potential to improve the process such that the data is usually distributed.

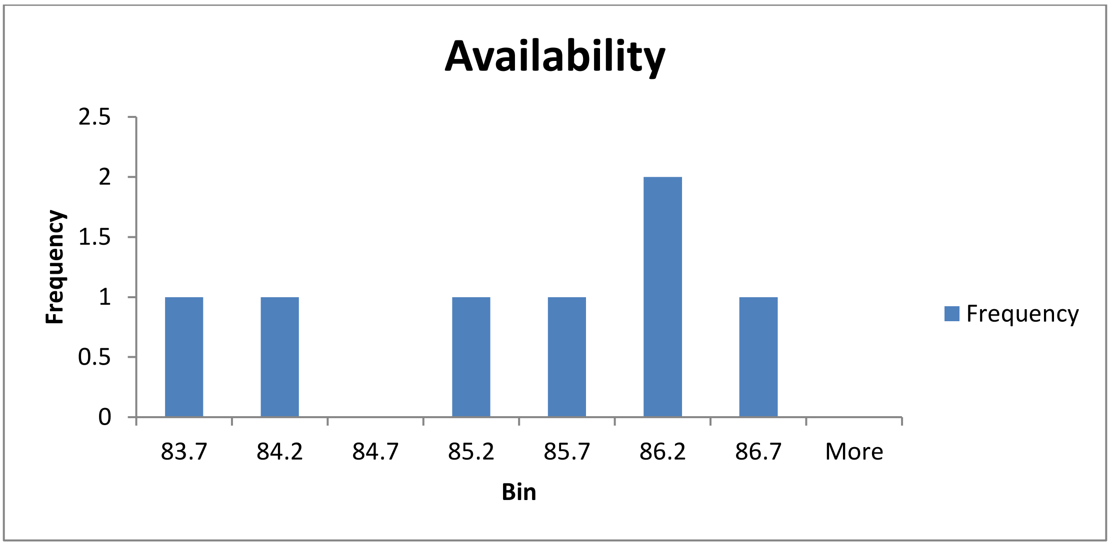

Figure 2: Availability skewness

The researcher assessed the highest contributor to the current availability score to identify low-hanging fruits and improve the score. It was found that the highest number of unplanned hours are due to equipment failures. The chart below indicates unplanned downtime categories and their contribution in percentage towards unplanned events.

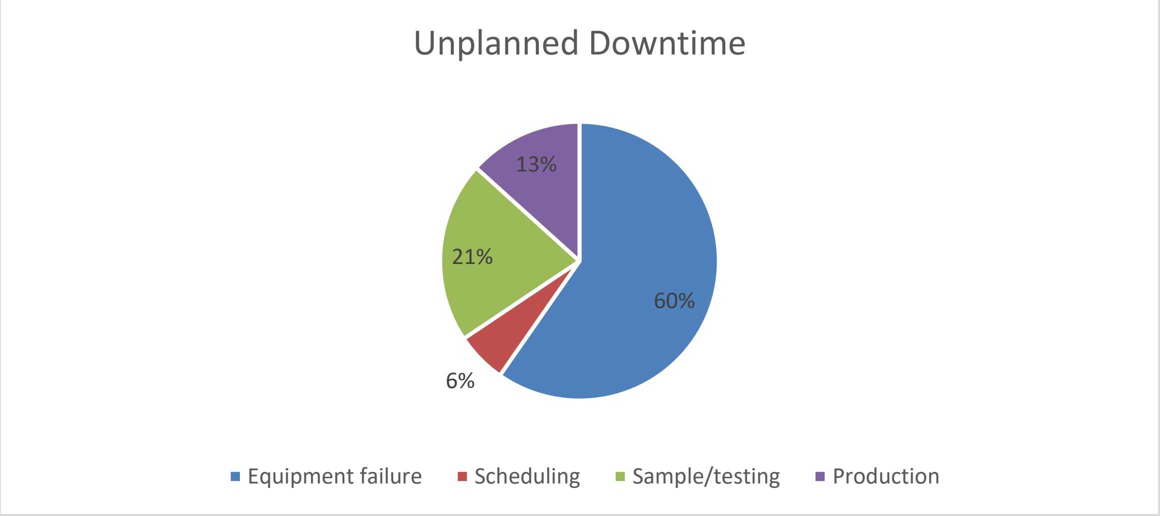

Figure 3: Unplanned downtime contributions

Equipment failure contributes to 60% of unplanned downtimes. The researcher suggests that identifying and categorizing inadequate actor equipment will help determine the cause of equipment failure and establish whether the failures are due to systematic configuration issues or poor operation or maintenance.

Findings on Pareto Analysis

The researcher identified valves, piping, and hoses as the most dominant failures. Valves were the highest failing equipment type. After assessing the type of equipment failure, it was apparent that the failures were due to common causes, and maintenance strategies were to be implemented.

In addition, the following were found:

- **There is no painting maintenance strategy**. Wall thinning to 0mm at a rate of 0.5mm/year resulted from the coating reaching the end of life, as confirmed by the Coating inspector. The coating function is to protect carbon steel from humidity and moisture. Maintenance of coating is necessary to sustain the protection. There are two layers of coating. The 1st layer is the barrier that protects the metal; however, this layer is compromised by UV. A 2nd layer is applied to protect the 1st epoxy-based layer from UV. External inspections are for corrosion; therefore, any corrosion findings mean that the coating has failed already, hence the need for a maintenance strategy for coated lines.
- **Unit checks/site walks do not include checks of the condition of line coating**. There is no priority in checking the coating condition; therefore, these have been run to failure. The absence of a clear distinction between areas of responsibility and 3rd party encroachment of our equipment results in not having unit checks or site walks for some of our equipment.
- **Lines at IV are generally not marked on the field**. Line identification is reliant on memory and the possibility of human error. If there are any findings in the field, it is impossible to enter on PACER due to the absence of field identification. This is, however, currently being addressed by the “Paint the Island” project.
- **The leak occurred on the MOGAS Ex Ref line, which is being used to transfer MOGAS from Site3 to Site2 via Site1**. It has a different line number at Site 3 (P-230390) and Site 2 (P-220170) but no line number at Site 1.
- **The position of the line where the leak occurred does not have a line number, nor does it appear on any EFD; hence, it is not registered on WIMS. Therefore, it cannot generate inspection schedules for the line and is** not being inspected.

Bathtub curve

After analyzing data based on the amount of time the equipment is in service before a failure occurs, the researcher was able to separate equipment types based on the time before failure and draw distinct characteristics of failure. It has been observed that some equipment fails soon after commissioning due to incorrect installation of the components and inaccurate material selection.

Some equipment is observed to fail randomly due to expected wear and tear, thus requiring frequent maintenance to maintain the equipment in a healthy status. Preventative maintenance will help determine when the failure will occur and perform maintenance interventions before the failure occurs, ensuring fewer disturbances in the shipping operations.

The researcher also observed that some of the equipment had more frequent failures after being in operation for an extended period, indicating that some equipment in service is old and needs to be replaced or upgraded to newer designs. Determination of asset life helps the company evaluate its return on investment to purchase upgrades that will last longer.

5 INVESTIGATION ANALYSIS/OEE CALCULATION

Availability: The researcher observed 63 shipping operations and recorded all shipping activities with assistance from the Production team. In the shipping activities, the delays were recorded, including the cause and duration. Based on the reason, each delay was assigned to either the Maintenance or Production team to assess areas for improvement. All Maintenance delays were due to equipment downtime, split between planned maintenance or faults that needed to be responded to. Shipping operations are expected to happen at any time and thus demand that all terminal equipment be available 100% of the time, 24 hours a day. All the delays from the shipping operation are subtracted from the total available time to obtain terminal Uptime. The formula below is then used to calculate the availability of the terminal:

$$Availability = \frac{Available\ time - Down\ time}{Available\ time}$$

$$Availability = \frac{2232 hours - 277 hours}{2232 hours}$$

$$Availability = 88\%$$

SAPREF has three main Berths for ships: Berth6, Berth7, and Berth8. Each Berth consists of 4 loading arms connecting the boat to the shore, and they are the primary means of product movement from/to the ship. When the boat arrives at berth, the ship name is documented for easy identification of the product. Below are assigned delays per berth for May 2023.

Performance: The researcher observed the planned production rates based on product types and recorded actual rates. There are various reasons why the equipment was not produced at planned production rates, including line sizing limitations, the product's viscosity, unavailability of equipment to support simultaneous loading, and poor equipment performance due to age. The actual production rates were divided with planned production rates to obtain the performance rate per the formula below.

$$Performance = \frac{Actual\ production\ rate}{Planned\ production\ rate}$$

$$Performance = \frac{5403.8}{6590}$$

$$Performance = 82\%$$

Quality: All processed product volumes were collected, and results from the lab were recorded on various ships and storage tanks before moving a product from source to destination. We use this formula to calculate the last element of OEE, Quality.

$$Quality = \frac{Processed\ amount - Defective\ amount}{Processed\ amount}$$

$$Quality = \frac{656356.575 - 16634}{656356.575}$$

$$Quality = 98\%$$

Now that all the elements of OEE are available, the researcher calculated the system's OEE using the formula.

$$OEE = Availability \times Performance \times Quality$$

$$OEE = 88 \times 82 \times 98$$

$$OEE = 71\%$$

The industry standard for manufacturing processes is 85% or higher. The score of 71% is 14% below the standard.

The researcher found that the OEE of the terminal equipment is currently 71%, which is 14% below the industry standard. The industry standard for manufacturing processes is 85% or higher. The most significant contributor to this score is equipment performance, which is 82%, which is the lowest of the three elements. The researcher recommends that an RCA be conducted to uncover the underlying causes of the poor performance of equipment.

The researcher also identified the current Availability performance of 88%, which is above the current target and has been achieved most of the time, as indicated in the chart below. According to [13], the Society of Maintenance and Reliability Practitioners suggests that the availability of batch-operated plants must be above 95%; therefore, the researcher recommends reviewing the target of 85%.

The graph below shows an indication of the type of equipment failure and when the failure occurs. It is also used to guide what maintenance strategy can be employed.

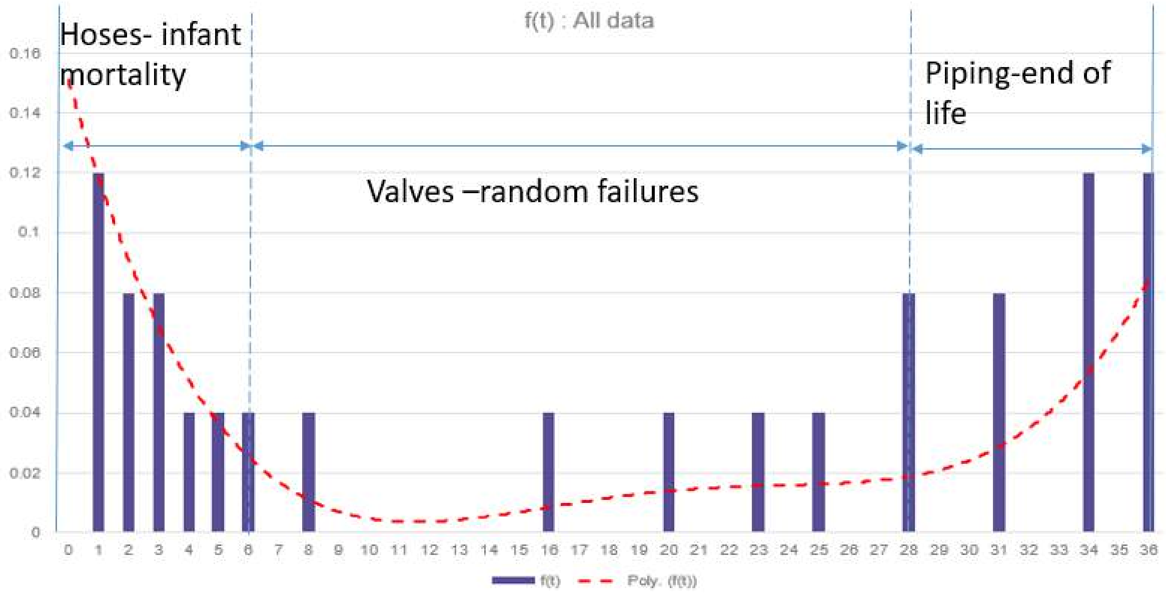

Figure 3: Type of equipment failures

In this study, equipment availability and performance impacted OEE significantly. The most significant contributor to low availability was equipment failures.

The implication of low OEE in berth performance has far-reaching consequences for a company, affecting operational efficiency, financial performance, customer happiness, and competitive positioning. The ports may improve their berth performance, increase service reliability, and maintain a competitive edge in the industry by recognizing the underlying issues and applying tailored solutions to address them.

6 RECOMMENDATION AND CONCLUSION

The study identified frequent failing equipment and further analyzed that on most failing equipment, there was no proactive identification of possible failures and mitigation to prevent the failures. Thus, there is a lack of preventative maintenance strategies. Below are recommendations to improve the system's performance and increase equipment availability.

The objective and purpose of this study were to identify existing equipment performance assessment/monitoring tools and to identify areas of improvement to enable shipping operations to continue without interruptions of equipment failure. After collecting and analyzing data, it was observed that equipment failures are due to human error during operation or maintenance.

Equipment failures have increased due to the increase in the number of operations being performed since the start of import mode. When applying the FMEA methodology, it has been visible that maintenance practices were able to restore functionality quickly to enable shipping operations to resume. Thus, there has been little focus and effort on understanding equipment failures at a deeper level. FMEA helps to look at all possible causes of equipment failure instead of the current route cause approach, which is standard practice for equipment failure.

The organization does not have an effective equipment performance measurement tool because the current focus is on ship servicing and not on the shipping delays, which are captured on every boat and identify delays like sampling, shift changes, equipment failures, product routing, and scheduling constraints. Data segregation has not been adopted to highlight equipment failures and poor performance. There has been no continuous improvement in shipping operations as equipment failures persist since OEE has not been applied previously. In this study, equipment availability and performance impacted OEE significantly. The most significant contributor to low availability was equipment failures. The study identified frequent failing equipment and further analyzed that on most failing equipment, there was no proactive identification of possible failures and mitigation to prevent the failures. Thus, there is a lack of preventative maintenance strategies.

The strategy forward would be to re-evaluate the status and develop a maintenance strategy using FMEA as a primary tool to focus on particular areas of attention in the process.

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UTILISING VALUE STREAM MAPPING IN IDENTIFYING WASTE AND IMPROVEMENT STRATEGIES IN COMPONENT MANUFACTURING

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ABSTRACT

During the latter half of the twentieth century, numerous business sectors underwent profound transformations due to global investments, technological innovation and the deregulation of various industries. One highly regarded solution within the realm of manufacturing engineering is value stream mapping (VSM), a lean technique, which serves as a fundamental tool that helps to identify wasteful practices and reduce process cycle times, as well as to facilitate process improvements. This study focuses on a manufacturing engineering organisation that produces automotive components in distinct product families, each available in numerous configurations. This study is qualitative in nature using a case study methodology. Through the application of VSM, it became evident that productivity enhancements can be achieved by eliminating non-value-added activities in the production process. For the purposes of this study, only the material handling aspect is considered.

Keywords: value stream mapping; industrial engineering; performance management

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1 INTRODUCTION

In today's highly competitive and rapidly evolving manufacturing landscape, the ability to optimise production capacity stands as a paramount concern for organisations across industries. Meeting the ever-increasing demands of the market, while maintaining operational efficiency and profitability, requires a systematic approach to identifying and addressing the bottlenecks and inefficiencies that often plague production processes. Nowhere is this challenge more evident than in the realm of component manufacturing, where precision, efficiency and consistency are not merely goals, but imperatives.

The field of component manufacturing is characterised by its intricacy and reliance on precision engineering, making it particularly vulnerable to production capacity constraints. Component manufacturers, often, find themselves grappling with insufficient production capacity, which not only hampers their ability to meet market demands, but also incurs significant opportunity costs. These constraints arise from a multitude of factors, including process inefficiencies, equipment underutilisation, suboptimal resource allocation, and ineffective workflow designs. As a result, addressing these issues has become a pressing concern for companies in this sector.

The significance of this study lies in its potential to offer component manufacturers a roadmap for enhancing their production capacity, thereby allowing them to meet market demands more effectively, reduce operational costs and, ultimately, improve their competitiveness. By uncovering the strategies, methodologies and best practices associated with VSM in component manufacturing, this research aims to equip organisations in this sector with the knowledge and tools necessary to drive transformative change.

2 LITERATURE REVIEW

At its essence, value stream mapping (VSM) represents a visual tool that allows organisations to comprehensively assess their current state of operations. Derived from lean principles, VSM traces the flow of materials, information and activities through a manufacturing process, highlighting areas of inefficiency, bottlenecks and non-value-added activities. It serves as a foundational tool for lean practitioners that enables them to visualise the entire production process - from raw materials to the end product [1].

VSM is guided by the principle of value-addition, wherein every step in the production process is scrutinised for its contribution to the final product. Non-value-added steps, often characterised by delays, excessive handling or overproduction, are identified and targeted for elimination or optimisation. By adopting VSM, organisations can transform their operations from traditional batch-and-queue models, to a more streamlined, continuous flow system [2].

The application of VSM is a fundamental industrial engineering technique that can be applied as a strategy to observe a product through the production process. This may be coupled with the application of time and method studies to ascertain labour and machine time, production flow, ergonomics, and the value stream of each component. The broader context of lean manufacturing, VSM stands as a pillar of continuous improvement. It emphasises a holistic approach to process optimisation, requiring cross-functional collaboration and a commitment to eliminating waste, in all its forms. The principles embedded in VSM align closely with the core values associated with lean management, and these are customer focus, waste reduction, and a culture of continuous improvement [3].

The researcher’s experience with VSM's efficacy is well-established in sectors such as in automotive and electronics manufacturing, its adaptation and impact within the specialised sphere of component manufacturing deserve dedicated attention. The intricacies of component manufacturing, including the diverse range of materials, complex machining processes, and strict quality standards, present unique challenges that must be addressed when implementing VSM [4].

In recent years, research efforts have increasingly focused on tailoring VSM to the specific needs of component manufacturing. Studies have explored the customisation of VSM tools and methodologies to address issues related to production capacity, material flow and shop floor layout optimisation. These adaptations recognise that, while the core principles of VSM remain consistent, their application must be nuanced to suit the intricacies of different industries and processes [5].

As organisations in component manufacturing strive to meet the demands of a competitive market, the adoption of VSM emerges as a compelling strategy for optimising production processes, enhancing capacity and, ultimately, bolstering competitiveness. The subsequent sections of this literature review will delve into key themes and findings, from existing research, that shed light on the methods, outcomes, and best practices associated with the integration of VSM in component manufacturing. Through this exploration, the aim is to distil the collective wisdom that can guide organisations toward the attainment of optimal production capacity in this challenging and vital sector [6].

Lean Manufacturing is based on the Toyota Production system developed by Toyota which focuses on eliminating waste, reducing inventory, improving throughput, and encouraging employees to bring attention to problems and suggest improvements to fix them. It was pioneered by the Japanese automotive Toyota in the 1950s and became one of the best adaptable manufacturing practices by many automotive industries [7].

The role of value stream mapping in identifying capacity

Value stream mapping (VSM), a core component of lean manufacturing, offers a systematic and visual approach to analysing production processes. Through the creation of current state maps, VSM allows organisations to visualise the flow of materials, information and activities, making bottlenecks and inefficiencies apparent. VSM's ability to provide a holistic view of the end-to-end process, positions it as a potent tool for identifying production capacity bottlenecks [8].

The VSM methodology encourages organisations to map their existing processes, distinguish value-added from non-value-added activities, and quantify lead times and cycle times. By doing so, organisations can pinpoint areas where capacity constraints are most acute and prioritise improvement efforts accordingly. Additionally, VSM's focus on data collection and analysis facilitates informed decision-making, enabling organisations to diagnose the root causes of bottlenecks and the opportunity to develop effective countermeasures [8].

Optimising material flow in component manufacturing through VSM

The efficient flow of materials through production processes is not only a fundamental operational concern, but also a decisive factor in maintaining competitiveness. Streamlined material flow ensures that materials move seamlessly from raw inputs to finished components, minimising lead times, reducing waste, and enhancing overall productivity. Recognising the paramount importance of optimising material flow, manufacturing organisations have turned to methodologies, such as value stream mapping (VSM), as a systematic approach to achieving this objective [9].

The significance of optimising material flow in component manufacturing

The continuous improvement of material flow in component manufacturing is emblematic of an organisation's commitment to operational efficiency, waste reduction and customer satisfaction. Efficient material flow entails a continuous and uninterrupted movement of materials, minimising bottlenecks, excessive handling and delays. Such efficiency not only reduces lead times, but also enables manufacturing organisations to respond rapidly to shifting customer demands [9].

Moreover, optimised material flow contributes to reduced work-in-progress inventory, lower storage costs and improved resource utilisation. These operational efficiencies translate into cost savings and increased competitiveness, as organisations can produce components with greater agility and at a lower cost [10].

Customer satisfaction is another compelling motivation for optimising material flow. In today's globalised marketplace, customers demand not only high-quality components, but also punctual deliveries. Efficient material flow facilitates on-time deliveries, instilling trust and loyalty among customers and reinforcing an organisation's reputation as a dependable supplier [11].

3 METHODOLOGY

This section of the research study outlines the methodology employed in the study. It begins by explaining the research's focus, which is to address the logistic challenges faced by the case company, specifically to improve the efficiency of the in-plant material supply process.

To achieve the research objective, a qualitative methodology was applied using a case study as a primary means of data collection. The abductive research process was employed for data analysis. The case study centres on aspects of the organisation's movement of materials from the storage area to the assembly line. In this endeavour, the primary means of data collection was direct observation on the shop floor. The respective protocols od company policy was followed to ensure that all employees were comfortable for the study [12].The literature study contributed to the literature review section and drew foundational knowledge from industrial engineering disciplines, especially lean manufacturing and material handling while identifying non-value adding activities.

4 RESULTS AND DISCUSSION

This study focuses on a manufacturing engineering firm that produces four distinct product families, each available in numerous configurations. However, once an order is placed for a specific product, it takes approximately 60 days to navigate through the production process. This extended lead time, coupled with order backlogs, has compelled the firm to quote a 70-day lead time to its customers. The company caters for both the national and international markets and ensures that realistic lead times are used in the process. This section of the study presents an overview of the information direct observation, measurement and experience collected through the case study.

Case study

To meet customer requirements, materials for the assembly processes must be readily available to operators. If these materials are not on hand, the processes come to a halt, resulting in a "starving" situation. Furthermore, for operators to effectively produce products, the stations that follow must have sufficient capacity. Insufficient capacity leads to stockpiling of materials, eventually leading to a "blocking" scenario. It is essential to ensure that the assembly stations remain operational during scheduled production, without any interruption of the production line. The role of the management of inventory section is crucial, it deals with raw materials and semi-finished (sub-assembly) products that is supplied to the assembly line. The are a number of preparation sections and assembly sections. According to the organisation, the replenishment process was not running smoothly, and operators often faced material shortages, sometimes needing to retrieve materials from the fabrication line themselves.

The organisation also experienced issues with material flow, with the lack of materials making it challenging to meet customer orders. This, in turn, resulted in the production of defective products, due to the increased pressure to produce when materials became available. When materials must wait for the next process step, it becomes difficult to trace and identify the causes of defects, as many components were produced some time ago, and the reasons for the defects may have been forgotten or lost.

The purpose of the case study was to identify non-value adding activities within the material supply process and explore potential improvements that could enhance efficiency. These efficiency enhancements are crucial to remaining competitive in a highly competitive market.

a. Material handling and transportation

The process of supplying materials involves various elements, including different activities, load carriers, and storage systems. These elements represent diverse variables that play a role in determining the effectiveness of the material supply process. You can refer to Figure 1 for a visual depiction of the process flow in relation to the material supply at the organisation.

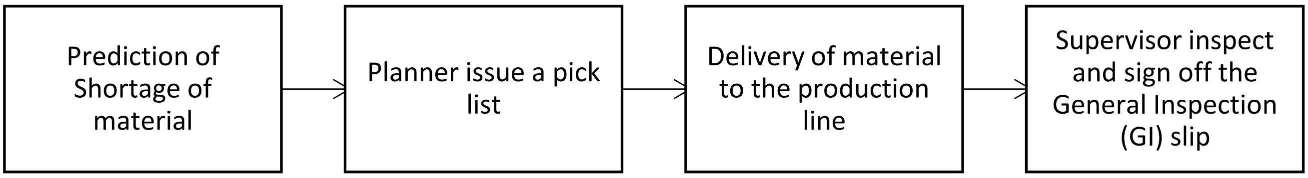

Figure 1: Process flow of material to organisation

In the material supply process, certain materials must pass through the fabrication line, before reaching the final assembly, while others have a direct route to assembly. Furthermore, the quantities of materials required at each station vary, depending on the specific circumstances, making the restocking process intricate and challenging to manage.

Components within the warehouse are systematically placed in designated positions within the storage racks. Operators follow a specific storage policy, by allocating pallets to these locations, based on part numbers. Because the timing and routes for material supply are unpredictable, the internal transportation method employed is referred to as "General assignment milk-runs".

b. Material handling systems and processes

Various types of load carriers are employed, based on their size, weight and the level of demand. These load carriers encompass pallets and racks. Pallets are specifically utilised for storing inbound materials, before they go through kitting and picking operations. The restocking process within the material supply involves operators actively searching for empty carriers. When operators encounter empty carriers at the assembly line, they take the initiative to refill them. The inventory is divided into two distinct categories: the higher shelves are allocated for material storage, while the lowest shelf is exclusively designated for the picking process.

In the material supply process, the lowest shelf is designated as a kitting area for picking components. This kitting location requires frequent restocking of pallets. The organisation's material store typically supplies various assembly lines with material, and their picking process is segmented into three zones, each managed by a separate picking operator. These zones include the new build manufacturing line, the re-manufacturing line, and the fabrication line.

When an empty pallet is identified in the kitting location within storage, or when the quantity on a pallet does not match the required quantity for the production order, restocking is initiated. Following restocking, the picker and packer select items and load them onto carriers designed to accommodate a maximum of 3 products per day.

The material warehouse is strategically positioned near the assembly line, ensuring that operators have immediate access to the required materials, at the right time. All the components intended for the assembly are stocked in the material store. Larger components are stored on trolleys, while smaller components are stored on pallets and bins.

Within the material store, there are plastic and boxes that contain smaller components, such as bolts and nuts, which are all easily accessible. When these boxes are emptied, picker and packers retrieve the empty kits and restock them from the material supply inventory. The transportation process from the material supply to the assembly line varies, depending on the number of empty kits and pallets brought by the operator and the various locations that need to be visited.

The routing within the assembly line follows a straight-line layout. Typically, operators transport one or two racks to the assembly line, though, sometimes, more are required. Material transportation within the material supply can also be dynamic, with picking operations sometimes being linked to nearby locations. Occasionally, the picking operations on the assembly line may appear somewhat disorganised, with operators shifting between different material locations, due to lack of demarcation and occasionally returning to the initial location.

c. Material supply operations

Material supply activities encompass a broad spectrum of processes and tasks that revolve around the acquisition, storage, transportation and delivery of materials, components and products within an organisation. These activities play a pivotal role in ensuring the availability of materials precisely where and when they are needed for various stages of production, assembly or distribution.

Table 1: Observed picker activities

	Average	**Picker 1**		**Picker 2**		**Picker 3**	
Activities	**%**	**Day 1**	**Day 2**	**Day 1**	**Day 2**	**Day 1**	**Day 2**
Transporting material	28.45	38.2	27.9	34.8	31.9	14.2	23.7
Material delivery	7.2	3.5	11.1	2.4	2.0	13.4	10.6
Collect empty pallets	4.6	0.2	3.9	1.2	2.3	14.1	6.8
Search for material	10.2	16.4	8.9	2.2	4.8	13.0	17.0
Scan material	0.2	0.2	0.1	0,0	0.3	0.0	0.0
Collect from storage	2.1	3.2	7.3	0.9	2.6	0.0	2.6
Cleaning	8.2	13.2	15.4	15.6	0.0	9.9	0.0
Re-packing	0.8	0.6	2.0	0.2	1.0	0.0	0.0
Computer	12.6	0.1	0.1	26.1	22.8	15.4	11.6
Attend meetings	2	2.1	0.1	2.2	0.0	0.0	0.0
Leave empty pallets	1.3	1.3	0.0	0.0	8.2	0.0	0.0

Picking material	9.8	8.1	18.1	6.0	7.0	10.2	14.4
Talking	2.1	0.2	6.1	0.8	1.0	2.6	1.1
Waiting	2.4	3.8	0	0.2	11.8	0.1	0.5

Figure 2 provides an overview in percentage of activities performed by the picker. It is important to remember that the picker works on different projects in the assembly line. The data provides an overview of the time spent by the picker on a particular product.

Figure 2. Percentage distribution of activities

Table 2. Distribution of activities

For the purpose of this study the following items were categorised as value adding while the others were considered non-value adding

Activities	**%**	Value-adding activities	Non-value adding
Picking and Transporting material	28.45	x	
Material delivery	7.2		x
Collect empty pallets	4.6		x
Search for material	10.2		x
Scan material	0.2		x
Collect from storage	2.1		x
Cleaning	8.2		x
Re-packing	0.8		x
Computer	12.6		x

Attend meetings	2		x
Leave empty pallets	1.3		x
Picking material(lost items)	9.8		x
Talking	2.1		x
Waiting	2.4		x

- **Non-value adding activities**

Table 3: Percentage of value adding and non-value adding activities extracted from Table 1

	Average	**Picker & Packer 1**		**Picker & Packer 2**		**Picker & Packer 3**	
		Day 1	**Day 2**	**Day 1**	**Day 2**	**Day 1**	**Day 2**
Value adding activities	13,6	28	16	4	9	11	14
Non-value adding activities	86,4	94	80	88	78	85	95

Non-value adding activities, often referred to as waste or non-productive tasks, are actions or processes within a workflow that do not contribute directly to creating value for the customer. These activities can include unnecessary movements, excess inventory, overproduction, waiting times, rework and other inefficiencies that do not enhance the quality or functionality of the final product or service. Identifying and minimising non-value adding activities is a key principle in lean manufacturing and process optimisation, with the aim to streamline operations and increase overall productivity.

To achieve enhanced efficiency in material supply, it is crucial to conduct a value analysis. By identifying activities that contribute value and those that do not, it is possible to minimise non-value adding tasks, subsequently boosting the company's productivity. The specific value analysis conducted in the case study yielded the results depicted in Figure 2.

In the context of lean production, the primary focus of the assembly operator is to engage exclusively in activities that add value, from the customer's perspective. An ideal material feeding system should support the assembly operator, by fulfilling requirements without necessitating the operator to move away from the assembly task. Picking and kitting operations are considered as value-adding activities; in other words, activities in the process of refining the product that contribute value to the customer. Conversely, non-value adding activities refer to actions performed during production, where no refinement occurs. These non-value adding activities can be categorised as both necessary and unnecessary.

d. Identification of waste

The case study identified wasteful activities, which were categorised based on framework of eight wastes. This identification process aims to enhance customer value, while reducing operational inefficiencies.

- **Waiting**

Waiting happens when employees wait for material to be delivered to the assembly line from the material store. At the organisation, three percent of all activities involve waiting for the supply of materials. This can occur when workers are delayed due to obstructions or when an operator is awaiting instructions or information. Additionally, waiting can occur during the searching process, when an operator is trying to locate the correct position, thereby reducing the efficiency of the material handling process. It's important to note that waiting represents squandering of both human resources and time, ultimately resulting in prolonged lead times.

- **Transportation**

Unnecessary transportation refers to the act of conveying work in progress (WIP) over extended distances, resulting in inefficient movements. This encompasses the transportation of materials, parts or finished goods into or out of storage, as well as between different stages of a process. In the organisation’s material supply operations, transportation accounts for nearly twenty-four percent of the total working time. This wastefulness involves lengthy transports, with a low number of pallets, lacking established routines. This has an adverse impact on resource utilisation, as the carriers' capacity exceeds what is actually utilised. When resource utilisation is low, the process cost is spread over fewer items, resulting in higher unit costs.

- **Material defects**

Products that have defects represent a loss, particularly when the quality necessitates repairs and adjustments. Within the material supply chain, faulty items can lead to unnecessary tasks such as retrieval, transportation, return and replacement of parts for the assembly line. It is deemed as inefficient to advance flawed items along the value stream and should be actively prevented. In the production line, pallets with high volumes were found to contain numerous products with quality issues. Failing to detect these defective items can result in detrimental consequences, like futile efforts and a decrease in quality, ultimately driving up costs. At the specific company in question, operators are required to traverse the inventory, in order to obtain approval for a damaged goods report from their unit manager.

- **Motion**

Unnecessary motion in the context of work activities encompasses actions like searching for, reaching for, or organising parts and tools. Within the specific company, this issue is particularly prominent, with the act of searching alone constituting over ten percent of the overall effort within the material supply process. This involves avoidable motions such as walking to locate tools or information. The placement of tools and materials plays a crucial role in contributing to these superfluous movements.

Identifying and mitigating unnecessary motion is imperative for streamlining the material supply process. In the case of this company, it is evident that a significant portion of work time is spent on avoidable tasks like searching for tools and information. Addressing this issue, by strategically placing tools and materials, can lead to substantial improvements in efficiency and productivity within the material supply process.

Additionally, there was an instance of wasteful walking, when an operator couldn't use a tow train to transport racks, due to a faulty carrier, necessitating manual transport. Another identified inefficiency arose from unclear labels on carriers, leading to extra movements while searching for accurate information regarding quantities, part numbers and locations. All of these needless movements consume valuable time and should, ideally, be minimised or, when feasible, eliminated.

- **Skills**

Underutilised resources stand as a prevalent form of waste, signifying that the existing resources aren't employed effectively. This encompasses situations where the expertise and skills of workers remain untapped. In this study, instances of unused resources arose when certain operators lacked authorisation for specific tasks, resulting in another operator having to step in. A notable inefficiency was observed in the allocation of resources. Specifically, the picking operators were found to be dedicating their time to cleaning tasks in the storage area and assembly line, rather than actively fulfilling their primary role of serving the assembly line. This diversion of resources highlights a potential area for optimisation and improvement in operational processes.

Cleaning activities accounted for over nine percent of the total working time in the material supply process. Both underutilised and overlooked resources represent inefficiencies in human resource allocation. A significant form of waste occurs when companies fail to tap into valuable ideas and improvements, due to a corporate culture lacking in employee involvement.

- **Inventory**

Excess inventory, whether it's raw materials, work-in-progress or finished goods, leads to various complications like extended lead times, potential obsolescence, damaged items, increased transportation and storage expenses, and delays. There's an issue where operators occasionally deliver more items to the assembly line than what was initially specified. Given the limited storage space, it's crucial to enhance the utilisation of available storage. Keeping the quantity of materials in storage to a minimum is essential to mitigate the risks of damage and to control storage costs. Achieving maximum overall efficiency requires careful consideration of both storage and handling processes.

5 RECOMMENDATION AND CONCLUSION

To enhance material supply efficiency, it is crucial to pinpoint the underlying causes of inefficiencies. This study is dedicated to this task, with a primary focus on identifying and mitigating non-value adding activities. Categorising these activities into specific types of waste, offers a systematic framework for well-organised and efficient efforts to minimise them. Through this approach, six specific types of waste were identified as contributing to an inefficient material supply process. Each of these wastes was subjected to detailed analysis, leading to the compilation of potential improvement strategies.

Remarkably, every identified waste yielded at least one proposed improvement. The integration of these proposals offers a comprehensive approach to reducing non-value adding activities at the organisation. The study suggests various strategies, including altering storage policies, optimising route planning, reducing batch sizes, implementing an integrated information management system, establishing standard work procedures, and persistently applying 5S and Kaizen methodologies, all of which work in conjunction with VSM. By implementing these improvement measures, it is feasible to greatly reduce non-value adding activities and, consequently, enhance the efficiency of the material supply process.

It is worth noting that different circumstances may give rise to distinct sets of non-value adding activities, leading to the development of alternative improvement methods. Organisations seeking to enhance their material supply processes can derive valuable insights from this research.

To enhance the efficiency of material supply, a manufacturing organisation should embark on a thorough analysis of its supply chain processes. This involves scrutinising the entire journey, from raw material procurement to final product delivery, with the aim of identifying and rectifying areas of inefficiency. One key strategy is the adoption of just-in-time (JIT) inventory management, which aligns production closely with customer demand, thus minimising excess inventory and associated costs. Cultivating robust relationships with reliable suppliers is paramount. Regular communication, sharing of demand forecasts, and collaborative inventory management strategies are essential components of this approach.

Visual management techniques, such as Kanban cards or electronic systems, can be employed to signal when it's time to replenish kits. Implementing barcode or RFID technology allows for real-time inventory tracking, automating the reordering process when stocks reach predetermined thresholds. Building strong relationships with suppliers and conveying JIT requirements is essential. Keeping a close eye on lead times from suppliers and adjusting reorder points and quantities accordingly helps prevent disruptions. Regularly reviewing and refining the kitting process is essential for ongoing improvement.

Cross-training employees to handle various tasks within the kitting process ensures flexibility and resilience in case of unexpected changes or absences. Implementing quality control measures at different stages of kitting ensures that the right components are included and meet required standards. Establishing a feedback loop with production teams encourages open communication, allowing for prompt resolution of any challenges. Identifying potential risks, such as supply chain disruptions or shifts in demand patterns, and developing contingency plans is crucial for risk management. By integrating these strategies, organisations can streamline their material supply process, reduce waste, and enhance overall operational efficiency. Regular monitoring and adjustments based on changing conditions are key to maintaining optimal performance.

Advanced forecasting techniques should be employed to accurately predict customer demand, enabling more precise planning and procurement. The application of lean manufacturing principles would help to streamline processes, eliminate waste, and improve overall operational efficiency. Transportation and logistics would also warrant attention, with a focus on optimising routes and modes, to reduce lead times and transportation expenses. Technological integration is crucial, and this should encompass advanced inventory management systems, enterprise resource planning (ERP) software, and automation solutions, to bolster visibility and control over the supply chain.

Standardised work procedures play a vital role in reducing variability and ensuring consistency in operations related to material supply. Quality management should be prioritised, to diminish material defects and enhance overall product quality, consequently minimising rework and waste. Key performance indicators (KPIs) should be tracked, including inventory turnover rate, lead times and on-time delivery performance, to provide actionable insights for improvement. Investing in employee training and development is pivotal, to ensure that the staff possess the requisite skills and knowledge to perform their roles efficiently. By fostering a culture of continuous improvement, employees would be encouraged to propose and implement process enhancements, with recognition and rewards serving as motivational drivers.

Supply chain strategies should be regularly reviewed and updated in response to shifting market conditions, evolving customer demands, and technological advancements. Monitoring supplier performance and quality is crucial, and this should involve the establishment of clear quality standards and regular audits schedule. Additionally, considering sustainable and environmentally-friendly practices would not only benefit the environment, but can also lead to cost savings in the long run. By adopting these recommendations, a manufacturing organisation can significantly enhance the efficiency of its material supply, resulting in reduced costs, heightened customer satisfaction, and an improved competitive edge.

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BENCHMARKING TOOL FOR SOUTH AFRICAN GOLD MINES’ COMMINUTION CIRCUITS

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ABSTRACT

The decrease in gold deposits around the world is increasing the focus on processing lower grade ores. Alternative processing methods need to be investigated to decrease operational costs that go hand in hand with processing lower grade ores. Comminution consists of reducing the size of minerals’ particle sizes to ease further processing thereof. The reduction of the particle sizes is achieved by the means of grinders and/or milling circuits which form comminution circuits. The comminution circuits of gold processing plants are the biggest energy consumers within the process and have the largest room for improvement. The objectives of this study include creating and validating a benchmarking tool that can be used to determine the current performance of gold comminution circuits in South Africa, compared to other gold comminution circuits worldwide. This study addresses the absence of a benchmarking tool for South African gold comminution circuits by establishing a suitable benchmarking method based off relevant gold mines in South Africa. The creation of this benchmarking tool should enable South African gold mines to compare and improve the operational efficiency of their comminution circuits, to strive to be more efficient.

Keywords: comminution circuits, energy intensity (EI), gold mines

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1 BACKGROUND

Africa is a mineral rich continent containing 30% of the world's valuable minerals, including gold [1]. Furthermore, 42% of the world's gold reserves can be found within the African continent with the majority found in South Africa [2]. South Africa contains one of the world's largest gold sources known as the Witwatersrand basin. It is estimated that the Witwatersrand basin has yielded more than a third of the gold produced globally [3]. There are seven major goldfields within the Witwatersrand basin that are being actively mined, with the goldfields stretching from the East Rand in Gauteng all the way to Welkom in the Free State [4].

The mining of gold was believed to bring substantial economic growth to South Africa in 2013, as various international investors' attention was attracted by the sudden growth in the South African Stock Market's turnover ratio [5]. South Africa used to be the top gold producer until the year 2009, where they then fell to fifth place in 2016, with China taking the number one spot for gold production. Gold mining is the biggest contributor to the mining sector in South Africa and this sector contributed 11.8 percentage points to the country's gross domestic product in 2020 [6]. The production of gold thus forms a vital part of the economic growth in South Africa.

The grade of gold being mined in South Africa is on a vast decrease due to gold being mined for more than a century. Factors that influence the vast decrease in ore grade includes the exhaustion of high-grade ore, technological challenges and the current depths of gold mines (the surface high-grade ore has already been mined and increasing mine depths hold various risks). The ore grades have been on a steady decline from the 1970s where the mean ore grade has decreased from 12 g/t, to 5 g/t in 2011 [7]. Most of the goldfields' higher grade gold minerals have thus already been exploited, leaving behind lower gold grades to be mined. Utility costs, such as electricity, have been on an exponential increase since 2008, increasing the operational costs of gold mining[†]. Considering the decrease of gold grade and the increase in energy costs, it becomes evident that alternative methods are needed to decrease the total energy consumption during gold mining.

1.1 Evaluation of comminution circuit improvements

The process technologies used, the presence of process optimizations, and the type of material being processed have a significant effect on the energy requirements of a gold processing plant. Electricity is one of the biggest operational costs of gold processing plants, due to high energy demands of operations during gold mining and processing [8].

There are two main stages within gold processing with comminution being the first part, where ore particles are reduced in size for further processing, and the second part where gold ore is chemically processed to remove gold from other minerals [9]. Figure 1 represents the entire flow of a gold processing plant[‡]. The comminution circuit can be found at the start of the whole process and is highlighted in the red section. The rest of the process falls within the processing part of gold production.

Comminution is the process whereby mineral-containing rocks are reduced in size for further processing and extracting of the key minerals [10]. Crushers are commonly used to ease the transport of gold-bearing ore from underground to the surface. This is achieved by breaking the bigger rocks into smaller pieces before hoisting the particles to the mine surface. Milling circuits are further used to reduce the gold ore to smaller particles to achieve the highest gold recovery during processing.

[†] https://poweroptimal.com/2021-update-eskom-tariff-increases-vs-inflation-since-1988/

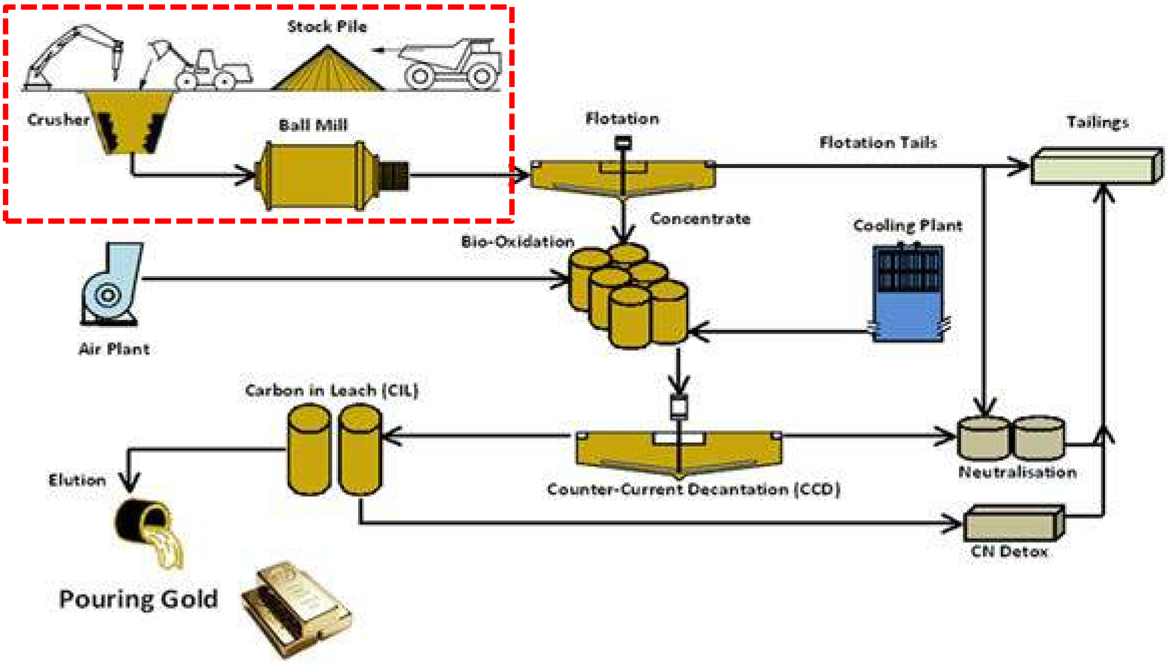

Figure 1: Gold Processing flow diagram ‡

The most energy-intensive process within gold mining and processing is the comminution circuit and accounts for approximately 50% of the total energy usage in gold mining [10]. The crushers within comminution circuits can range from anywhere between 180 kW up to 1 200 kW depending on the amount and type of ore being mined. Grinders on the other hand can range anywhere from 4 015 kW up to 22 MW [11].

Different methods have been investigated to decrease the energy consumption of milling circuits. A study by Young [12] suggests that the method of rock blasting could have a significant effect on the energy consumption during the milling of the specific rock. Increasing the rock fragmentation is believed to ease the milling process - in the end reducing the amount of energy required to further comminute the rock particles. The optimization of the rock blasting yielded finer run-of-mine with a decrease in grinding energy ranging from 10% up to 35%. This method has shown successful decreases in certain mining operations but complete failures in other mining operations [12]. This method can become rather extensive as it needs to be applied to every mining operation differently, due to the type of ore being worked on as well as the downstream equipment that needs to be adjusted accordingly. This method is however believed to become more common as ore grades decrease while utility costs increase [12].

The decrease in ore grade over the years is forcing various mines to change their operating conditions. Waste rock and tailings are collectively being treated together with gold-bearing ore to account for the decrease in gold grade while the comminution circuits are not necessarily altered to work optimally under these new conditions. This study aims to understand the characteristics of the feed material entering the comminution circuits so that the necessary alterations can be made to achieve a more optimal comminution circuit, thereby reducing energy consumption. By investigating the ore characteristics and the crushability work index of the mill, Sarpong *et al.* [13] found that adding x% of waste material with y% ore, allows the comminution circuit to run at full capacity and not overworking it. In turn

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‡ https://www.conroygoldandnaturalresources.com/projects/clontibret

reduce the time of the material in the mill before it reaches the desired sizes. In turn reducing energy usage [13].

The effect of liberation on the comminution of particles was investigated by Runge *et al.* [14] to determine the efficiency of cyclones versus screens. This study showed that screens or the combination of screens and hydro cyclones shows a much better liberation of particles followed by an improved liberation of coarse particles. Literature studies also indicate that hydro cyclones show poor liberation when referring to the regrind streams. The results of the study indicate that a combination of screens and hydro cyclones result in an overall improvement in the liberation of particles, which in turn decrease the amount of particles that need to undergo regrinding. The decrease in the amount of particles that need to undergo regrinding in turn reduces the total comminution energy required [14].

Ore sorters were proposed by Lessard *et al.* [15] to either reduce the total energy consumption of the comminution circuit or increase the throughput of the comminution circuit. To reduce the energy consumption of the comminution circuit, the ore sorters are proposed to be placed between two crushers. The underflow particles are allowed to enter the mill directly while overflow particles are fed into the next crusher. This prevents there being an excess in overflow particles in the mills, which in turn should reduce the milling energy. This also prevents the finer particles from being recirculated in the crushers unnecessarily. The use of these bins shows a reduction of 5.9MW to 3.2MW in the crushers and a reduction in the mills from 51MW to 16 MW [15].

During this study, it was found that the second line of mills could be turned off, using only one line of mills reducing the total energy consumption. Increasing the feed rate would require 7 crushers for this study instead of 3, with the same amount of ball mills. In return, an energy reduction of 61% is achieved, with almost triple the feed going in. This method however will need addition costs to add the extra crushers [15].

The effect of a high-pressure grinding roll was investigated to determine the efficiency thereof on the particle distribution. The results yielded a finer particle distribution than the conventional jaw crushers. The high-pressure grinding roll furthermore creates micro cracks within the particles, which in turn improves the leaching capability of lower grade ores up to 11% [16].

There are various technological improvements being investigated that could ease the process of determining the current efficiency of mills, and also predict what the efficiency could be by altering certain parameters. This could be beneficial for the comminution industry as it is often time and cost consuming when factors such as mill speed and liner heights need to be physically investigated. The researcher proposed comparing the use of a simulation program called discrete element method (DEM) to the actual working of a ball mill and also empirical method [17].

All three of the investigated methods showed that the best accuracies can be seen at a mill speed of 80%. However, the DEM further showed the same energy consumption as the actual mill during different rotational speeds [18]. DEM is further used to determine the collision energy of particles within different types of mills. This study investigated the effect of particles shapes and energy on the breakage of the particles. This can further be used also to determine the sweet spot of a mill’s rotation speed and feed to get the best breakage points for further processing [17].

1.2 Problem Statement and Objectives

There are various methods proposed and investigated as alternative or improvements to the current comminution circuits, however none of these methods are based solely on the comminution of gold ore in the South African region. The problem statement is thus that there does not exist a benchmark for gold comminution circuits in South Africa. The lack of a benchmark makes it difficult for gold mines to know where their current performances. By creating a benchmark for gold processing plants in South Africa the comminution energy of this sector could potentially be decreased.

The objectives of this study consist out of creating a benchmark based on a group of South African gold mine comminution circuits and validating this benchmark with a global benchmark. Creating a benchmark for South African gold mine comminution circuits should allow comparison between the different gold processing plants to determine which of these gold processing plants are being operated the best. This should also give an indication of which gold processing plants can be improved based on the better performing gold processing plants. Using the global benchmarking tool, created by Ballantyne [19], to validate the newly constructed benchmark should give an indication on whether the South African based benchmark falls within the ranges set out by the global benchmark.

2 METHODOLOGY

2.1 Background

Creating a benchmark for South African gold mines is important for the gold mines to know what their current efficiencies are and whether there is room for improvement. Benchmarks further play an important role in the conservation and management of electricity by supplying solutions for ineffective systems. Ahmad *et al.* [20] listed four levels for energy based benchmarks ,namely, physics based benchmarks, data driven benchmarks, energy forecasting models and hybrid approaches. Data driven models are best used when a large amount of data needs to be processed with minor deviations between the upper and lower limits [20].

By using the data from different mines, a data driven approach will be used to create a comparative benchmark to evaluate the performance of South African gold plant's comminution circuits.

Extensive work has been carried out by Ballentyne on the benchmarking of comminution circuits. Ballentyne felt the need to create such a benchmark that would include data from various mines over the world to find a common benchmark that could be applicable to all types of mineral comminution circuits. The first attempt by Ballentyne included over 60 different gold and copper mines located in Australia [10]. Building onto this benchmarking tool he further developed another benchmarking tool which included the data from over 140 mines worldwide and covering nine different commodities (with gold mines being more than half of the total mines used in his study) [21].

A variation of four different benchmarking graphs is created based on different comminution factors. These four factors are the Bond intensity, size specific energy, tonne intensity and grade intensity. The reasoning behind these four factors are discussed below [22]:

- Bond intensity curve: This curve is based on the amount of energy required for comminution based on the ore's specific hardness. This graph thus gives an indication of the amount of comminution energy required to break ore with a specific hardness and will be based more specifically on specific regions that will have the same type of rock/ore.
- Size specific energy: This model is based on the amount of comminution energy required to get the outflow at a specific fineness as required for further processing
- Tonne intensity: This model is based on the amount of tonne ore fed into the comminution circuit and the relevant amount of energy required to comminute the ore.
- Grade intensity: This model uses the result of the amount of mineral that is produced at the end of the process in relation to the amount of comminution energy required.

This method is more difficult to apply due to the inconsistent change in the ore grade currently being mined throughout South Africa.

For this study, the tonne intensity will be used to create a benchmark for the comminution energy of South African gold mines, based off six different gold mines. The gold mines considered for this study is based off of the type of ore being processed by their respective processing plants, together with the availability of data from these gold mines.

The data collection for the benchmark will include the comminution energy usage and number of tonne milled by six undisclosed gold mines within South Africa. The data to be used stretches over three years which will be used to compare the performance of the gold processing plants over different years. A breakdown of the method used for this study is shown in Figure 2 with detailed descriptions of each step to follow.

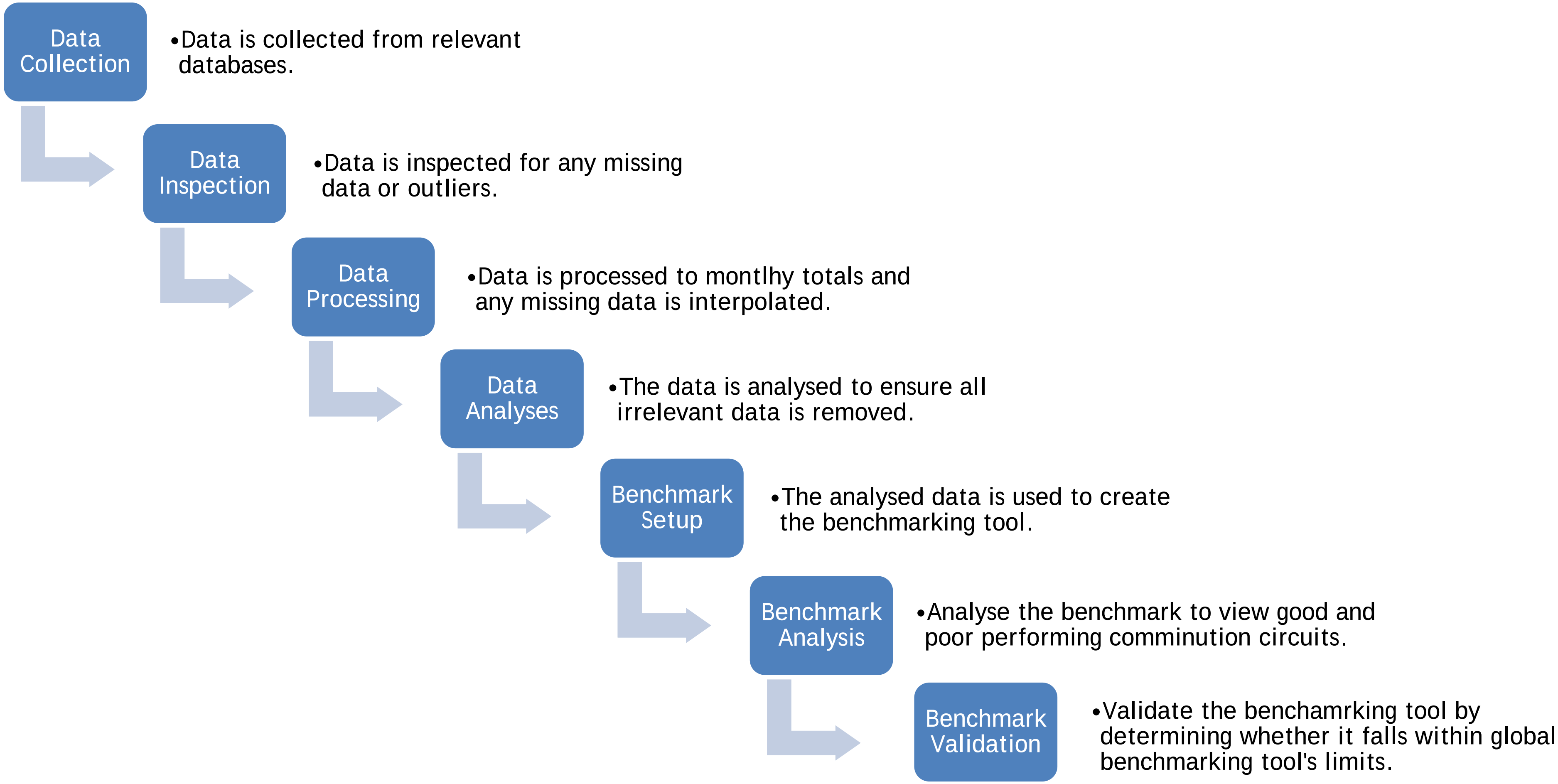

Figure 2: Benchmarking Tool Method

2.2 Data collection, inspection and processing

The first step entails collecting the relevant data needed to determine the baseline performance of gold processing plants. The energy usage data for the comminution circuit sectors is a primary data source that is readily available to be collected. This data is obtained in half hourly intervals from an online system where the data is automatically logged from the various power meters and is available for a time period of three years dating back. The format of this data is in a CSV which can be processed by using excel [23].

The tonne milled is recorded by various meters through the gold processing plant and is obtained by the mining personnel in charge of the specific sections. This data is usually logged by the mining personnel on a monthly basis and is thus secondary data [23].

Once all the relevant data has been collected from the different sources, the data needs to be inspected to ensure that there are no missing or faulty data points within the sources. Inspecting the data goes hand-in-hand with processing, as the data needs to be processed from the raw text-based file (usually a CSV file extension) to a more structured spreadsheet output, such as Microsoft Excel [23].

The half-hourly energy data that is obtained in a CSV format, is transposed onto an Excel sheet and summed to create daily energy consumption totals. This is done for every energy meter that is present on the gold processing plant. Once all the data is in a daily format, it is easy to look for any missing or faulty data. Missing data will show a daily energy consumption of 0, while faulty data will often be negative values, or any extreme values that are clearly not possible measurement readings [23].

Filtering the missing and faulty data can lead to gaps within the data that needs to be used. To retrieve the data, the mining personnel can be contacted to verify whether they have the correct data values for the missing and faulty data points, otherwise these data points can be replaced with by the means of interpolation or ratio imputing [23].

In the instance where energy consumption data is missing, ratio imputation can be used together with the tonne milled date to create substitute values for the missing data points. This can be done due to the direct relationship between the mill’s energy consumption and the amount of tonne treated. In the case of missing tonne treated data, interpolation can be used to create substitute values as the data pool for the tonne milled consists of a wider range [24].

There is one more step before the data is ready to be analysed. This step entails removing any irrelevant data that will have an unusual effect on the outcomes of the analyses. Outliers are identified and removed from the pool of data by the means of Grubb’s test [25].

The data sample size might vary regarding different gold processing plants. This is due to gold processing plants changing their operations at certain time frames within the period of data that is being used. The data sample will be split into three operational years for each mining operation.

2.3 Benchmark setup and analysis

On the completion of collecting and analysing the relevant data, the benchmark model can be created. The benchmark is created by a series of bars in a bar chart that represent a specific mine’s comminution intensity (power usage over tonne milled) over the total cumulative annual production. For this model, the x-axis is a cumulative axis with each bar on the bar chart representing a different mining operation in an ascending energy-intensity order [10].

Annual data for each mining operation will be used to compare itself to previous years using this benchmark. This process will be repeated for each mining operation, whereby all the benchmark models will then be combined to create one benchmarking tool. This benchmarking tool will then visually represent all the energy intensities (EI) and number of tonne milled for the South African gold mines. Comparing the results to one another, the benchmark should indicate which mining operations are more energy efficient and which can be improved to reduce their energy intensities [21].

2.4 Benchmark validation

To validate this benchmark, the data used to set up the benchmark can be added to the global benchmark set up using the same method [21]. From these results, the position of the various mines on the benchmarking tool can be compared to the positions on the global benchmarking tool to determine whether the South African benchmarking tool falls within the ranges of the global benchmarking tool [19].

3 RESULTS AND DISCUSSION

A benchmarking methodology created by Ballentyne was reproduced and adapted to create a benchmarking tool based on the comminution circuits within South Africa. The data used to reproduce this benchmarking tool includes the energy consumption in kWh for six different gold mines in South Africa. The data for the six gold mines, over the three year interval was collected from the online system, inspected for faulty or missing data and then processed. None of the data regarding the energy consumption was faulty and could be used for further analysis.

The total tonne milled for each mine was also collected with the percentage waste rock and reef ore available. This data was collected for all six mines over a period of three years. The inspection of the data resulted in no missing or faulty data points for the three year period. The data was then processed for each mining into three different years, thus creating eighteen different sets of data to be used to create the benchmarking tool.

The collected data is used to create the benchmarking tool which can be used to determine how energy efficient a selected gold mine is operating compared to its pear or alternative production years. Bar charts were created for each gold mine, comparing the energy intensity of each mine to itself over a span of three years, as shown in Figure 3. The bar chart consists of the energy intensities on the y-axis and the percentage cumulative tonne milled on the x-axis. The x-axis creates a perspective of the amount of material milled for each mining operation the ease the process of comparing one gold mining operation to another.

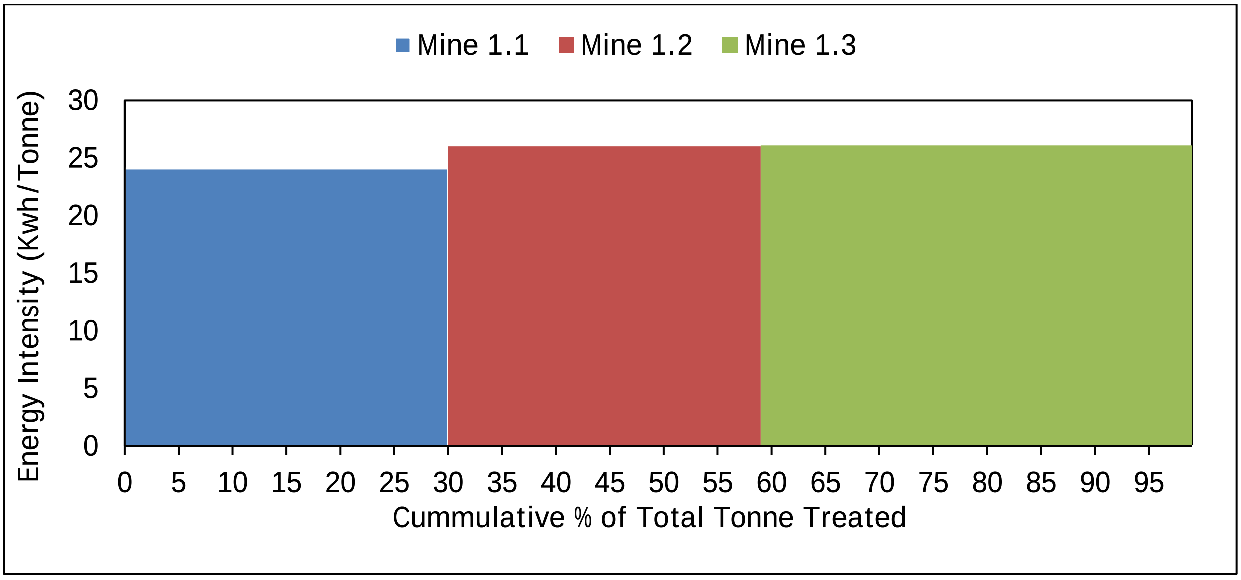

Figure 3: Mine 1 Comparison over 3 years

The results indicate that the energy intensity of Mine 1 increases from the first year and then stays constant at year three. However, the percentage tonne treated in year three is significantly more than year two. This shows better performance in year three as much more material was milled at the same energy intensity.

Combining all six mines' data over three years, a benchmark is created with eighteen data sets, shown in Figure 4.

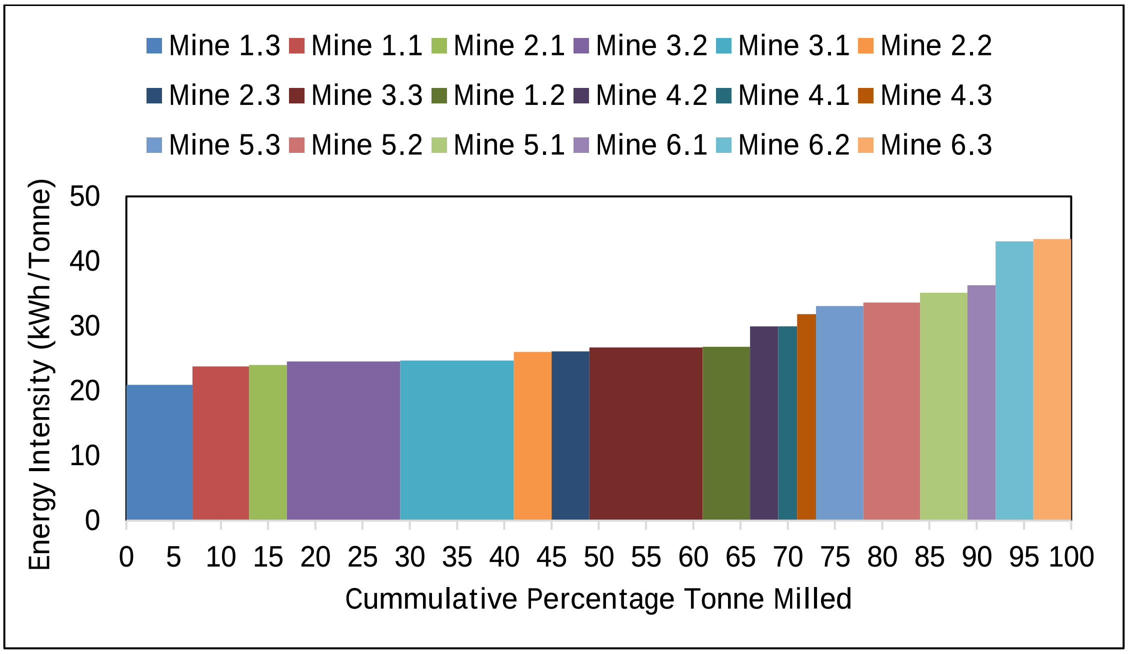

Figure 4: Gold comminution circuit benchmark

The different data sets are arranged according to increasing energy intensity. Interpreting Figure 4, it is clear that the mining operations to the left side show a lower energy intensity while the mining operations to the right show a higher energy intensity. The goal for each mining operation is to compare their energy intensities to that of the gold mining operations that perform at a lower energy intensity, while at the same time taking into consideration the difference in the amount of tonne milled.

Using Mine 2.3 and Mine 3.3 as an example, both of these gold mining operations have similar energy intensities, however there is a noticeable difference in the tonne milled by each operation. The respective tonne milled by Mine 2.3 and 3.3 are 4% and 12% of the total, respectively. Mine 3.3 thus mills three times the amount of tonne than Mine 2.3. This thus gives an indication that Mine 3.3 is performing better than Mine 2.3 as it is performing at the same level at three times the capacity.

Furthermore, taking Mine 6.3 into consideration as well and comparing it to Mine 2.3, it is clear that Mine 6.3 has a much higher energy-intensity than Mine 2.3. Both of these mines mill the same amount of ore but there is a large difference in their intensities. The benchmark thus indicates that there is much room for improvement on Mine 6.3. There are however various factors that could affect the energy intensities of different gold mining operations. One of these factors is the type of material that is being milled, whether it be waste rock, reef ore, or a combination of the two.

A regression model is created as an assisting tool to the benchmarking tool where the composition of each mine's feed into the mills can be seen. Figure 5 shows the energy intensities of each gold mining operation with the percentage waste rock present in each mine's feed.

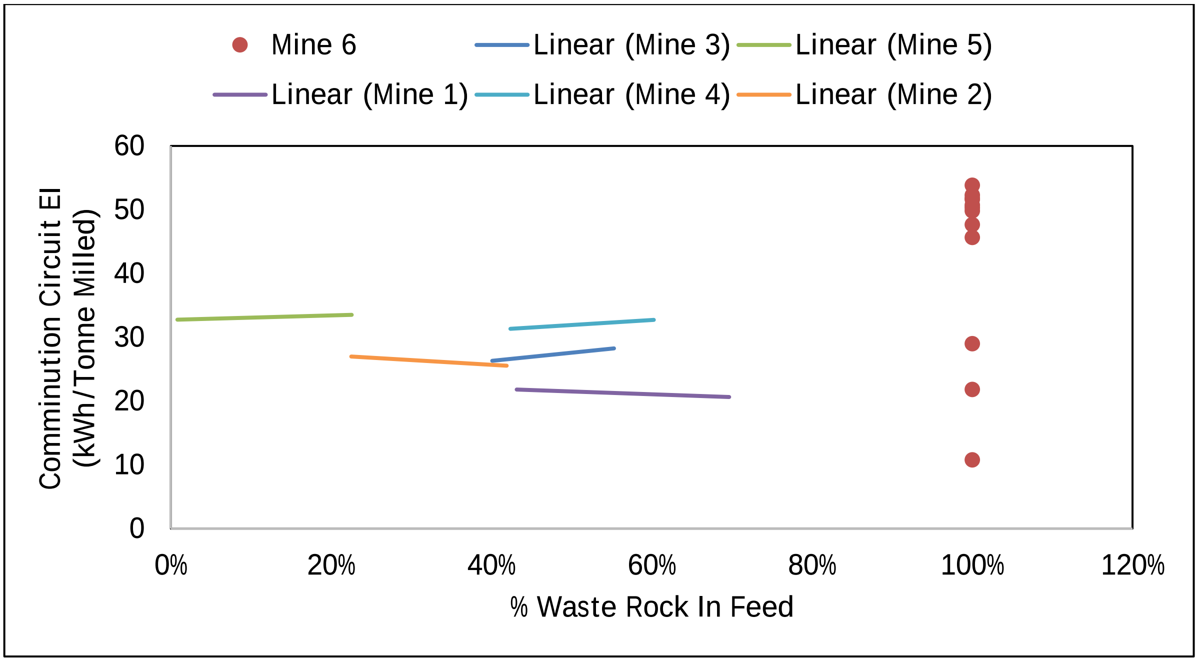

Figure 5: Regression Model

Comparing Mine 2 and Mine 3 once again, Mine 3 contains a higher percentage of waste rock that is milled than Mine 2. This thus gives an indication that the energy intensity of Mine 3 should be quite higher as waste rock consists of a harder material. But in this case both Mine 2 and Mine 3 have similar energy intensities. Taking the results for Mine 3 from both Figure 4 and Figure 5, it is evident that Mine 3 has better operating conditions than Mine 2 and Mine 2 needs to apply some optimizations to the comminution circuit to improve the energy intensities.

Figure 4 and Figure 5 can thus be used to compare all the mining operations used to determine which of the operations are being operated the most energy efficient. The operating conditions/philosophies of the better performing operations can then be applied to the other operations to try and improve their energy efficiencies. Once that has been applied, all of the operations can start applying new technologies mentioned in the literature to try and further improve their energy intensities.

A validation model is created by recreating the benchmark created by Ballentyne. A total of 80 mines' energy intensities were used to create a similar benchmark as shown in Figure 4. The x-axis for this model is however kept constant due to the lack of information. The South African gold mines' data is added to the benchmark created from Ballentyne data to determine whether the reproduced model fits within the limits. In Figure 6, the South African mines are represented by the coloured lines, with the green section representing the specific mine's total reef ore milled and the red section the total waste rock milled.

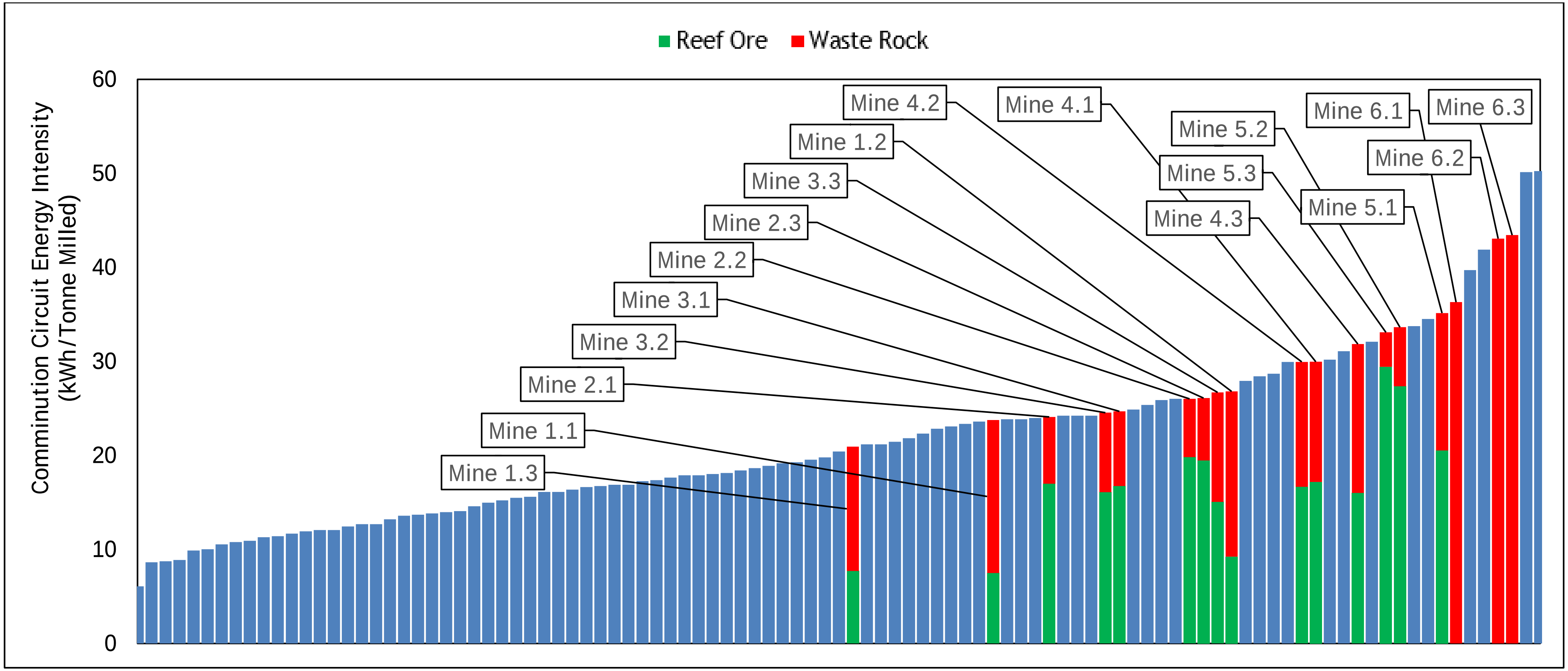

Figure 6: Validation Model - South African Gold Mines with Global Gold Mines

All the South African gold mines' comminution circuit energy intensities fall within the range of the benchmark created by Ballentyne. This indicates that the benchmark created for the South African gold mines is suitable for its purpose and be used to compare the energy intensities of the different gold mines. Figure 6 also indicates that there is much room for improvement within the South African gold mines, as their energy intensities are all on the higher end of the benchmarking tool. This indicates that the South African gold mines' comminution circuits are not being operated optimally (or the material being processed is of a harder nature than other countries' materials).

The methods of improving the energy consumption of comminution circuits should thus be implemented at the Sout African gold mines to improve the overall energy intensity.

4 CONCLUSION

A benchmarking tool has been developed to compare the energy intensities of the comminution circuits across six different South African gold mines. This tool provides insights into which mines are performing efficiently and which need improvement. By identifying the better-performing mines, the underperforming ones can adopt similar operational strategies to enhance their energy efficiency and improve their rankings. Additionally, the mines already performing well can explore alternative methods to further reduce their energy intensities.

The benchmarking tool has proven effective in distinguishing between good- and bad-performing comminution circuits and aligns with the benchmark set by Ballantyne [19]. By developing a benchmark based on data from six South African gold mines, this study provided a framework for comparing the energy efficiency of different gold mining operations. The validation against a global benchmark confirmed the applicability and relevance of the findings, indicating areas for potential improvement in South African mines.

Future benchmarks could delve deeper into the energy intensities of comminution circuits by examining ore characteristics, such as the Bond index. Further studies should focus on determining the Bond index for materials from each South African gold mine, providing a clearer picture of whether the perceived inefficiency is due to the comminution circuits themselves or the inherent hardness of the milled material.

Benchmarking is crucial in industrial engineering, driving performance improvements in gold processing plants and fostering continuous improvement across the industry. The benchmarking tool not only highlights efficient plants but also guides less efficient ones towards better practices, ultimately leading to cost and energy savings driven by data-driven insights. This approach delivers significant value to gold mines by enhancing overall operational efficiency.

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COMPACT 3D PRINTED TURNTABLE DESIGN FOR INDUSTRIAL 3D SCANNING APPLICATIONS

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ABSTRACT

This research introduces a method for creating a medium sized turntable that is especially suited for industrial 3D scanning uses. A 500mm diameter turntable was designed to maximize scalability and minimize production costs, while also enabling smooth integration into current scanning settings. This was achieved by leveraging the limitations of a common 220mmx220mmx220mm 3D printer. The availability of turntables in this size range is very limited. The design achieves the ideal balance between functionality and efficiency by carefully considering industrial engineering principles, such as material selection, structural integrity, and manufacturability. The turntable's modest footprint guarantees compatibility with a variety of industrial applications, and its modular design facilitates simple assembly and maintenance. This breakthrough emphasizes the promise of industrial engineering approaches in expanding additive manufacturing solutions for practical applications, especially around high-precision 3D scanning, while accepting the constraints of traditional 3D printing technology.

Keywords: 3D Scanning, Turntable, Design, Artec EVA

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1 INTRODUCTION

The primary function of 3D scanning technology is to generate point cloud geometric samples of an object that is then transformed into surfaces that reconstruct the object scanned. With 3D scanning being an integral part of the modern-day technology boom in the industry, 3D scanning has been part of the world since the 1960s[1]. As 3D scanning was initially used it involved the use of lights together with cameras and projectors to obtain the surfaces of the object scanned. Since the 1960s, the technology and process of 3D scanning have improved, and labour-intensive processes used in the 1960s were left behind[2]. White lights, lasers, and shadowing technologies are used to capture more accurate surfaces of various objects. During the 1990s full body scanners hit the market and the advancement in the 3D scanning technologies greatly improved. Currently there is a continuing improvement in the field of 3D scanning as there are multiple companies that span multiple industries that use 3D scanning for various applications, such as in the additive manufacturing and medical industries, thus leading into further research in the field of technology[2].

In the construction and civil engineering industries, 3D scanners are used to verify as-built drawings, documentation of historical sites, site modelling, and establish benchmark parameters for existing structures. Moreover, the technology is used to reverse engineer objects by scanning these objects and generating a digital version which can then be modified and manufactured. Within the medical field, the 3D scanning process is used to scan a disabled patient's affected area and then model and produce possible prostheses around the digital model to save on manufacturing time and manufacturing costs. The 3D scanning technology is also used in law enforcement as the scanner which can help document crime scenes and help recreate or reconstruct an accident scene[2].

For objects of small to medium-sized nature, it is necessary to have more stability and accuracy in terms of the scanning procedure to minimize scanning errors and background 3D noise. Therefore, to minimize the errors picked up by a 3D scanner, a turntable where the object can be placed and rotated can be introduced while the 3D scanner can be placed in a stationary position. As there is to be less external noise and motion deviation from the scanning procedure, less error or background noise will be captured. Various turntables are available to be purchased, but the size restriction and the affordability of these tables make the purchasing of the items very difficult. Thus, a 500mm diameter turntable is designed and 3D printed, and all the parts are designed to fit on any basic 220mmx220mm 3D printer for ease of manufacturing and assembly. The turntable is also used to compare the two different scanning procedures of a manual handheld scanning versus a stationary structured scanning method.

2 DESIGN AND MANUFACTURING OF TURNTABLE

The turntable is designed with a diameter of 500mm to address the size constraint of a general 3D printer with a print base of 220mm by 220mm. By keeping the print base size constraint in mind, the modular design of all the parts makes it easy for the parts to be printed individually as well as makes it easy to do troubleshooting on individual printed parts. Thus, when a misprint or printing error occurs, only a single part has to be reprinted and not the whole table itself. Together with the modular printing process, the design enables the turntable to be easily assembled, disassembled, and also transported. This design makes access to a turntable a lot more accessible to individuals and to industry-relevant individuals or companies without having to spend a large amount of time or money on the accusation of a medium-sized turntable.

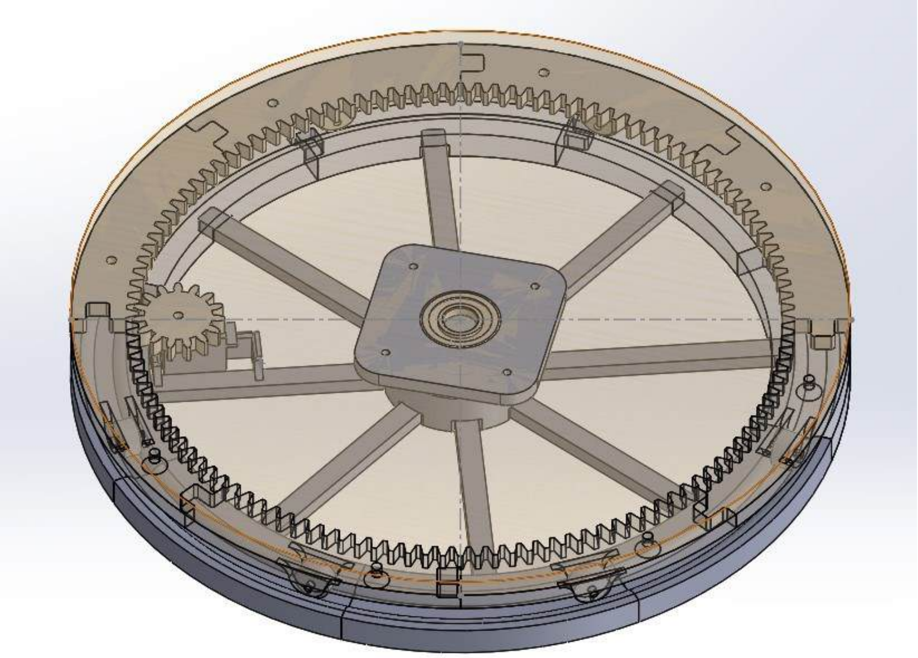

Figure 1: Fully Assembled Turntable

The manufacturing of the 3D printed 500mm diameter turntable was done on a Creality Ender 5 3D printer. A fully assembled Computer Aided Design (CAD) model can be seen in Figure 1 to illustrate the complexity of the turntable and its parts. The selection criteria for the material used in the printing process was based on that the material needs to be widely available, cheap, and strong enough for the intended use of the printed parts. Two types of printing materials are the onset primary materials, which are Acrylonitrile butadiene styrene (ABS) and Polylactic Acid (PLA). According to Ultimaker.com, PLA is a good material with good quality in terms of engineering properties, but ABS is the material to be used if a lot more physical work is to be done with the printed components. Both of the materials cost around the same at R300 for a 1kg spool of plastic. Any other material can be used to print the turntable as the function of the turntable in terms of the weight of parts and changes in part sizes.

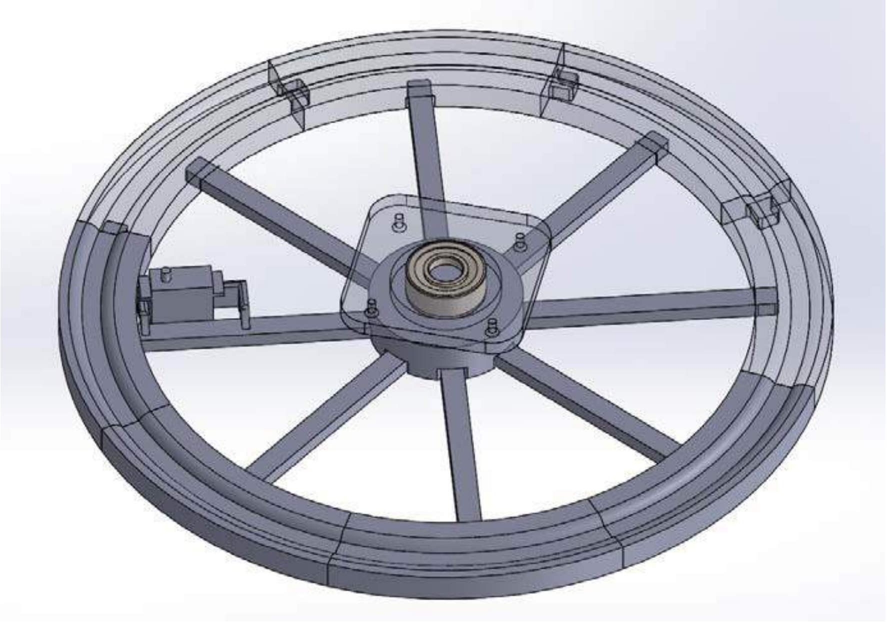

Figure 2: Base Rail assembly.

In Figure 2 and Figure 3, two sub-assemblies for the Base Rail assembly and Top & Gear set assembly show the two separated halves of the turntable. The top and gear set are supported in the middle of the structure with a tapered bearing and on the outer rim of the base by small rubber-lined roller bearings for maximum weight distribution to the bottom rail assembly.

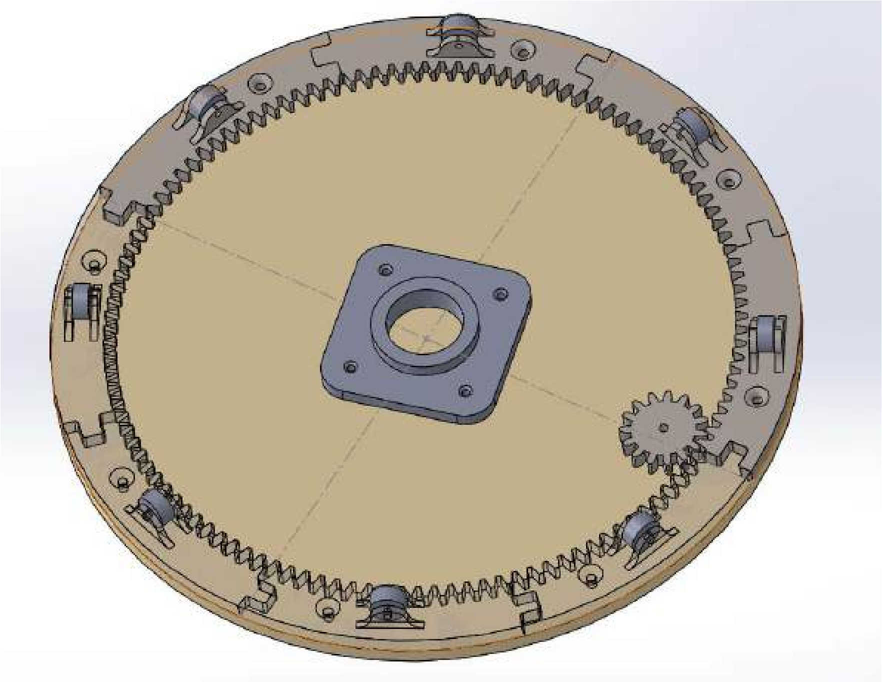

Figure 3: Top & Gear set assembly.

Ultimaker Cura 5.5 is the slicing program that is used to slice the imported 3D CAD models of the different parts printed into layers so that the 3D printer can be instructed to print the parts with selected parameters. For each turntable application, the parameters will vary for the slicing and printing software. For the current test unit, the parameters used are shown in Table 1. Ultimately, the plastic part of the turntable is printed, then post-printing cleaning is needed to clean up the parts so that each part fits together easily.

Table 1: Slicing/Printing Parameters

Parameter	Unit
Filament Thickness	4 mm
Nozzle Size	0.4 mm
Layer Height	0.2 mm
Wall Thickness	1.2 mm
Top/Bottom Thickness	0.8 mm
Infill Density	20 %
Infill Pattern	Cubic
Nozzle Printing Temperature	220 ºC
Built Plate Temperature	60 ºC
Print Speed	80 mm/s
Travel Speed	200 mm/s
Built Plate Adhesion	Brim
Brim Width	8 mm
Print Cooling	Enabled

With the turntable assembled with all the printed plastic parts and support bearings, the top base and gear set is turned by a Tower Pro MG 996R servo motor with a stall torque of 15kg·cm when supplied with a 6-volt power supply. The servo is driven by a coded Arduino Uno board that activates the servo, by the push of a button for 1 second and stops for 2 seconds on repeat until the stop button is pressed when a certain scanning process is complete.

3 ARTEC EVA 3D SCANNER & SOFTWARE

The 3D scanner used is the Artec Eva handheld 3D Scanner, produced by Artec 3D, and the company headquarters is based in Luxembourg. The Artec Eva scanner is designed and manufactured to generate 3D scanned models in a relatively short time. Meanwhile, the complexity of the model also plays a role since the scanner has set limits. The specification of the Artec Eva 3D scanner is displayed in Table 2 [3]. This Artec EVA is a structured light type of scanner and it has been used in multiple additional studies for producing customized orthoses[4].

Table 2: Artec EVA Specifications

Spec	Measurement
3D point accuracy, up to	0.1 mm
3D resolution, up to	0.2 mm
3D accuracy over distance, up to	0.1 mm, 0.3 mm/m
Working distance	0.4 - 1 m
Volume capture zone	61,000 cm³
Texture resolution	1.3 mp
3D reconstruction rate for real-time fusion, up to	16 fps
Data acquisition speed, up to	18 mln points/s
3D light source	Flashbulb
3D mesh	OBJ, PLY, WRL, STL, AOP, ASC, PTX, E57, XYZRGB
CAD	STEP, IGES, X_T
Minimum computer requirements	Intel Core i7 or i9, 32 GB RAM, NVIDIA GPU with CUDA 6.0+ and at least 2 GB VRAM

As the minimum requirements are known, a HP Z440 workstation with a Xeon E5-1650 processor, 32GB RAM and a NVIDIA GeForce GTX 1060 6GB GPU is used in this study. The processing power of the setup used for the scanning process is more than adequate. For the capturing of the raw data from the 3D scanner and to do the post-processing procedures of the 3D scanned model, Artec Studio 17 is used.

4 3D SCAN AND EXPORT PROCESS

A rectangular box is used as an example of the scanning procedures and to compare the scanning methods with each other. The rectangular box is shown in Figure 4. The first scanning method is to put the test unit on the turntable and secure the 3D scanner to a stationary position. As the turntable rotates, with the object placed on it, the scanner will be placed in a stationary position to implement the scanning process. The second method entails that the test unit or object is placed on a stationary flat surface, and the 3D scanner is to be held by hand. The scanning process is initiated while the person moves around the object to complete the scanning process.

Figure 4: Test example (Rectangular box)

There are three individual scans done per scan test as the object is to be placed right up, turned upside down, and placed flat on its back. Each method will include three separate scan tests to compare the two scanning methods. As the Artec EVA has a High-Definition (HD) scanning option to include in scans, one test scan will be without the HD option enabled, and two scan sets with the HD option enabled.

Scanning can begin as the object is placed in the correct location and orientation. With the Artec EVA 3D scanner, the optimum distance from the scanner to the object is between 640mm and 740mm; as the object is within the optimum range, the scanning can begin. As the scanning progresses, it is necessary to let the scanning process continue until a full 360-degree rotation is done before a scan is stopped. The orientation is changed, and the scanning procedure is continued and repeated until all scanning iterations are completed. Each scan iteration is accompanied by an error factor that illustrates the quality of the frames captured. To get good results from frames captured from the Artec EVA scanner, the error factor can be between 0 - 0.3 and moderate results between 0.4-0.9. When the error factor exceeds 0.9, the frames are not acceptable[5]. The error factor illustrates the quality of the frame captured, thus the quality of the surface capture and possibly interference from background noise (objects) that is not relevant to the object scanned.

After all the necessary scanning procedures have been followed, the post-scanning procedures can begin. The post-scan processing is done the same way throughout the study to get the best overall results over all the scans. The post-processing procedure used is listed below:

1. Base Remove
    - ➢ Remove the base the object is placed on, as the base is irrelevant to the end product.
2. Remove Background noise.
    - ➢ Remove all additional small or big objects (Noise) that can be recorded during the scanning process and are irrelevant to the end product.
3. Align all three cleaned-up scan data sets.
    - ➢ Automatic alignment is done by aligning Geometry and Texture points recorded from the scans of the object.
4. Global registration.
    - ➢ All the one-frame surfaces of the aligned data is converted to a single coordinate system.
5. Outlier remove.
    - ➢ Remove additional outlier data missed in previous steps.
    - ➢ Level 2 3D noise level
    - ➢ 3D resolution 0.5 mm
6. Fusion (Sharp).
    - ➢ Combining all captured and processed frames together to create a polygonal 3D model.
    - ➢ 3D resolution 0.5 mm
    - ➢ Exclude frame with an error factor of 0.8 and above.
7. Remove small objects.
    - ➢ Remove possible small objects that are missed from previous removal processes.
8. Smoothing.
    - ➢ Smoothing evens out noisy areas in the 3D model.
    - ➢ 10 steps
9. Mesh Simplification.
    - ➢ To reduce the polygon mesh density to reduce memory used.
    - ➢ Shape deviation to a resolution of 0.05 mmm
    - ➢ Maximum allowable deviation from the original scan
10. Export Mesh
    - ➢ Export the mesh to any of the allowed file types.

With the scanning process and post-scan processing completed and a mesh file exported, the mesh file can be imported to a CAD program. Within this study, the mesh file is imported into Solid Works as a solid body so that the interaction between polygons is possible and to take distance measurements.

5 RESULTS

The rectangular box object that is used as an example for the 3D scanning was measured in 6 locations, three locations that related to measurements from side to side at the top, middle, and bottom of the object. Additionally, the other three measurements are taken front to back at the top, middle, and bottom of the object. In Figure 4, the green lines are a representation of the location where the measurements were taken. The measurements taken are the length between two points and is displayed below:

1. Side to Side
    - Top = 100.6 mm
    - Middle = 100.8 mm
    - Bottom = 100.6 mm
2. Front to Back
    - Top 100.5 mm

- Middle = 100.5 mm
- Bottom = 100.5 mm

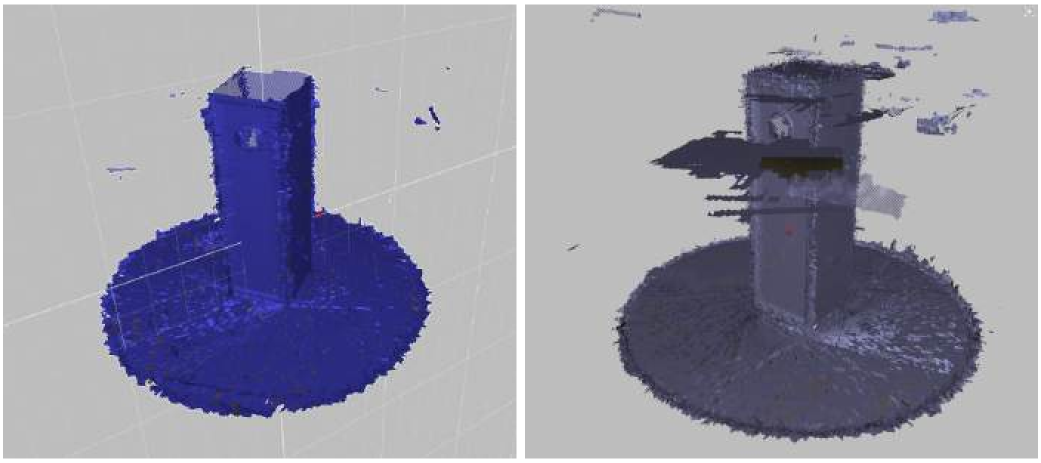

Figure 5; (a) Stationary Turntable Scan; (b) Handheld 3D Scan

Before any post-processing is done and any measurement data is extracted, it can be seen that with a comparison shown in Figure 5(a) and Figure 5(b) there is a lot more background noise related in the handheld 3D scan than the stationary turntable scans. From Figure 6 (a) the lowest minimum error factor from frames scanned and rendered comes from the scans done by the use of the turntable and stationery Artec Eva scanner. Thus, it can be said that the maximum error factor as it is captured comes from the handheld scan procedures, as seen in Figure 6 (b).

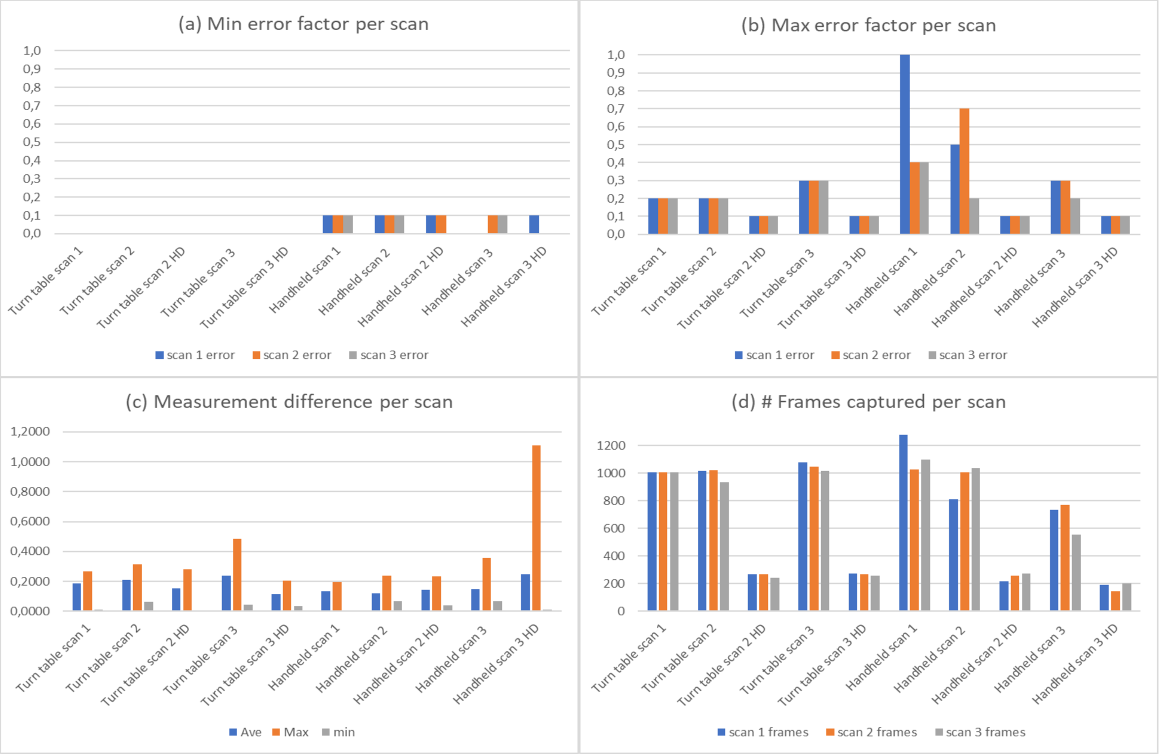

Figure 6; (a)Min error factor; (b) Max error factor; (c)Measurement difference; (d)# Frames captured

With the combination of data from Figure 6 (c) and Table 3, it can be seen that the difference in measurements from the physical rectangular box to the 3D Scanned meshed object imported to a CAD program the difference percentage is less than 1%. As previous studies and general academic studies show that when the difference in measurements is equal or less than 5%, the results are acceptable [6].

Table 3: Physical vs 3D Measurement differences (mm)

	Top sides	Middle sides	Bottom sides	Top Front	Middle front	Bottom front
Turn table scan 1	0.2391	0.1467	0.2361	0.0092	0.2674	0.2165
Turn table scan 2	0.3124	0.2697	0.2657	0.0629	0.0811	0.2570
Turn table scan 2 HD	0.0540	0.1921	0.0057	0.2814	0.1987	0.1915
Turn table scan 3	0.4844	0.3488	0.3588	0.1184	0.0716	0.0412
Turn table scan 3 HD	0.0632	0.0327	0.0500	0.2033	0.1866	0.1391
Handheld scan 1	0.1598	0.1247	0.1963	0.1440	0.1610	0.0059
Handheld scan 2	0.0750	0.1168	0.2371	0.0658	0.1464	0.0772
Handheld scan 2 HD	0.1544	0.1213	0.0388	0.2347	0.1593	0.1463
Handheld scan 3	0.1473	0.0741	0.0657	0.3564	0.0705	0.1781
Handheld scan 3 HD	0.1597	0.0416	0.0927	1.1081	0.0767	0.0084

6 CONCLUSION

With the photographic difference between the pre-processing scans of the turntable and handheld scanning, together with the minimum and maximum error factors, it can be seen that a turntable makes the processing process, noise extraction etc., of the 3D scans a lot more convenient, easy and less time-consuming. As can be seen from the results shown in Figure 6 (b) as more error and noise relate to more time spent on post scan processing. Even if the difference in measurements of the two scanning methods is not significant, there is still the need for a medium-sized turntable that is easily accessible or manufacturable, as there are not a lot of affordable medium-sized turntables on the market. Thus, the turntable can be manufactured with a basic 3D printer using affordable materials. This turntable can be used in a hobbyist environment as well as in an industrial environment. The manufacturing parameters can be varied and applied as the use for the turntable is known. Future research may include the use of a robotic arm with distance-measuring sensors to keep the 3D scanner at an exact distance from an object's surface while the object is rotating on the turntable. This will be to see if further errors or background noise can be filtered before any processing takes place.

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INDUSTRY 5.0 CONCEPTS AND COMPONENTS: A SCOPING LITERATURE REVIEW

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ABSTRACT

The term "Industry 5.0" was coined to represent a new phase of industrialisation. It builds on the technological advances of Industry 4.0, with a stronger focus on human centricity, sustainability, resilience, personalisation and customisation, and bioeconomy. Through human-machine collaboration, it is shifting the focus from economic value to societal value and well-being. A scoping literature review was conducted to explore existing studies on the Industry 5.0 frameworks. The findings reveal key concepts of Industry 5.0 and the key components that drive these components such as Cobots, AI, Digital Twins, Internet of Things, Big Data, Mixed realities, and Blockchain. The study's implications highlight the need for organisations to integrate these frameworks to enhance productivity and sustainability. This review offers valuable insights for practitioners and policymakers aiming to navigate the transition towards Industry 5.0.

Keywords: industry 5.0, human-centric, resilience, sustainability, scoping literature review, framework

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1 INTRODUCTION

There have been numerous industrial revolutions, from the mechanisation of production and steam power during the First Industrial Revolution to the ecosystem of ideas and technologies such as the Internet of Things (IoT) and the Cyber-Physical System (CPS) in Industry 4.0 [1]. However, as with any industrial revolution, it has a few shortcomings. Industry 4.0 lacked a strong emphasis on human interaction and collaboration, sustainable and ethical practices, and a beneficial drive for business and social success [2] [1]. These shortcomings paved the way for the emergence of Industry 5.0.

The term "Industry 5.0" was coined by the European Commission to represent a new phase of industrialisation [3]. It builds on the technological advancements of Industry 4.0, with a stronger focus on human-machine collaboration, customisation, innovation, resilience and sustainability, shifting the focus from economic value to social value and well-being [4]. It places the well-being of the industry worker at the centre of focus and emphasises the collaboration of human skills such as creativity, decision-making, and complex problem-solving with advanced technologies [1].

As this concept is still emerging, there is a unique opportunity to explore what the key concepts and components of the Industry 5.0 framework consist of. Most existing papers focus on specific scenarios or address only one or two elements of Industry 5.0. Therefore, this study plans to investigate the available literature on the general frameworks and elements of Industry 5.0 to assist organisations in implementing Industry 5.0.

It is important to clarify the use of frameworks and models. According to Difference Between [5], a framework provides an overall structure and shows the relationship between key different elements. It can help to organise and structure concepts and theories. A model is typically more prescriptive and detailed and aims to achieve a specific outcome [6].

In summary, while both frameworks and models are used to structure and organise knowledge, frameworks are more general and descriptive, focussing on the relationships between concepts, whereas models are more specific and detailed, aiming to explain or predict specific behaviours or outcomes. Therefore, a framework is best suited to the nature of the study to provide a general knowledge structure of Industry 5.0.

2 METHODOLOGY

A scoping review is the optimal methodology for this investigation due to the broad nature of the research questions [7]. It excels at mapping existing frameworks, clarifying key concepts, and identifying knowledge gaps - ideal for exploring Industry 5.0 frameworks.

The review will follow the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) guidelines and protocol. The protocol provides the plan for the scoping review and is important in limiting the occurrence of reporting bias. After creating the detailed protocol, the eligibility criteria for selecting studies or evidence sources are clearly defined. The review identifies and searches relevant databases and search engines to retrieve studies or evidence.

A search strategy is formulated to identify relevant studies, and a systematic process is used to select sources based on eligibility criteria. Data from the selected sources are extracted and organised through a charting process. The findings of individual sources are synthesised to identify common themes, patterns, or gaps in the literature.

The general results of the findings, common themes, and trends are discussed. The review concludes with a summary of the evidence, a discussion of limitations and implications for practice, policy, or future research, along with any recommendations. Finally, the resources allocated and the role of the funders are described.

Industry 5.0, the next iteration of industrial automation, emphasises a human-centred approach alongside the technological advances of Industry 4.0. The objective is to identify key elements in the new industrial revolution through the following research questions.

- **RQ 1: What are the key concepts in the Industry 5.0 frameworks?**

  Concepts are the higher-level ideas and theories that underpin the Industry 5.0 paradigm.

- **RQ 2: What are the key components of the Industry 5.0 frameworks?**

  Components are the specific technologies, systems, and approaches that make up the Industry 5.0 framework.

Through this investigation, we can establish a foundation for future Industry 5.0 frameworks, ensuring that they provide all the necessary guidance for successful industry-wide adoption. The following inclusion and exclusion criteria are established as part of the protocol.

Table 1: Inclusion & Exclusion Criteria

PRISMA Phase	Type of the criteria	Description of the criteria
Identification	Inclusion	Publication year > 2016
		Title, abstracts, or keywords containing terms: ("Industry 5.0" or "Fifth industrial revolution" or "5th industrial revolution") and "manufacturing"
	Exclusion	Duplicated Articles
		Articles not published in English
Screening	Inclusion	Industry 5.0 concepts or components are the main or one of several topics that are reviewed, surveyed, or discussed.
	Exclusion	Articles out of the scope based on titles and abstract assessment
		Studies solely focused on Industry 4.0 or earlier industrial revolutions (unless explicitly compared to Industry 5.0)
		Full text not available

The following engineering-related databases are used: ScienceDirect, Scopus, IEEE Xplore, Web of Science, and Google Scholar. The keywords used in the search strategy are shown in Table 2. To limit the number of studies relevant to the study topic, no synonyms for 'Framework' are used in the search strategy.

Table 2: Keywords for Search Strategy

Keywords	Synonyms
Industry 5.0	'Fifth Industrial Revolution', '5IR', '5th Industrial Revolution'
Framework	n/a

3 RESULTS

The search strategies were drafted by the authors and further refined. The final search strategy is found in the table below, conducted on 18 May 2024.

Table 3: Search terms and results

Search terms and database	Science Direct	Scopus	IEEE Xplore	Web of Science	Google Scholar	Total
(“industry 5.0” OR “fifth industrial revolution” OR “5th industrial revolution” OR 5IR) AND (framework)	96	447	174	216	71	**1004**

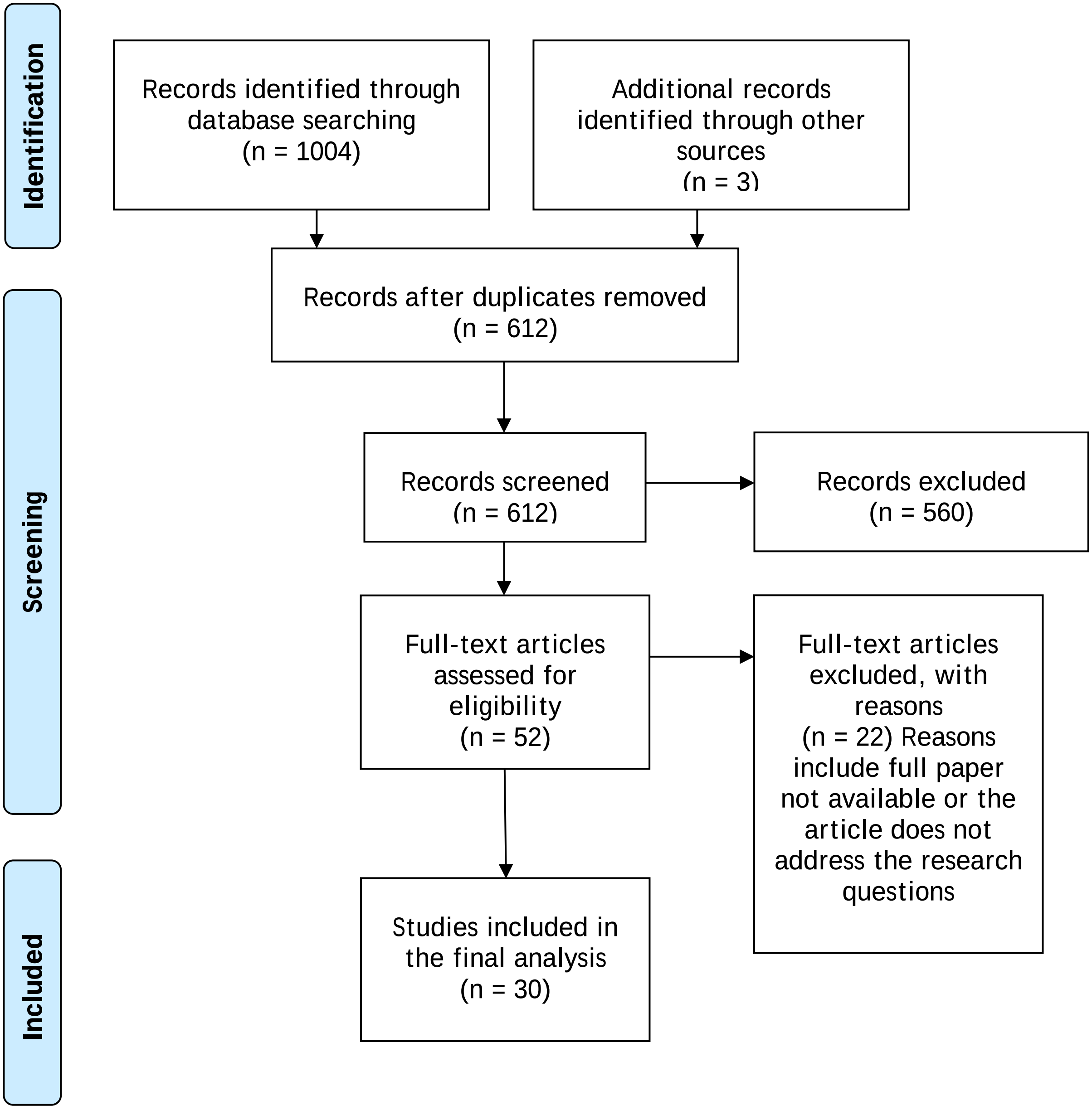
Search terms were used to search the title, abstract and keywords. However, since Google Scholar is a search engine, not a database, to limit the number of articles, only keywords were searched. Other sources include publications by the European Commission since they are a key driver and initiator of this transition.

The final search results were exported to Rayyan, a web application designed to organise, manage and facilitate the screening process. Based on the search, 1008 resources were gathered from 5 databases. After the duplicates were removed, a total of 612 citations were identified from searches of electronic databases and review article references. Based on the research protocol used to perform an initial screening, 560 were excluded, with 52 full-text articles to be retrieved and evaluated for eligibility and to ensure they directly address the research questions and objectives and provide relevant information about the industry 5.0 frameworks.

Of these, 22 were excluded for the following reasons:

- Unable to retrieve the full article.
- Focus on a very specific application of a technology.
- Industry 5.0 is only used as a reference and is not discussed in the paper.
- Focus only on challenges, opportunities, advantages, disadvantages or risks.
- Focus only on industry 4.0 technology frameworks.

The remaining 30 studies were considered eligible for this review.



3.1 RQ 1: What are the key concepts in the Industry 5.0 frameworks?

Figure 1 shows the most common to least discussed concepts in the 30 included articles. Each of these concepts will be discussed individually to understand the definition and application.

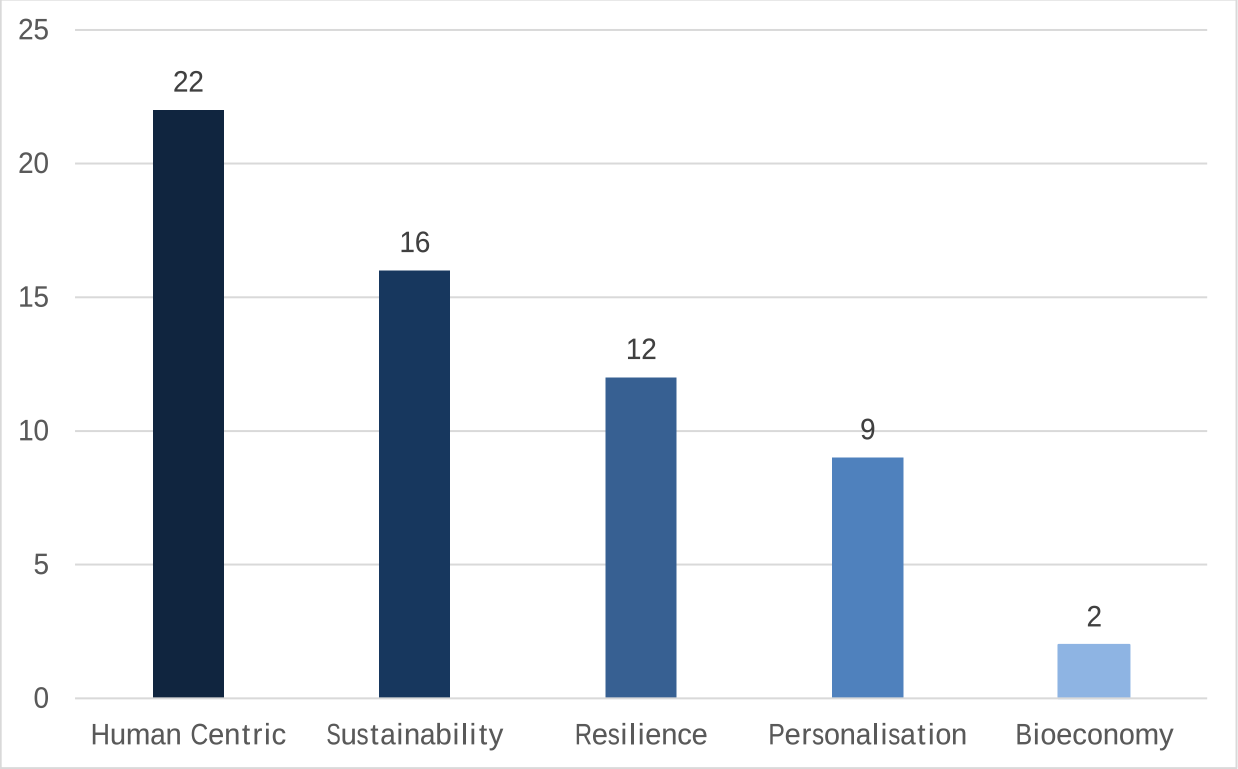


Figure 1: Number of articles discussing Industry 5.0 Concepts

3.1.1 Human-centric design

The authors emphasise that technology is not a replacement for humans, but a collaboration between people and machines to create more value-added for customers [8], [9]. It enhances their role in manufacturing by placing more importance on human intelligence and improvement of quality [10]. Industry 5.0 will eliminate monotonous and tedious tasks and pave the way for curiosity, empathy, creativity, and judgment [8], [11]. Humans will take on greater responsibility and increased supervision of systems [11]. Therefore it is imperative to hire the right people with the right skills to work safely alongside machines [12].The goal is to enhance workplace safety, minimise errors, and increase productivity through human-machine interaction [13].

Human centricity focuses on improving physical and mental well-being and viewing humans as assets. This includes incorporating principles such as autonomy, development, and psychological safety [14]. The 5C human-machine relations framework is introduced to implement the principles of coexistence, cooperation, collaboration, compassion, and coevolution [15]. A human-centric interaction model is created that consists of three elements: 1) human-machine understanding (2) human-machine collaborative intelligence, and (3) human-machine communication [15].

Technology will be used to benefit humanity, generate new employment opportunities, and increase productivity. This will lead to the upgrading and reskilling of workers [16]. Somroo [17] also states that modern automated industries are considering adding the human element back into their technological systems and strategies to get the most value from automation. It combines the best of both worlds, the speed and precision of automation with the cognitive abilities and critical thinking of humans [9]. Machines and humans should work as collaborators and not as competitors [9].

3.1.2 Sustainability

Organisations concentrating only on profit are finding it increasingly difficult to succeed in a global, unpredictable, and competitive environment. For companies to be sustainable, they need to achieve a symbiosis between economic, technological, social, and ecological aspects [9], [11]. Ahamed [11] states that Industry 5.0 emphasises sustainable supply chain management, incorporating elements such as 'employee education and training, working conditions, the balance between productivity and wages, technology versus human redundancy, optimal product quality, sustainable governance, and a business ethics code'. Sustainability is also argued to be driven by the implementation of digital transformation and pro-social and pro-environmental solutions in organisations [18]. There is a shift in typical economic models to circular economy models to improve overall sustainability considering social and environmental needs and challenges [18].

There is also a rise in environmental policies to reduce waste material and improve waste management. More companies are prioritising environmental sustainability, aligning with the growing demands of international organisations, government regulations, and customer expectations [8]. The 6R principles of upcycling are introduced to accompany Industry 5.0 namely, recognising, reconsidering, realising, reducing, reusing and recycling [17],[18], [19]. Akundi [20] also mentions the 6R principles as a means to promote human values and needs.

3.1.3 Resilience

Resilience is the organisation's ability to return to a stable state after expected and unexpected conditions such as geopolitical shifts and global crises, ensuring that critical infrastructure remains operational during challenges [21] [22]. It involves building robust supply chains, systems, networks, and societies capable of responding quickly to threats and recovering efficiently from failures [14]. Industry 5.0 improves resilience in manufacturing by using flexible, agile, and adaptable technologies [18].

There are two types of resilience, "self-resilience" for employees and "system resilience" for human-machine systems, this encourages collaboration to reach goals that neither could reach independently [21]. This allows for a robust system that can adapt to changes [23]. The European Commission found that enforcing environmental and social governance criteria leads to better resilience [24]. Resilience in organisations is especially important where they provide critical services such as healthcare or security [24].

3.1.4 Personalisation and Customisation

A key concept in Industry 5.0 is moving from mass production to mass personalisation and customisation [8]. This can be achieved through the collaboration between humans and advanced, intelligent, high speed and precise machines [17]. By including critical thinking within processes, mass personalisation can be achieved based on customer needs and expectations.

The demand for human touch is expected to grow as customers increasingly seek to express their individuality through their purchases. This trend reflects a new level of personalisation and a sense of luxury that businesses must address [11]. Kovari [13] states that the combination of human skills and smart factories will enable companies to respond quickly to market changes and demands.

3.1.5 Bioeconomy

The bioeconomy is described as one of the visions for Industry 5.0 by focussing on breakthroughs in agriculture, healthcare, and biosciences [25]. Sindhwani [25] defines a bioeconomy as 'the conversion and production of renewable biological sources into value-added products such as food, bioenergy and biobased products'. This includes a wide variety of industries such as agriculture, forestry, fisheries, technology, energy, and manufacturing industries.

Bioeconomy will act as an enabler for the symbioses between ecology, industry, and economy through the use of bioinspired technologies [14], [21]. The demand for bioinspired technologies is expected to increase due to the growing need for clean, affordable, and sustainable energy. These technologies will be part of bioinspired systems [26].

3.2 RQ2: What are the key components of the Industry 5.0 frameworks?

A recent report by the European Commission outlines six desired characteristics of technologies that support the concept of Industry 5.0 [27]:

- Human-Centric Solutions
- Bio-Inspired Technologies
- Real-Time Digital Twins
- Cyber-Safe Data Transmission
- Artificial intelligence
- Technologies for Energy Efficiency and Trustworthy Autonomy

Figure 2 shows the components most common to least discussed in the 30 articles included. Each of these components will be discussed individually to understand the definition and application.

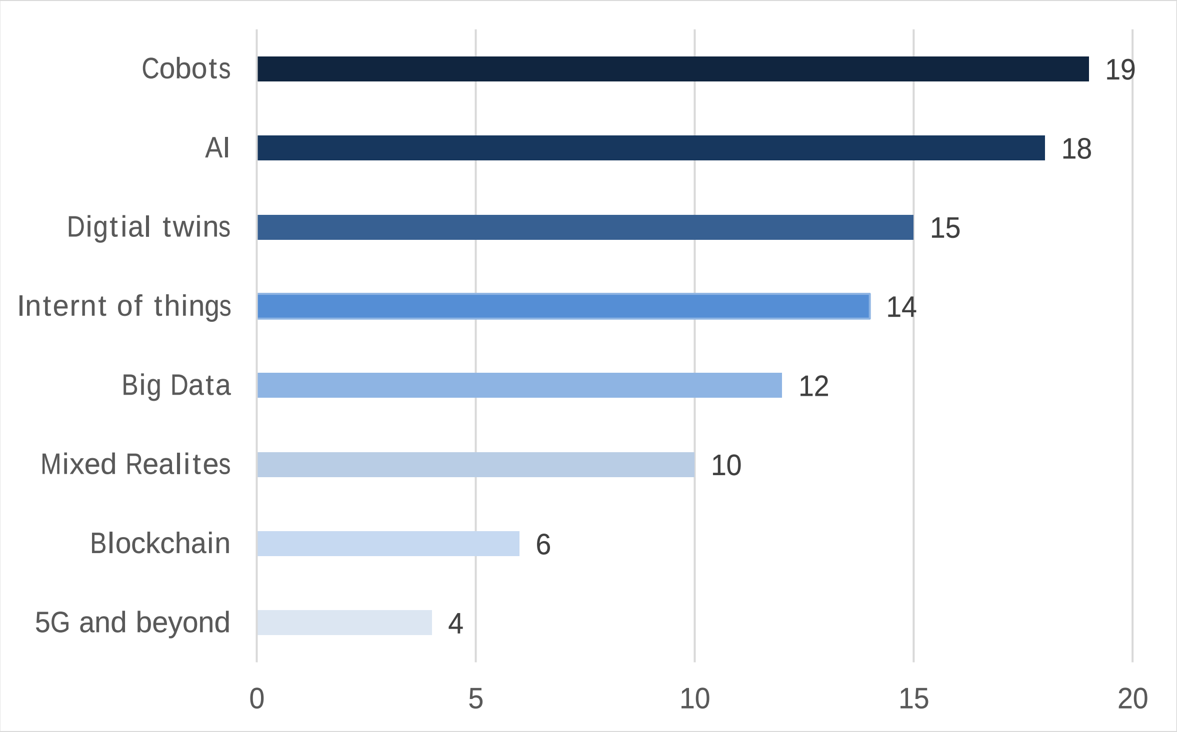


Figure 2: Number of articles discussing industry 5.0 Components

3.2.1 Collaborative Robots (Cobots):

According to George [8], the definition of a cobot is a robot designed to physically interact with people in a shared workplace where safety is prioritised. These robots collaborate with humans on the production line and learn from them. Cobots can recognise and adapt to the activities of their colleagues, creating a safer and more efficient work environment [13].

Specifically in a manufacturing setup, there are two concepts: a) Allowing humans to work on customised, personalised and creative tasks. b) Utilising robots for repetitive and labour-intensive tasks. This can help mitigate risks on the job [20]. By integrating human intelligence and cognitive processes into computers through cognitive computing, they can create more value add. Cobots are also discussed when describing smart factories and improved communication between components and humans [17]. Humans are connected to smart factories through intelligent devices [9].

Another author discussed cobots' role in intelligent healthcare, where cobots can monitor patients' conditions and assist doctors in performing surgeries and handling routine medical tasks allowing doctors to focus on more complex tasks [13]. In manufacturing, consider an example where a technician is performing maintenance on a piece of machinery. The cobot, equipped with a camera, observes the technician's actions, analyses the images using machine learning, and predicts the technician's next steps using fNIRS (functional Near-Infrared Spectroscopy) and deep learning. The cobot then provides the necessary tools and parts to assist the technician when needed [21].

3.2.2 Artificial Intelligence (AI):

AI is a collection of technologies based on AI models and techniques, including machine learning and natural language generation. It is designed to provide services or insights that are challenging or impossible to attain solely through human effort or conventional technologies [28].

By leveraging AI technology together with human-centred digitalisation, we can increase the productivity and sustainability of an organisation. It is the responsibility of organisations to realise the benefits of AI by adopting, extending, and implementing AI tools [29]. For example, artificial intelligence is used to improve predictive forecasts and, therefore, reduce excess manufacturing [18]. According to Akundi [20], AI can meet the personalisation needs of customers in the manufacturing industry and provide faster feedback [30].

3.2.3 Digital Twins

Digital twins are virtual replicas of physical devices or systems that collect real-time data and are used to gather insights and analytics [28]. These twins assist organisations in developing and optimising production processes and can improve predictive maintenance in the manufacturing industry [13]. In the banking sector, Digital Twins can customise products and services, improve the accuracy of automated financial statements, quickly identify technical issues, improve risk management, and avoid investments in high-risk projects [17].

3.2.4 Internet of Things (IoT)

It refers to the network of interconnected software, sensors, and devices that communicate data with other devices, systems, applications, and users to create a comprehensive network infrastructure [28]. It connects different people, systems, data, devices and processes [30]. With the use of smart sensors, IoT devices, and human insights, organisations can gather and analyse data to gain insight into processes [13] [14]. IoT data gathering and analysis are useful when monitoring products and machinery to achieve predictive maintenance [30]. In the banking sector, IoT is used to address challenges related to customer retention and satisfaction [17].

3.2.5 Mixed Realities (Augmented Reality (AR) and Virtual Reality (VR))

Augmented reality integrates digital information with the physical world through computer-generated content such as text, video, or animated 3D models [28]. Virtual reality provides a fully virtual experience that completely isolates the user from the real world, utilising advanced user-computer interfaces for simulation and real-time interaction [28].

This type of technology allows workers to interact and engage with processes and equipment in virtual environments [13]. Since the operator is in a safe environment, this makes it a great tool for training and education and is cost-effective and time-saving [31] [32].

3.2.6 Big Data Analytics

Big data is large volumes and a variety of data sets that need to be handled and processed accordingly [14] [28]. Using big data can support decision-making strategies and automation [30]. Big data analytics helps to understand customer behaviour, product promotions, and process customisation thus improving production efficiency, and reducing costs [17]. It enables organisations to develop successful business strategies and maintain their competitive edge. The use of human creativity and data insights is vital for optimising the value derived from big data [10].

3.2.7 Blockchain

Blockchain creates transparency and provides secure storage for encrypted data [30]. Blockchain technology is used to improve energy efficiency and resource use through process management [18]. It is used to create secure and transparent transactions when improving ESG reporting [14]. Blockchain also has significant potential to improve supply chains by increasing transaction efficiency, reducing costs, and improving security [10].

3.2.8 Other Technologies

Other technologies mentioned or briefly discussed in the articles include exoskeletons, drones, additive technology, edge computing, cloud computing, cyber security, multilingual speech and gesture recognition, tracking technologies, bioinspired safety and support equipment, decision support systems, smart grids, machine learning, federated learning, internet of intelligence, quantum computing, cognitive robotics, bioinspired technology, smart cities, holography, bionics, hybrid intelligence, radio frequency identification (RFID), cognitive cyber-physical systems, human interaction and recognition technologies, intelligent energy management system (IEMS), industrial smart wearable (ISW), horizontal and vertical system integration, and 5G and beyond.

4 DISCUSSION

While Industry 4.0 is focused on technology, Industry 5.0 is focused on value. Industry 4.0 provides the tools and technologies, and Industry 5.0 uses them to create a positive impact on societal and environmental levels. This scoping review has identified key concepts and components essential for the successful implementation of Industry 5.0 frameworks, offering valuable insights into the future of industrial practices. Based on the results above an Industry 5.0 framework is created and visualised in Figure 3.

Figure 3: Industry 5.0 Framework: Key Concepts & Components

Industry 5.0 places human well-being at its core, emphasising the collaboration between humans and machines using the 5C principles (Coexistence, Cooperation, Collaboration, Compassion, Coevolution). Integrating human skills such as creativity, decision-making, and problem-solving with advanced technologies like collaborative robots (cobots) enhances workplace safety, reduces errors, and leads to the reskilling and upskilling of the workforce. Humans still need to make certain immediate or unscheduled decisions that robots will not be able to.

Sustainability in Industry 5.0 encompasses economic, technological, ecological and social dimensions. It involves sustainable supply chain management practices, circular economy models, and the application of the 6R principles (recognising, reconsidering, realising, reducing, reusing, and recycling). Organisations need to work within the limits of our planet. Companies must balance profit with social and environmental responsibilities to succeed in a global, unpredictable environment. Resilience is critical for organisations to withstand and recover from disruptions. Industry 5.0 enhances resilience through flexible, agile, and adaptable technologies. Building robust supply chains and systems capable of quick response and recovery is essential. Enforcing Environmental and Social Governance (ESG) criteria further strengthens organisational resilience.

Resilience is the ability of an organisation to maintain stability during crises, ensuring critical infrastructure remains operational. It involves building robust supply chains, systems, and networks that respond quickly and recover efficiently. Industry 5.0 enhances resilience through flexible, agile, and adaptable technologies. The two types of resilience are "self-resilience" for employees and "system resilience" for human-machine systems, promoting collaboration for achieving shared goals.

From a customer perspective moving from mass production to mass personalisation and customisation is key in Industry 5.0. Advanced technologies like AI and digital twins enable companies to tailor products and services to individual customer needs, enhancing satisfaction and loyalty. From a system perspective, the bioeconomy focuses on the sustainable production and conversion of renewable biological resources. Bioinspired technologies, driven by the need for clean, affordable, and sustainable energy, promote the symbiosis between ecology, industry, and the economy.

Lastly, Industry 5.0 will positively impact employees by exploring different and alternative job roles and training through reskilling and upskilling. It will enhance the quality and health of their working environment through innovative solutions and better organisational governance and ethics. The review identified several critical components supporting the Industry 5.0 framework, including collaborative robots, artificial intelligence, digital twins, the Internet of Things, mixed realities (AR and VR), big data analytics, blockchain, and other emerging technologies. These components collectively enhance human-machine interaction, improve operational efficiency, and drive innovation.

The transition to Industry 5.0 presents several challenges, including legal, psychological, regulatory, and social issues. The evolving roles of HR and IT departments will need to address these challenges by fostering a culture that supports human-machine collaboration and continuous learning. Additionally, integration and technological challenges, such as ensuring interoperability between systems and maintaining data security, require robust leadership and strategic planning.

5 CONCLUSION

Industry 5.0 represents a transformative phase in industrialisation, focusing on human-centric, sustainable, and resilient practices. By integrating advanced technologies with human skills, organisations can achieve greater productivity, customisation, and sustainability. The concepts and components identified in this review provide a foundational framework for the successful implementation of Industry 5.0, guiding organisations towards a future where technological advancements and human well-being are harmoniously balanced.

This study is limited by the scope of the available literature and the rapidly evolving nature of Industry 5.0 technologies and frameworks. Future studies should focus on developing comprehensive implementation strategies for Industry 5.0, considering the unique needs of various industries. This paper lays a robust foundation for future empirical investigations across various industries. Industrial engineers can utilise this framework to assess the transition and implementation of Industry 5.0 within different sectors. Research should also investigate the long-term impacts of Industry 5.0 on workforce dynamics, environmental sustainability, and economic growth. Recommendations to organisations include investing in employee training and development, fostering innovation through collaboration, and adopting flexible, adaptive technologies to improve resilience. Additionally, policymakers should create supportive regulatory environments that encourage sustainable practices and technological integration.

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A SYSTEMATIC LITERATURE REVIEW ON ASSET MAINTENANCE PRIORITISATION APPROACHES RELEVANT TO WATER INFRASTRUCTURE

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ABSTRACT

While various maintenance prioritisation approaches exist, there is a need for a comprehensive understanding of their effectiveness, applicability, and implications for resource allocation and risk mitigation in water infrastructure maintenance. The study aims to identify, examine gaps and best practices in existing knowledge regarding maintenance prioritisation as applied to water infrastructure assets. A systematic literature review methodology was utilised, adhering to the PRISMA reporting protocol, to explore the Scopus database for literature addressing maintenance prioritisation approaches. The findings reveal that organisations commonly use risk-based approaches to prioritise maintenance tasks. The literature emphasises the importance of considering the frequency and consequences of failure when setting priorities for maintenance tasks. Additionally, popular methods for priority-setting include risk assessment and failure mode effect analysis. The study findings could enhance industrial engineers' contributions to maintenance optimisation and inform the development of a prioritisation framework for water infrastructure maintenance for a small South African municipality.

Keywords: maintenance prioritisation, water infrastructure, systematic literature review

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1 INTRODUCTION

Municipal water infrastructure plays a crucial role in sustaining communities, industries, and ecosystems by providing reliable access to clean drinking water and ensuring the adequate disposal of wastewater, both of which are fundamental for public health and economic development [1].

The effective functioning of municipal infrastructure depends heavily on the maintenance practices implemented to address challenges ranging from ageing components to unexpected failures [2]. Velmurugan & Dhingra [3] and Chong et al. [4] emphasise that effective planning for asset maintenance encompasses various maintenance techniques and requires making wise choices among maintenance options.

Mobley [5] highlighted that effective maintenance is crucial for operational reliability and efficiency. Despite widespread awareness, inadequate maintenance procedures in the water industry persist, underscoring the need to optimise operations while minimising risks and costs [6, 7].

Municipalities face multiple water infrastructure challenges, such as managing aging assets, budget constraints, and increasing maintenance demands [4, 8]. These challenges are compounded by the need for effective resource allocation. Consequently, municipalities often defer maintenance to reduce expenses and direct resources toward more critical areas, leading to the accumulation of maintenance backlogs [4].

Balzer and Schorn [9] acknowledged the compounding challenges facing the water industry due to rising demand. Furthermore, the interplay between limited resources and the need for robust and sustainable water infrastructure underscores the necessity of a comprehensive understanding of the latest best practices and context-specific approaches for prioritising maintenance [10].

This study aims to investigate the maintenance prioritisation approaches commonly applied to water infrastructure assets. By conducting a systematic literature review (SLR), the study seeks to identify and examine gaps and best practices in the current knowledge of maintenance prioritisation for water infrastructure assets. The findings will inform the development of a prioritisation framework for water infrastructure maintenance, focusing on reducing service delivery interruptions and enhance infrastructure reliability.

2 BACKGROUND OF THE STUDY

According to Mutamba [11], water infrastructure encompasses essential physical components and mechanisms that play a crucial role in delivering safe and reliable water services to communities. However, these assets inevitably degrade overtime, impacting their reliability and functionality [12]. Thus, strategic maintenance is vital to ensure safety and stability while minimising repair costs.

Maintenance activities encompass regular inspections, condition assessments, identifying of critical components, repairs, and the developing of maintenance plans [3, 4, 9]. Despite these efforts, resource limitations often result in maintenance backlogs, necessitating the prioritisation of maintenance tasks to ensure operational continuity.

Maintenance prioritisation, as explained by Chong et al. [4], is a technique utilised to ease the immediate burden of maintenance requests, enabling the immediate handling of pressing issues. However, postponed tasks require attention eventually, underscoring the need for judicious decision-making by maintenance practitioners.

Effective asset management decision-making is pivotal for developing cost-effective maintenance programs and enhancing infrastructure performance [13, 14]. This systematic approach allows utility companies and municipalities to make well-informed decisions regarding intervention strategies [2, 13, 14].

Given financial constraints and dynamic regulatory landscapes, prioritising maintenance based on risk exposure and critical criteria is crucial. Chirito [14] and Petersdorff and Vlok [13], emphasised developing targeted maintenance strategies to address the challenges posed by aging infrastructure and evolving needs .

The complexity of creating a comprehensive maintenance prioritisation system for municipal water infrastructure is acknowledged by the Development Bank of Southern Africa [15], Mutamba [11], and Mnguni [16], emphasising the need to consider the unique characteristics and interdependencies of water infrastructure assets.

To address the aforementioned complexity, it is imperative to analyse the selection and implementation of context-based maintenance prioritisation strategies, as articulated by Teixeira et al [17]. This study acknowledges the research conducted by Chong et al. [4] and Wing et al. [18], which explored factors and methods for prioritising maintenance. However, while comprehensive, these studies did not specifically target water infrastructure assets.

The SLR conducted in this study could enhance understanding of maintenance decision-making processes in water infrastructure management by evaluating various maintenance prioritisation approaches. The study is driven by the recognition that current approaches may not yield optimal outcomes, potentially resulting in costly and ineffective maintenance practices or a narrow focus on high-consequence assets. The goal is to provide recommendations for improving maintenance prioritisation strategies and asset management practices in the water sector, ensuring efficient management and safeguarding of critical water infrastructure assets to continuously provide vital services to communities.

3 METHOD

The study follows an SLR methodology to assess and interpret relevant research on asset maintenance prioritisation strategies relevant to water infrastructure in line with Kitchenham [19] and Siddaway et al.'s [20] approach. The systematic literature review (SLR) study consolidated existing information on asset maintenance prioritisation strategies relevant to water infrastructure. Through meticulous documentation of the methodology, the study ensured a comprehensive overview of current strategies, facilitating the identification of best practices and prevailing trends in the field. The approach not only aided the understanding of asset maintenance but also underscores the importance of replicability and transparency in research, as emphasised by Grant and Botha [21]. The SLR is guided by Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [22].

3.1 Research protocol

Table 1 provides a detailed account of the research protocol, which includes information on the purpose of the study, research questions, inclusion criteria, exclusion criteria, databases searched, keywords used and quality assessment criteria employed.

Table 1: Research protocol

Purpose of the study	To investigate the maintenance prioritisation approaches commonly applied to water infrastructure assets
Research questions	**RQ1**: What are the prevalent water infrastructure asset maintenance prioritisation strategies in literature? **RQ2**: What are the key factors influencing the selection of maintenance prioritisation strategies in managing water infrastructure?
Inclusion criteria	• The paper discusses maintenance prioritisation being applied to water infrastructure management. • The research paper focuses on asset management in water infrastructure.
Exclusion criteria	• The paper is a duplicate publication. • The full text of the paper is not in English except for the title. • There is no access to the full text of the paper. • The research paper loosely uses terms and synonyms related to maintenance and prioritisation. • The research paper focuses solely on maintenance prioritisation outside the context of water infrastructure. • The research papers that are unrelated to the primary focus of the study.
Search Database	Scopus
Keywords	"water infrastructure" and "asset management" and "maintenance prioritisation"
Quality assessment criteria	• All duplicate literature must be removed. • Correct scientific methods must be used throughout the research study. • The overall methodology should be described in a manner that allows the study to be replicated. • Recovered literature should be checked for relevance and credibility. • Proper grammar, syntax, and terminology should be used to ensure the reader fully understands the research's intentions and outcomes.

3.2 Search strategy

The primary approach used to gather data involved searching the Scopus databases for articles using specific keywords related to "maintenance prioritisation", "asset management", and "water infrastructure". Search terms were carefully selected to reflect the main themes presented in the research questions while considering spelling variation, synonyms and usage differences. The approach followed increases the chances of identifying relevant studies [20].

Table 2 presents alternative terms used to encompass any potential differences in spellings or usage of synonyms.

Table 2: Search terms (alternative terms included)

Search terms	Alternative search words
Water infrastructure	
Asset management	Infrastructure management
Maintenance prioritisation	Maintenance prioritization, maintenance priority, maintenance management, maintenance priority setting, maintenance planning, maintenance scheduling, reliability-centred maintenance (RCM), priority setting methods, maintenance strategy selection

3.3 Search scope

The SLR review was conducted on the Scopus database, and only papers published in the last ten years, i.e. from January 2014 to December 2023, were reviewed to advance the existing research. The Scopus database was chosen for its extensive repository of peer-reviewed literature, providing a significant range of research contributions relevant to our research questions. The search returned a total of 442 studies which underwent scrutiny and evaluation following the PRISMA guidelines.

3.4 Study selection

Guidelines for selecting papers in this study adhered to the exclusion and inclusion criteria outlined in Table 1. The screening process involved a thorough examination of each paper's title, abstract, and full text. This comprehensive evaluation aimed to determine the potential relevance of each paper to the research objectives and adherence to the specified criteria. Papers that did not meet these criteria (described in Table 1) were excluded from the study. Despite retrieving many articles, many were not directly related to water infrastructure due to their abstract nature. Each article's abstract was carefully examined, and those considered relevant were further explored.

Ambiguous abstracts led to a review of the conclusion section or a rapid assessment starting from the introduction to determine relevance. Articles that remained unclear were ultimately disregarded.

Figure 1 summarises the selection stages followed in this study which included the removal of articles that were duplicated (DP), non-English studies (LC), studies that did not allow full access (NF), unrelated to the study's primary focus (NR) and studies that casually related to this study. This led to the remaining 14 eligible articles which were further analysed.

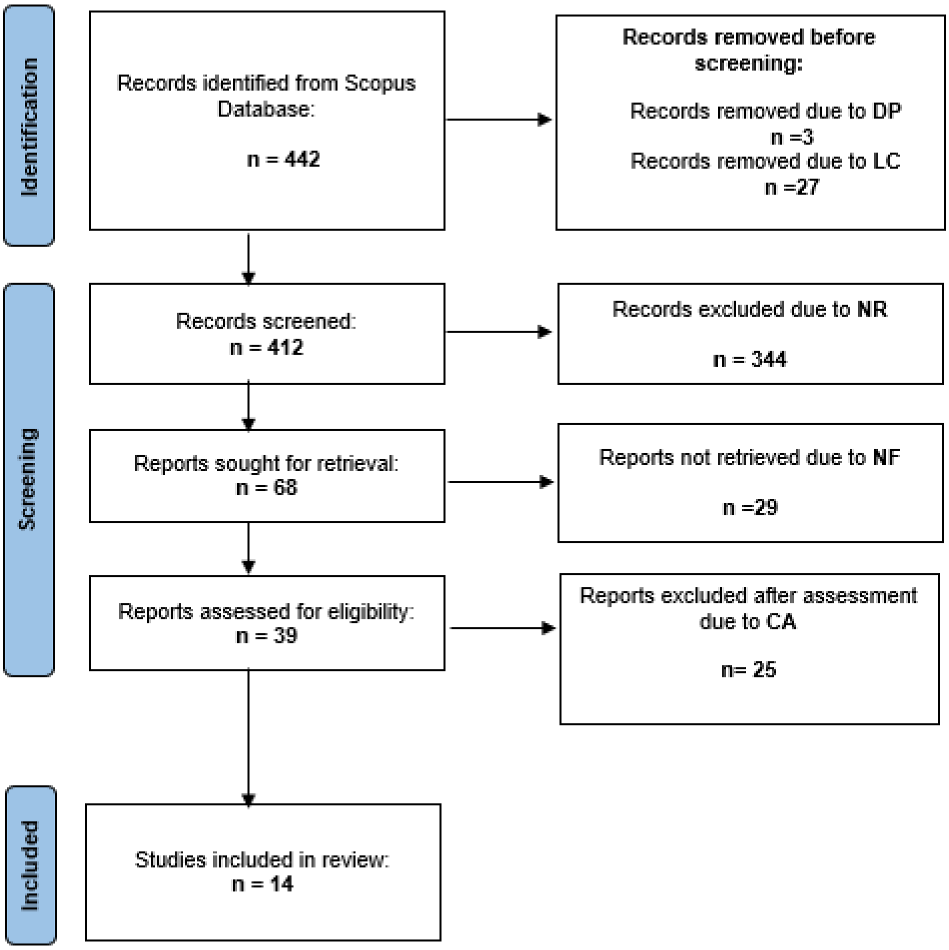

Figure 1: PRISMA flow diagram for systematic reviews [22]

3.5 Quality assessment for relevant studies

The quality of relevant literature was evaluated by thoroughly reading the articles. The retrieved studies were examined to determine their relevance to maintenance prioritisation in water infrastructure asset management and the factors they addressed. Evaluation criteria included language use, writing credibility, and reputable scientific research methods used in the literature.

3.6 Data analysis

To address the research questions outlined in Table 1, a total of 14 articles were selected for in-depth study. The data collection and review process were intentionally open-ended, permitting exploration of various aspects related to maintenance prioritisation without imposing predefined categories or biases. This approach facilitated a comprehensive examination of the topic.

The extracted data encompass diverse elements of maintenance prioritisation, including various methods, models, factors, algorithms, frameworks, tools, and decision-making processes. These elements form the basis for further analysis and synthesis aimed at effectively addressing the research questions and objectives of the study.

A qualitative analysis was employed to interpret the collected data, specifically through the application of descriptive coding. This method was chosen to identify the maintenance prioritisation strategies utilised in addressing water infrastructure maintenance issues and to determine the factors influencing these prioritisation decisions. Table 4 provides a summary of the literature included in the study, listing relevant references and offering a brief overview of each article's content.

4 SYSTEMATIC LITERATURE REVIEW FINDINGS

4.1 Literature overview

Figure 2 below illustrates the distribution of studies on water infrastructure maintenance by country, revealing a notable lack of contribution from developing countries. The majority of studies were conducted in the Netherlands and the USA, constituting 30% of the reviewed journal articles and conference papers.

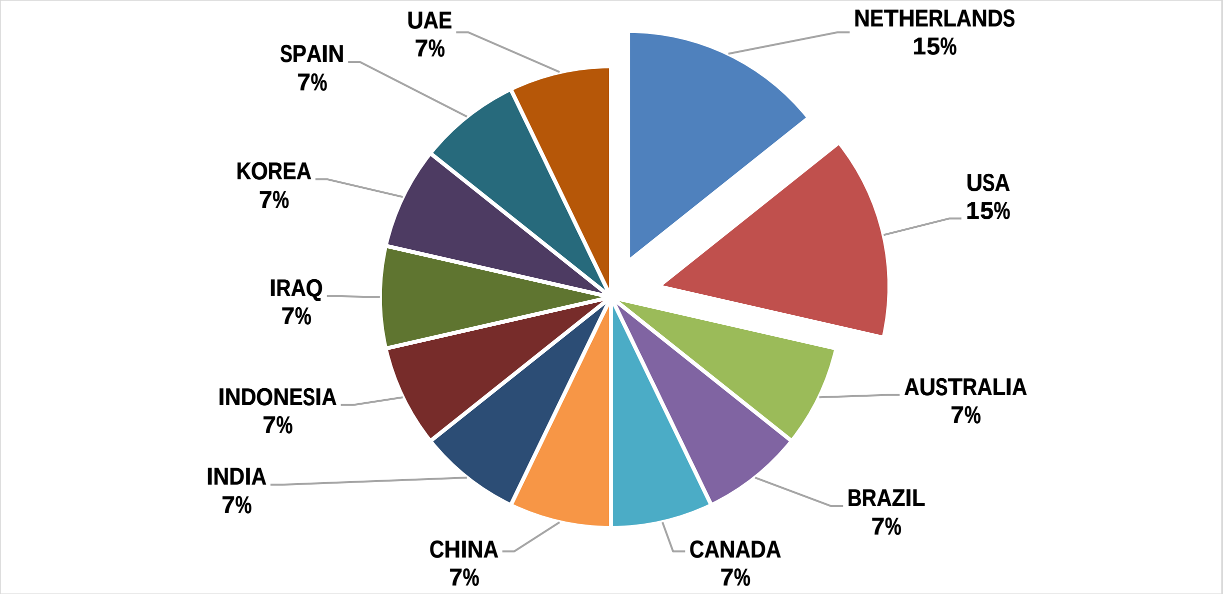

Figure 2: Countries in the reviewed studies

The water distribution and wastewater infrastructure are essential elements of urban systems, ensuring access to clean water and proper wastewater management. However, research exhibit a notable maintenance priorities discrepancy between these two infrastructural types, as depicted in Figure 3. Literature predominantly emphasises maintenance of water distribution infrastructure pipeline networks.

The emphasis on pipeline networks in both water distribution and wastewater infrastructure is justified by their essential role as the backbone of these systems, facilitating water transportation. Their critical function, susceptibility to deterioration, and significant economic implications underscore the focus on pipeline maintenance. Any disruptions in these pipelines can lead to severe consequences, highlighting the need for prioritised maintenance efforts.

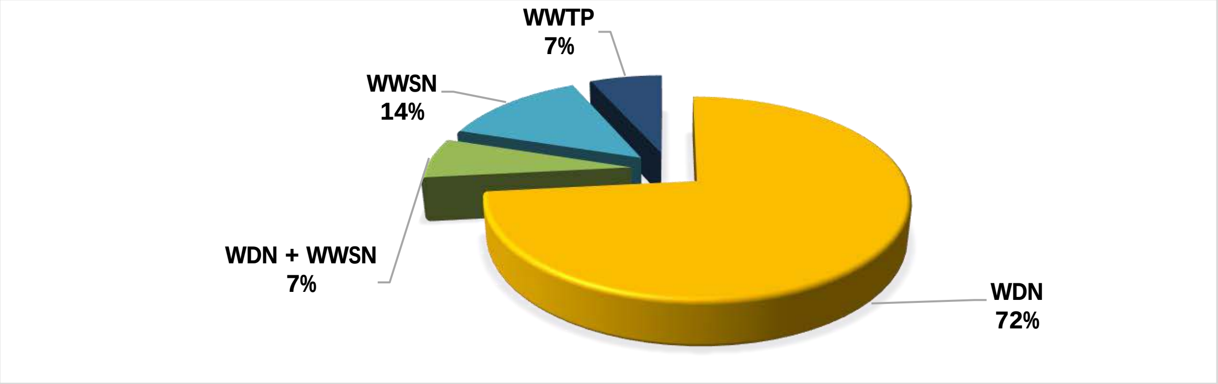

Figure 3: Application context of the reviewed studies (wastewater sewage network (WWSN), wastewater treatment plant (WWTP), water distribution network(WDN))

4.2 Prevalent maintenance prioritisation strategies

Table 3 provides a summary of common maintenance prioritisation strategies used in the water infrastructure sector, identified through a systematic literature review. The summary categorises the strategies, techniques, or methods employed, along with corresponding references from eligible articles meeting the inclusion criteria.

Table 3: Maintenance prioritisation strategies

Strategy/Approach	Method/ Technique	Reference
Risk-based	• Risk analysis + Complex network theory analysis • Fuzzy-FMEA • Risk analysis/assessment) + Risk map • Risk assessment • AHP-fuzzy model • FMECA + Life cycle cost analysis • Risk assessment	[23-28]
Asset criticality analysis	• Segment Criticality Measure/assessment/analysis • Graph theory method • Element-based simulation approach + Critical index • Graph theory	[29-32]
Optimisation	• Non-dominated Sorting Genetic Algorithm • Multi-Objective Genetic Algorithm	[33, 34]
Multi-Criteria Decision Analysis (MCDA)	• FFM-EA + FMRPI-FMTI Risk diagram • Strategic Options Development and Analysis + ELECTRE TRI-nC method	[35, 36]

Table 44: Summary of the studies included in the review

Author	Factors considered	Prioritisation approaches	Results
[29]	Asset criticality, impact on service delivery	Segment Criticality Measure/assessment/analysis	Framework for scheduling maintenance routine
[23]	Risk, asset criticality	Risk analysis + Complex network theory analysis.	Risk-informed decision support framework for integrated water and road infrastructure asset management.
[33]	Condition - economic cost, network reliability, and network health	Non-dominated Sorting Genetic Algorithm	A Life Cycle Oriented Multi-objective Optimal Maintenance model for Water Distribution
[35]	Asset condition, risk, budget constraints	Fuzzy-Failure mode effect analysis(FFM-EA) - Risk Priority Index and the Total Intensity (TI)-AHP, FMRPI-FMTI Risk diagram	Fuzzy-based Multi-Criteria Decision Support System for maintenance of wastewater treatment plants
[30]	Asset criticality, impact on service delivery	Graph theory method	A method of Identifying critical elements in drinking water distribution networks
[34]	Risk , asset criticality, proximity, budget constraints, asset condition	Multi-objective genetic algorithm (MOGA)	A decision support system to design water supply and sewer pipe replacement intervention programs
[32]	Asset criticality	Element-based simulation approach Criticality index	A methodology to Identify Critical Pipes Using a Criticality index
[25]	Risk, asset condition	Fuzzy-FMEA	A risk-based method of identifying and prioritising causes of failure for maintenance planning
[24]	Risk	Risk analysis/assessment) Risk map	Framework for risk assessment of pipes in a WDN for maintenance prioritisation
[26]	Asset condition, risk, budget constraint	Risk assessment - risk rating matrix; Life Cycle Costs analysis	Risk-based approach to develop a maintenance strategy
[36]	Asset criticality, asset condition	Strategic Options Development and Analysis (SODA), Elimination and Choice Translating Reality (ELECTRE TRI-nC) method,	A methodological framework for sorting the water distribution network areas for the maintenance plan.
[31]	Asset criticality	Graph theory method	A method of identifying the most critical elements in a network with respect to malfunctioning of the whole system.
[27]	Environmental impact, risk	AHP-fuzzy model	An AHP-fuzzy model to determine maintenance priority based on environmental factors
[28]	Asset condition, asset criticality, risk	Failure mode effect analysis Asset Criticality analysis Life cycle cost analysis	Water asset replacement maintenance prioritisation procedure

Figure 4 shows that 43% of the analysed studies employed a risk-based strategy to prioritise maintenance activities based on the likelihood and consequences of asset failure. Given the substantial impacts of water infrastructure malfunctions on public health and environmental safety, this approach is crucial. The widespread use of risk-based methods underscores their effectiveness in providing proactive maintenance for vital assets and in mitigating long-term expenses by preventing significant failures.

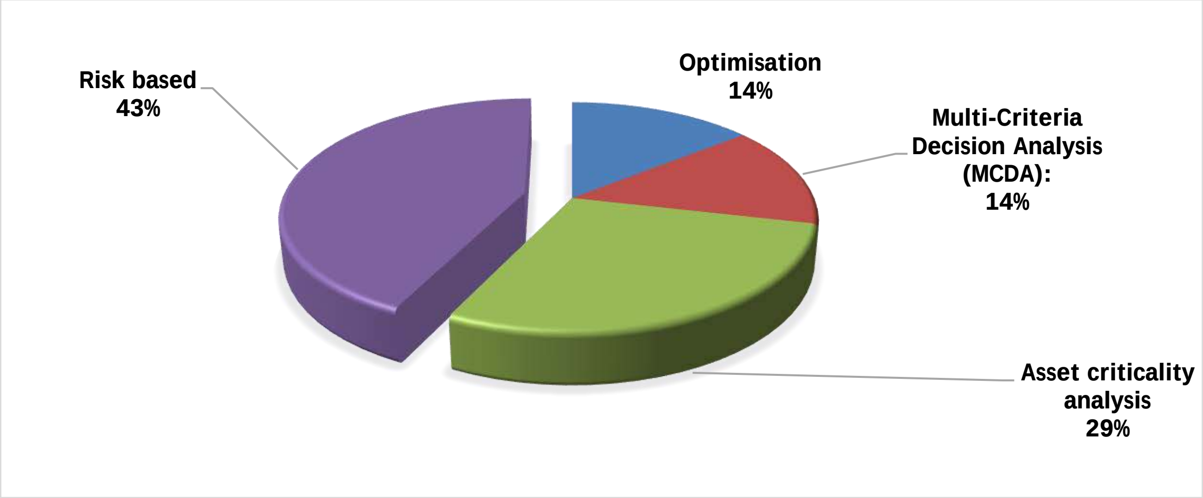

Figure 4: Application of maintenance prioritisation approaches

The importance of risk management techniques in maintenance prioritisation extends beyond identifying high-risk areas within water infrastructure networks. Maintenance practitioners not only address these high-risk areas to prevent potential failures that could endanger public health, safety, and the environment, but also utilise risk assessments to inform resource allocation decisions [23-25].

In addition, risk assessment is essential for ensuring regulatory compliance in water infrastructure management. Non-compliance with regulatory standards, such as pipeline leakages or deteriorating wastewater treatment plants, can lead to contamination or poor water quality, violating water utilities' obligations to provide safe and continuous clean water [26].

Asset criticality analysis, comprising 29% of reviewed articles, ranks as the second most dominant approach, as shown in Figure 4. This analysis evaluates each asset in the water infrastructure network to determine its significance. Assets deemed crucial, either due to their key role in the system or their potentially severe impact if disrupted, are given top priority in maintenance operations. A study by Tornyeviadzi et al [29], employed segment criticality analysis to identify specific segments within the water distribution network (WDN) that can undergo maintenance without causing operational disruptions or hindering service delivery.

Incorporating asset criticality analysis emphasises the importance of maintaining high-priority components within water infrastructure and enables effective resource allocation by establishing priorities necessary for optimal functionality and uninterrupted service delivery across all networks involved.

Given the necessity to balance multiple objectives and navigate conflicting constraints during decision-making, multi-criteria decision analysis (MCDA) methods offer a comprehensive approach to assessing maintenance priorities aligned with organisational goals and stakeholder preferences [28, 35, 36]. Figure 4 shows that MCDA approaches account for 14% of the studies. Multi-criteria decision analysis involves the use of multiple criteria to evaluate and prioritise maintenance activities. These criteria can include risk, cost, asset criticality, and other relevant factors [28]. This approach provides a structured framework to balance various competing factors. The adoption of MCDA indicates the recognition of complexity involved in asset management decision-making and multifaceted nature of maintenance prioritisation in water infrastructure.

Although potentially powerful, multi-criteria optimisation is the least common approach in the reviewed literature (Figure 4). It employs mathematical and computational techniques to determine efficient resource allocation and maintenance schedules with specific objectives like cost minimisation or asset reliability maximisation. For instance, in a study conducted by Chu et al. [33], the genetic algorithm was utilised to optimise maintenance schedules by exploring trade-offs between conflicting objectives, such as minimising risks and maintenance costs while maximising system reliability, all within the constraints of available resources or system limitations. Chu et al. [33] asserted that genetic algorithms help decision-makers identify maintenance strategies that effectively balance multiple goals by generating a varied set of pareto-optimal solutions to enhance operational efficiency, reduce costs, and prolong asset lifespan.

4.3 Key factors influencing maintenance prioritisation

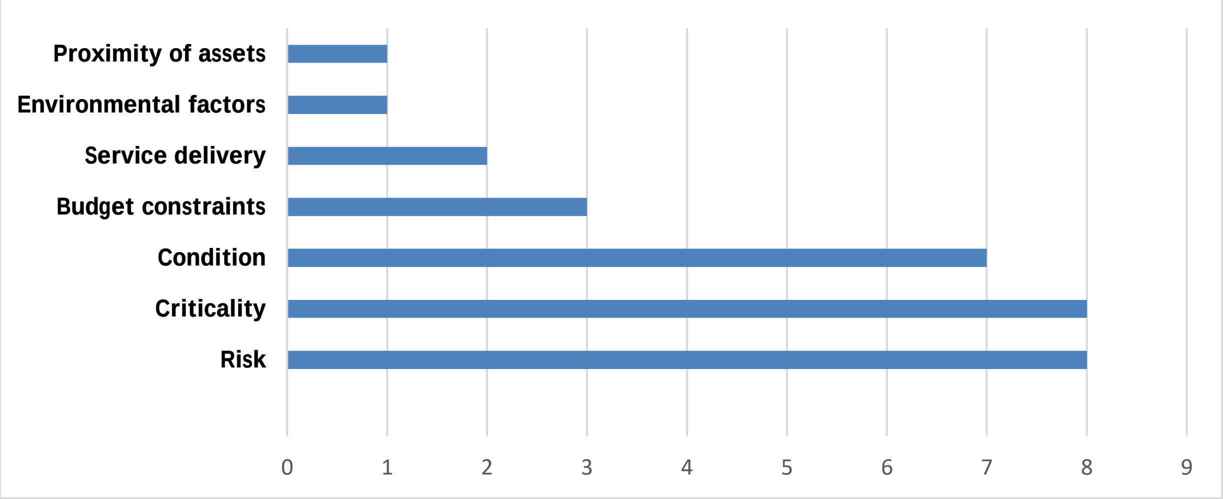

Figure 5: Factors on maintenance prioritisation

Figure 5 shows the key maintenance prioritisation factors that emerged from the study: criticality, asset condition, risk, budget constraints, service delivery, and proximity. The analysis of these factors reveals a multifaceted decision-making process influencing maintenance prioritisation in water infrastructure. The interaction between these factors in determining maintenance priorities for water infrastructure is complex and dynamic, with each factor uniquely shaping the decision-making process. Equipment risk, criticality and condition had top frequency of discussion in the papers considered.

The study findings reveal consistent theme of risk consideration across various aspects when prioritising maintenance for water infrastructure assets (Figure 5). Evaluating risk involves analysing both the probability and potential consequences of asset breakdowns [26]. This process helps identify assets that may pose significant risks to public safety or system functionality.

By prioritising risk assessment, water infrastructure managers can prevent serious accidents and protect high-risk assets through strict adherence to safety protocols. This emphasises the importance of avoiding hazards to mitigate potential risks proactively. Mazumder et al. [23], emphasised the importance of considering the potential impact of failure, particularly in the context of buried pipelines that could affect nearby infrastructure. This underscored the necessity of integrating risk assessment into maintenance planning to proactively address risks and enhance the resilience of water infrastructure systems.

The condition of water infrastructure assets is also a critical factor. Maintenance decisions are heavily influenced by the physical state of the infrastructure, with deteriorating assets requiring immediate attention. By monitoring and conducting inspections, water utilities can identify assets in poor condition or at risk of failure, a sentiment echoed by Al-Attar et al. [35]. Notably, the age and condition of assets are intertwined with their lifecycle, with assets deteriorating towards the end of their life and requiring increased maintenance, as observed by Chong et al [4]. The knowledge of the asset age and asset condition helps prioritise maintenance tasks, addressing immediate risks and preventing service disruptions or safety hazards over assets in better condition.

Water infrastructure assets in poor condition can lead to service disruptions, impacting consumer satisfaction and regulatory compliance [34]. Identifying critical assets, particularly those in poor condition or at higher risk of failure, is crucial as they can significantly impact water quality, service reliability, and public health if they fail. Condition assessment is a fundamental aspect of many models, such as life cycle-oriented maintenance and criticality index methodologies, which prioritise maintenance based on the current state of the assets.

Criticality is a key factor in the decision-making process, especially when it comes to prioritising, budgeting, and planning for repairs and replacements as articulated by Katheeri et al. [28] and Marlim et al. [32]. Asset criticality becomes even more imperative in scenarios involving aging infrastructure, limited budgets, asset interdependencies, and potential impacts on network performance or operations. These insights echo findings from studies by Al-ttar et al. [35] and Marlim et al. [32], highlighting the central role of asset criticality in guiding maintenance prioritisation efforts to enhance the resilience and reliability of water infrastructure systems.

In summary, SLR findings indicate that a balanced approach, considering both technical and practical factors, is essential for effective maintenance prioritisation in water infrastructure. By integrating these diverse factors and strategies, maintenance practitioners can develop comprehensive maintenance strategies that improve water infrastructure resilience, optimise resource use, and ensure continuous service delivery.

5 DISCUSSION

5.1 Discussion of the SLR

The systematic literature review (SLR) identified a consistent theme of risk consideration and the implementation of risk-based strategies, demonstrating the effectiveness of risk management techniques in the maintenance prioritisation of water infrastructure systems.

Tools such as risk assessment, risk matrices, FMEA, FMECA, and risk maps augment the decision-making process aimed at mitigating the associated risks. By identifying critical failure modes and assessing risks, decision-makers can optimise maintenance planning, allocate resources efficiently, and enhance the overall reliability of water infrastructure systems. Risk assessments prioritise maintenance efforts on critical assets to prevent potential issues and improve practices. However, the study revealed that due to resource constraints, maintenance practitioners tend to focus primarily on addressing maintenance risks that pose the greatest threat to their business objectives.

The success of a decision-making system relies heavily on amassing sufficient and relevant data [35]. Limited access to asset data poses significant challenges, hindering effective infrastructure monitoring and problem resolution. Reliable data is fundamental to understanding the current condition of assets, predicting future performance, and formulating appropriate maintenance and management strategies. The SLR revealed the difficulty of conducting thorough risk assessments with inadequate data, underscoring the necessity of robust data collection strategies to enhance asset condition monitoring and evaluation. Chu et al [33], further proposed that dependable data collection and model validation are crucial for scientifically managing water distribution networks.

Multi-criteria decision analysis (MCDA) approaches effectively incorporate qualitative factors into decision-making processes, particularly when information or analytic resources are scarce. MCDA supports maintenance decisions involving multiple factors, constraints and adapts as more data becomes available. However, selecting the appropriate MCDA technique for resource allocation remains challenging. Techniques such as the analytic hierarchy process (AHP), failure mode effect analysis (FMEA) and others have inherent strengths and weaknesses that must be evaluated to determine their suitability in specific context, as demonstrated by Pereira et al. [36] and Maryati & Romdoni [27]. These techniques can be complex and require specialised knowledge, which may not be available in some municipalities.

Life cycle-oriented, multi-objective optimisation and multicriteria decision models are important for balancing objectives such as cost, reliability, and service level in comprehensive maintenance management. Optimisation techniques can significantly reduce operational costs and enhance service delivery, which is increasingly important as water utilities aim to improve financial sustainability and operational efficiency. While promising, these approaches are less widely adopted due to complexity and resource demands.

Advanced analytical techniques, fuzzy logic, and decision support models are prevalent, yet there a need for customised models to handle uncertainty and complexity in maintenance decision-making. Life cycle cost (LCC) analysis for budget allocation and asset replacement/renewal decisions as noted by Katheeri et al. [28]. However, there is a lack of comprehensive discussion on the practical implementation of LCC analysis in the reviewed studies.

In summary, the literature indicates the need for adaptable maintenance prioritisation strategies that incorporate structured decision-making methods, consider resource constraints, and employ advanced analytical techniques.

5.2 Gaps in literature and recommendations for research

A notable research gap exists regarding the economic consequences of maintenance decisions, particularly in water infrastructure management. This gap hinders effective collaboration between technical and financial teams, potential leading to misalignment between technical decisions and financial constraints, resulting in suboptimal resource allocation and inefficiencies.

There is an identifiable gap in the literature regarding the development of tailored solutions and strategies for managing water infrastructure, particularly in the developing countries of Southern Africa.

Currently, most research studies tend to narrow their focus to specific situations, concentrating on prioritising maintenance for individual assets. However, this approach often results in a fragmented understanding, lacking a comprehensive strategy that considers the interconnectedness of all assets within a portfolio. This fragmented approach poses challenges for practitioners, who may struggle to implement these findings across different contexts. Therefore, future research efforts should aim to refine existing solutions and assess their effectiveness across a range of settings. By doing so, we can bolster the resilience of water infrastructure worldwide, ensuring that strategies are adaptable and beneficial in diverse environments.

The synthesis of the research outcomes highlights several critical implications for academic research in water infrastructure maintenance. Researchers can undertake several strategic studies to enhance water infrastructure asset management practices and understand their implications across various dimensions:

- Studies can assess the effectiveness and outcomes of different asset management approaches. By employing longitudinal research, scholars can track how asset distribution changes over time and its consequent effects on maintenance performance, resilience, and sustainability.
- Future research in water infrastructure asset management should prioritise the integration of emerging trends such as advanced analytics, machine learning, IoT technologies, and digital twins. Digital twins allow for predictive maintenance, where potential issues can be identified and resolved before they lead to costly failures. Incorporating these advanced technologies enhances the effectiveness and efficiency of maintenance operations and contributes to the overall reliability and sustainability of water infrastructure systems. With improved prediction and optimisation mechanisms, the lifespan of assets can be extended, and the risks of catastrophic failures can be significantly reduced. Therefore, future research must continue to explore and refine these technologies. Ongoing innovation will ensure that asset management practices evolve in line with the demands of modern infrastructure systems. By staying ahead of technological advancements, asset managers can better safeguard water infrastructure, ensuring its resilience and reliability for future generations
- Examining asset management across different industries can uncover transferable strategies and best practices. Comparative analysis can identify common challenges and opportunities for cross-sector collaboration and knowledge sharing, providing a broader understanding of effective water infrastructure asset management.
- Conducting cost-benefit analyses of various maintenance strategies will help water utilities and policymakers understand the economic impacts of investing in advanced maintenance technologies and practices. These evaluations can provide a solid economic rationale for adopting innovative asset management approaches.

By synthesising insights from these areas, researchers can contribute to the development of robust, efficient, and sustainable asset management practices for water infrastructure assets.

5.3 Contribution of the study

The study consolidates and analyses existing research on maintenance prioritisation for water infrastructure assets, providing a holistic view and comprehensive understanding that is often missing in individual studies. The study identifies and compiles commonly used maintenance practices and effective strategies from various sources, offering a clear guide for maintenance practitioners to adopt proven approaches in the water industry. By effectively prioritising maintenance, water infrastructure managers can optimise resource allocation, reduce downtime, and extend the lifespan of critical assets.

By examining the breadth of existing literature, the study identified areas needing further exploration, thus acting as a guide for future research by pinpointing unexplored areas, emerging trends, and technologies (as highlighted in section 5.2) in the maintenance of water infrastructure assets. The review allows for a comparative analysis of different maintenance prioritisation strategies, highlighting their applicability to various contexts within water infrastructure. This study is valuable as it provides a comprehensive synthesis of current knowledge and sets the stage for future advancements in the field, ultimately contributing to more efficient, reliable, and sustainable water infrastructure management. The study offers a clear and reproducible methodology, that will enable other researchers to build upon these findings, ultimately contributing to more efficient and sustainable maintenance practices for water infrastructure assets.

5.4 Limitations

This SLR was based on publications from 2014 to 2023. The SLR exclusively considered English-language publications, potentially excluding significant studies published in other languages. The SLR solely reviewed research indexed in the Scopus database, thereby leaving out pertinent studies published elsewhere. Additionally, the SLR did not include grey literature, even though these sources can sometimes offer valuable insights and data. This exclusion was because grey literature is often not peer-reviewed and may lack the rigorous quality control and academic validation that peer-reviewed journal articles and conference papers provide. This decision was made to ensure the reliability and credibility of the data included in our systematic review. The wide variety of research goals and methodologies among the reviewed studies created substantial heterogeneity, precluding the possibility of conducting a meta-analysis.

6 CONCLUSION

This study presented a systematic literature review of maintenance prioritisation strategies in the water infrastructure sector. It enhanced the understanding of maintenance prioritisation practices applied to water infrastructure assets, highlighting prevailing strategies (section 4.2) and the dominant factors considered (section 4.3). The review underscores the necessity for data-informed, holistic maintenance prioritisation strategies in the water infrastructure sector.

Current efforts emphasise risk-based and criticality analyses, which constitutes 72% of the maintenance prioritisation strategies employed. However, there is considerable room for advancement. Future research should aim to develop comprehensive, data-driven strategies that leverage advanced analytics, machine learning, and predictive modelling. These strategies should evaluate entire asset portfolios rather than individual components, allowing for the identification of trends and failure modes across various water infrastructure assets. This approach would enhance long-term performance and sustainability. Addressing the identified gaps requires creating adaptable, universally applicable maintenance strategies capable of addressing diverse contextual challenges, especially in underrepresented regions such as developing countries in Southern Africa.

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AN INVESTIGATION INTO THE STATE OF ART OF QUANTITATIVE PERSPECTIVES ON SUSTAINABILITY INITIATIVES: A SYSTEMATIC REVIEW OF LITERATURE

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ABSTRACT

To respond to the ever-increasing sustainability demands, society, organisations, and businesses must employ innovative practices and technologies. Businesses need to be more sustainable in the way that they conduct their operations, and need to investigate and uncover opportunities to effectively transition to more sustainable services, products and business operations. The contribution (both positive and negative) that a business's operations and practices have towards the promise of a sustainable future should be considered. The impacts of sustainability initiatives of a business are often challenging to quantify due to the ambiguity that exists around the conceptualisation and definition of impact assessment approaches and the lack of universally applicable methods, primarily due to the contextual differences between businesses. This paper provides a systematic literature review to explore state-of-the-art approaches in quantifying sustainability impacts. The review aims to consolidate current knowledge and highlight the best practices and methodologies for sustainability assessments in business contexts.

Keywords: Sustainability, quantitative perspective, systematic literature review

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1 INTRODUCTION

In the face of escalating climate change, humanity finds itself at a pivotal juncture where urgent action is necessary. Businesses are being placed under scrutiny due to the potential for substantial effect and capability of change towards sustainability. Sustainability could also foster long-term growth and resilience in a business. While many businesses have started integrating sustainability principles into their strategies, others find difficulty in implementing sustainability due to barriers such as lack of understanding, limited resources, insufficient stakeholder engagement, and inadequate measurement tools [1]. Without reliable ways to measure sustainability, there is a reluctance to implement sustainability principles. Hence, there is a need to simplify and bridge the gaps to quantify sustainability.

To bridge this gap in quantifying sustainability, one must first understand the meaning of sustainability as well as other relevant terms. Definitions of sustainability have been debated for many years, without consistency. In essence, sustainability is a multifaceted concept that requires achieving equilibrium among various factors to ensure the survival of the planet [2].

In the business sector sustainability is often coupled with the theory of the *triple bottom line* (TBL) which was defined by Elkington in 1998 [3]. The TBL is defined as expansion of the environmental agenda in a way that integrates the economic and social lines [3]. The TBL and sustainability are often used interchangeably. The TBL's framework aims to place equal value on economic, environmental, and social dimensions, where the economic dimension refers to the organisation's impact on the economy, social refers to how the company treats its people both internally and within the community, and the environmental dimension is focused on the company's impact on the environment [3].

Sustainable development was defined by Brundtland in 1987 [4] as *"development that meets the needs of the present generation without compromising the ability of the future generations to meet their own needs"*. The Brundtland report has gained significant attention with further momentum gained due to increasing pressure from society and stakeholders. This has evolved where in the 21st-century sustainable development integrates economic, social, and environmental goals with a focus on equity, resilience, technological innovation, and global-local alignment.

In addition to this, Peter Drucker was attributed to saying, *"If you can't measure it, you can't improve it"* [5]. This encapsulates the importance of measurement in management and the improvement of sustainability. To get companies to make a change towards sustainability to improve for the future, measurements of sustainability must be considered. Quantifying sustainability is achieved through using numerical values. Due to the large number of factors effecting sustainability, it can be considered as a multi-objective optimisation problem.

Therefore, the purpose of this paper is to review the peer-reviewed articles that have been published before 2024, to consolidate knowledge and organise information quantifying sustainability. To fulfil this research objective a systematic review of literature is performed with a focus on quantifying sustainability in businesses.

Following the introductory section, this paper contains a further five sections. Section 2 explains the approaches and methods followed in this paper. Section 3 is divided into two subsections respectively describing both the bibliometric analysis and the content of the articles analysed. Section 4 contains a discussion on key findings and insights found in the literature. Finally, the paper is concluded in Section 5.

2 APPROACHES AND METHODS

This paper will follow the *preferred reporting items for systematic reviews and meta-analyses* (PRISMA) approach which was defined by Moher, Liberati, Tetzlaff, and Altman [6] and further elaborated on by Liberati, Altman, Tetzlff, Mulrow, Gøtzsche, Ioannidis, Clarke, Devereaux, Kleijnen, and Moher [7]. This has since been updated and therefore the original is referred to as PRISMA 2009 and the updated approach is referred to as PRISMA 2020 [8]. This paper will be following the PRISMA 2020 approach, which will be referred to as PRISMA for the remainder of this paper. The PRISMA methodology involves a checklist of 27 items and a three-phase flow diagram to improve the quality of the systematic review [6].

The high-level overview of the PRISMA approach used is illustrated in Figure 1. This approach involves three phases, namely, ‘identification’, ‘screening’, and ‘included’.

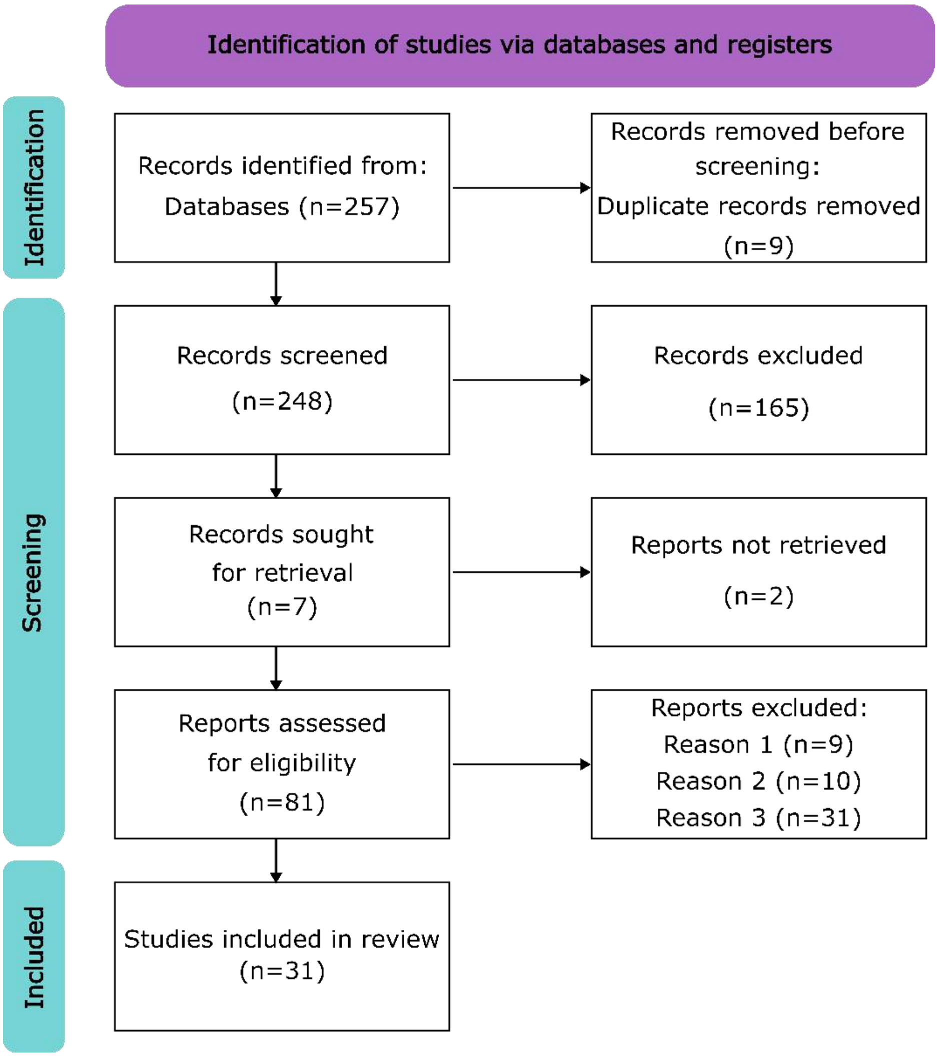

Figure 1: Flow of information through the different phases of a systematic review, adapted from PRISMA 2020 [8]**.**

These three phases of the PRISMA approach outlined above will be elaborated on in the sections below. Section 2.1 discusses the identification phase, touching on the identification of databases, key words, and search strategies to identify relevant literature. Section 2.2 describes the screening processes elaborating on the criteria in which the articles are evaluated. Finally, Section 2.3 which is concerned with the inclusion phase of the PRISMA flow diagram, displays the articles which are included in the remainder of the paper.

2.1 Phase 1: Identification

The first phase of the PRISMA review is identification which aims to select only the relevant literature using keywords and search strategies in a search database. The databases that are identified as having an extensive library are Scopus, Google Scholar, and *Web of Science* (WoS).

The database that is primarily used is Scopus, where Scopus is a comprehensive and trusted abstract and citation database of peer-reviewed literature [9]. Additionally, Google Scholar provides a user-friendly platform for ‘scholarly literature’ [10]. Finally, WoS is a collection of multiple databases tailored for researching scientific and scholarly literature [11]. For clarity and simplicity, this paper considers database searches restricted to articles published before 2024, which the author can access. This is deemed as extensive because the inclusion of several years provides a sufficient timeframe for investigating the state of the art.

Once the databases are chosen, the identification of relevant keywords is used in the respective databases to filter articles to increase the likelihood of obtaining relevant literature. Keywords are identified through a preliminary search of relevant articles [12], [13], [14] to obtain relevant keywords and combinations of keywords that relate to *quantifying, sustainability, and business*. Keywords are subsequently combined to derive search strategies. The search strategies utilised are displayed below in Table 1.

Table 1: Literature database and the corresponding search strategies.

Database	Search strategy	Number of sources
Scopus	(TITLE-ABS-KEY (“measure* sustainab*" OR "quanti* sustainab*”) AND TITLE-ABS-KEY (“Business*" OR "corporate*”) OR TITLE-ABS-KEY (“sustainab*" AND " framework " AND " quanti*”)) AND PUBYEAR < 2024	129
Google Scholar	sustainability framework "measure* sustainab*" OR "quanti* sustainab*" OR "Business*" OR "corporate*" OR "sustainab*" "quantify sustainability"	104
WoS	((ALL= ("measure* sustainab*" OR "quanti* sustainab*”)) AND ALL= ("Business*" OR "corporate*”)) AND ALL= ("sustainab*" AND " framework " AND " quanti*"), exclude 2024	23

The table shows the results from a search conducted on the 19th of April 2024. The search resulted in 129 articles identified from Scopus, 104 articles from Google Scholar, and 23 from Web of Science as displayed in Table 1. The PRISMA methodology then states to remove duplicate articles. To eliminate duplicates the titles were evaluated and any duplicates were removed. There were 9 duplicates found resulting in 247 articles from an initial search of the databases.

2.2 Phase 2: Screening

Following the identification of relevant articles, an initial abstract and title screening is conducted, where the keywords are reviewed in context to guarantee that the article comprehensively addresses all pertinent aspects of quantifying sustainability within a single business. This reduced the number of articles from 247 to 83 articles.

The next phase involved finding the articles that were sought for retrieval. This paper is confined to articles that the author can access. Seven articles were sought for retrieval of which five were received and therefore two were inaccessible. Therefore, 81 articles are screened for possible inclusion in this paper.

As shown in Figure 1 which displays the PRISMA methodology (found on page 3), the next phase is screening which involves identifying studies from the literature search for inclusion in the paper by selecting only the relevant literature based on a predefined set of criteria. Criteria one concerns the involvement of sustainability within the article which must also discuss at least two of the three sustainability dimensions. Criteria two involves the quantification or measurement of sustainability and criteria three considers whether the study is based on a single business. If an article does not meet any of these three criteria, it is excluded from the research, and the reason for its exclusion is documented. A high-level overview of the screening process is displayed in Figure 2 below.

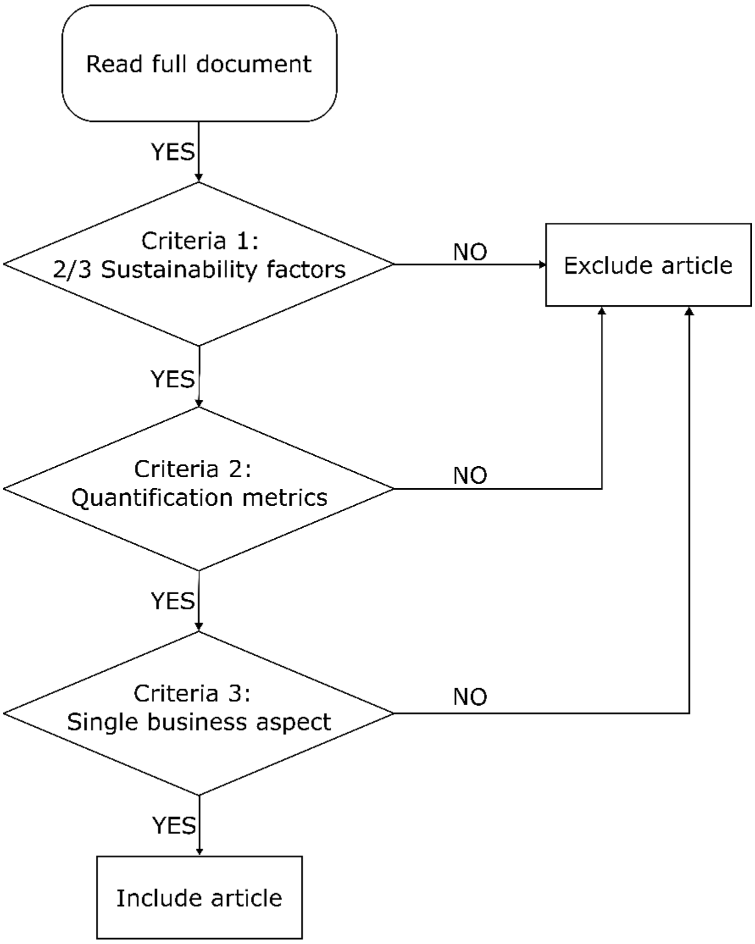

Figure 2: Screening process.

There are nine articles that are excluded due to criteria one, ten that passed criteria one but failed at criteria two, and 31 that passed criteria one and two but failed at criteria three.

It should be noted that the primary criterion for excluding articles is their relevance to a single business. This suggests there may be a significant gap in the literature; while many articles discuss quantification and sustainability, there is a noticeable lack of overlap when it comes to their applicability to individual businesses. This may indicate a need for more focused research on how sustainability metrics can be tailored specifically to the needs and contexts of single businesses.

2.3 Phase 3: Inclusion

The identification and screening phases resulted in 31 articles that are analysed in the remainder of the paper. The citations of each article can be found adjacent to their respective year, with a total for each year as seen in Table 2.

Table 2: The included articles.

Year	References	Number of articles
2000-2013	[14], [15], [16], [17], [18], [19], [20]	7
2014	[21]	1
2015	[22], [23]	2
2016	[24], [25]	2
2017	[26], [27], [28]	3
2018	[12], [29], [30]	3
2019	[31], [32], [33]	3
2020	[34]	1
2021	[35], [36], [37]	3
2022	[13], [38]	2
2023	[39], [40], [41], [42]	4
TOTAL		31

The most recent 10 years' publications are displayed per year with the remaining years grouped together due to the small number of relevant articles published per year. The fact that the oldest article meeting the criteria was published in 2001 further illustrates the growing topicality and relevance of this area of research over time.

3 RESULTS AND ANALYSIS

The results and analysis are performed on the 31 included articles. This section is divided into two sub-sections: The first presents a bibliometric analysis aimed at identifying publication patterns and trends, while the second provides a content analysis which examines the themes and topics discussed in the literature.

3.1 Bibliometric analysis

The topics that are discussed include the prominence of the publication years, authors, articles, and graphical location of the articles. Graphs are generated by using Bibliometrix [43].

3.1.1 Annual Scientific Production

Analysing the publication years of articles helps track the evolution of research topics and methodologies over time, revealing trends and shifts in academic focus. It also highlights periods of significant scientific advancement or interest, indicating how ideas have developed and spread through the scholarly community. Figure 3 illustrates the number of relevant articles that were published in each year with the *X*-axis representing the year of publication from 2001 to 2023 and the *Y*-axis indicating the number of articles published each year.

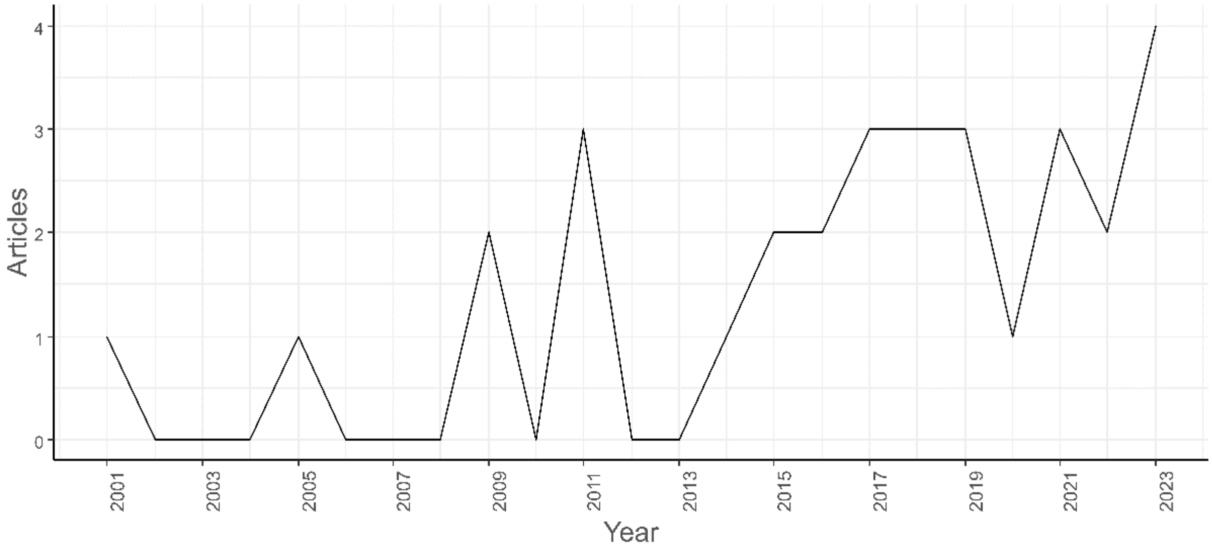

Figure 3: Annual scientific production.

Figure 3 illustrates that although the annual output of articles is limited, there is a slight upward trend that may indicate an increasing interest in this research area. Furthermore, the limited number of articles meeting all criteria suggests a potential gap in the research field.

3.1.2 Author Scientific Production

There is no single author who dominated the field with a prolific output of articles, with the most authors only having published once within the field. The four authors that produced more than one article are, namely, Helling, R [21], [23], Kuosmanen, N [17], [18], Kuosmanen, T [17], [18], and Zhang, Q [15], [21] producing two articles each.

3.1.3 Prominence of the Article

The number of citations an article receives is a crucially important metric in academic research, serving as an indicator of its influence and relevance within a field. High citation counts generally suggest that the work has significantly contributed to its discipline, guiding further research and being recognised as valuable by peers. This metric is often used to assess the impact and quality of a researcher's work, influencing decisions related to funding, promotions, and academic recognition. Table 3 showcases the number of citations per relevant article with column 2 showing the number of times each article has been cited globally and column 1 representing the titles and publication years of the most cited articles for the top 10 most cited.

Table 3: Most cited article.

Paper	Total Citations
HUSSAIN N, 2018, J BUS ETHICS	586
SZÉKELY F, 2005, EUR MANAGE J	464
ANSARI ZN, 2017, J CLEAN PROD	269
DELAI I, 2011, SOC RESPONSIB J	139
KRAVCHENKO M, 2019, J CLEAN PROD	128
SILVA S, 2019, J CLEAN PROD	124
ZHANG Q, 2014, COMPUT IND ENG	104

KUOSMANEN T, 2009, ECOL ECON	87
HOLLIDAY C, 2001, HARV BUS REV	82
DE VILLIERS C, 2016, J CLEAN PROD	73

Table 3 indicates that three articles have received significantly more citations than the others, with the most having 584 citations, followed by 464 and then 269. The articles with very few citations are relatively recent, which may explain their lower citation count.

3.1.4 Country Scientific Production

The graphical location of an article in a bibliometric network can reveal its centrality and influence within the field, indicating how foundational or interconnected it is. Additionally, its position can identify its thematic cluster or community, highlighting its role in specific research topics or trends. Figure 4 is in the form of a world map which illustrates the number of relevant articles that have been produced in each country. Countries are shaded based on the number of articles in blue, whereas higher producers of articles are shaded darker.

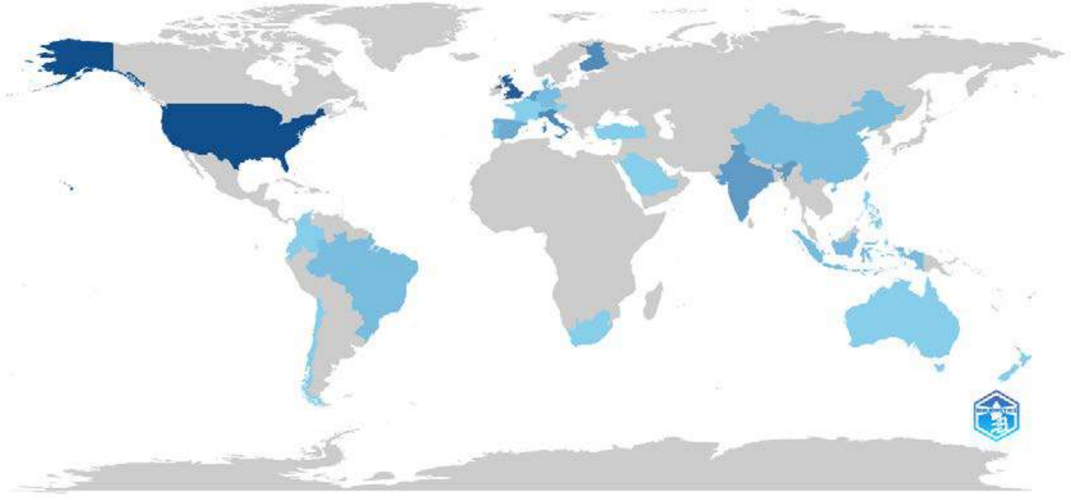

Figure 4: Country scientific production.

The figure documents the quantity of each country's publications with 26 countries in total having contributed to the field with USA having the most publications at 9, closely followed by UK with 8. This shows the relevance globally as out of only 31 articles, 26 countries contributed.

3.2 Content Analysis

The content analysis section explores the qualitative aspects of the collected literature, aiming to uncover underlying themes, patterns, and trends within the research. This analysis seeks to identify common topics, key findings, and prevalent discussions that define the field. This approach provides a deeper understanding of the research landscape, highlighting significant contributions, gaps in knowledge, and potential areas for future study. The following section will focus on the main topics and frameworks that were prevalent in research.

3.2.1 Topics and Themes

A strategic diagram is utilised to display the themes and topics that are discovered in the literature. Strategic diagrams in content analysis visualise the thematic development of a research field by organising themes along two dimensions: Development degree (density) and relevance degree (centrality) [44]. Where development degree (density) indicates how well-developed a theme is, with high-density themes showing mature research areas and relevance degree (centrality) measures a theme's influence within the field, with high-centrality themes being broadly relevant and influential [44]. This is further split into four quadrants, niche, motor, emerging or declining and basic. The strategic diagram for the relevant literature is shown in Figure 5.

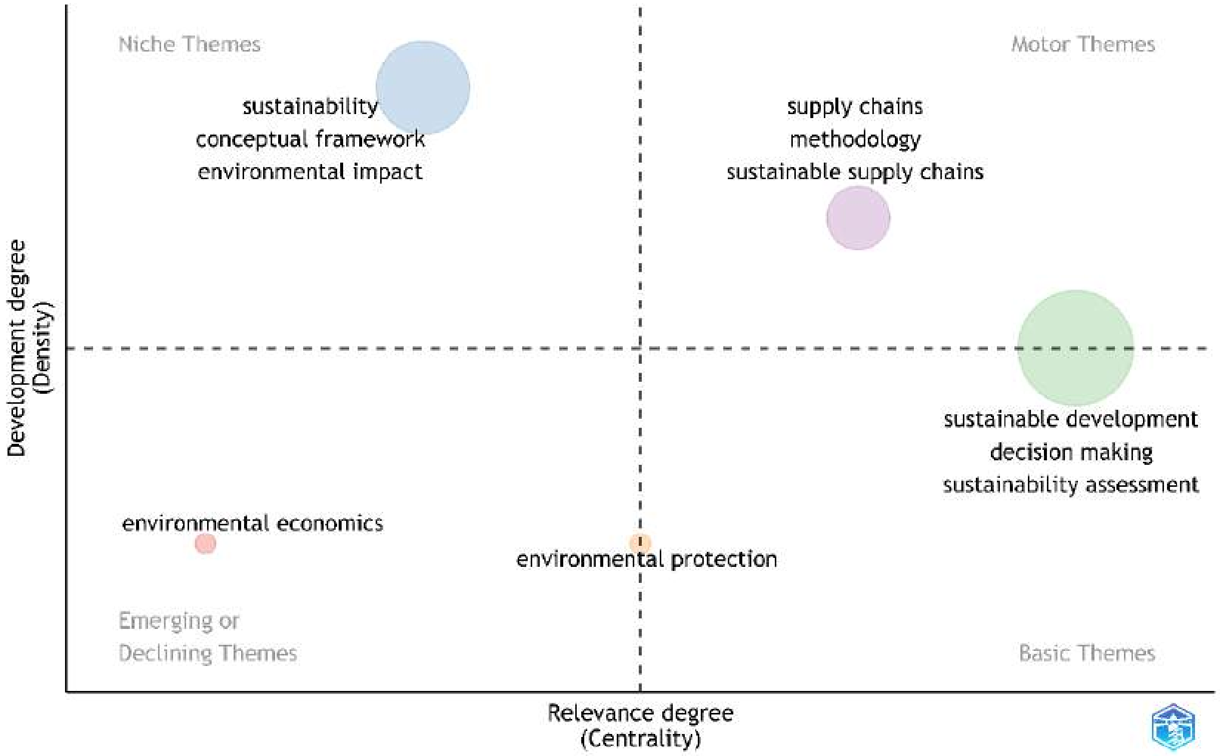

Figure 5: Thematic map.

Niche themes (upper left), consisting of high density and low centrality, consider specialised areas with a narrow focus. Within the relevant literature there are 3 themes that are identified namely, sustainability, conceptual framework, and environmental impact. Motor themes (upper right) consist of high density and high centrality areas. These well-developed, central areas drive the field forward. The themes identified include supply chains, methodology, sustainable supply chains, sustainable development, decision making, and sustainability assessment. Emerging or declining themes (bottom left) consist of low density and low centrality areas. These are themes that are either new and developing or losing relevance and include environmental economics. Basic themes (bottom right) consist of low density and high centrality areas. These fundamental areas are widely relevant but not deeply developed, and the theme identified in this category is environmental protection.

In sustainability reporting, this strategic diagram highlights key themes, emerging trends, and fundamental yet underdeveloped areas. It aids in identifying research priorities, guiding future studies, and enhancing the standardisation and impact of sustainability frameworks.

3.2.2 Keywords Analysis

This section aims to analyse the keywords from all 31 articles which are analysed to uncover research trends, identify knowledge gaps, highlight collaboration opportunities, and inform policy and decision-making. This provides insight into the primary focus of the articles and the key areas of interest for the authors. This is investigated through the use of a table that lists the most relevant words in descending order of their occurrence as shown in Table 4 which suggests their importance or frequency in the analysed literature. The first column shows the list of keywords that have been identified as most relevant. The second column shows the number of occurrences of the keyword in the analysed set of articles, with a higher number indicating more frequent usage.

Table 4: Keyword frequency

Words	Occurrences
sustainable development	10
sustainability	7
decision making	4
sustainability assessment	4
life cycle	3
sensitivity analysis	3
supply chains	3
sustainability indicators	3
sustainability performance	3
conceptual framework	2

Sustainable development is the keyword with the highest frequency (ten occurrences), indicating that it is a central theme in the analysed literature. This is followed by sustainability with seven occurrences, which is another major focus area that is closely related to sustainable development. Decision making and sustainability assessment each have four occurrences, suggesting that processes and evaluations related to sustainability are significant research topics. Life cycle, sensitivity analysis, supply chains, sustainability indicators, and sustainability performance each appear three times. These keywords highlight important aspects of sustainability research, from methodologies to performance metrics. Conceptual framework has two occurrences. This keyword suggests a focus on theoretical or conceptual approaches within the research.

It should be noted that both the strategic diagram (Figure 5), and the keyword analysis (Table 4) can be linked to the keyword strategy (Table 1) to highlight the most frequently occurring keywords and identify those that are under-represented. This comparison helps pinpoint strong and weak areas within the research. Both figures reveal that sustainability is the most prominent field. Notably, the keyword "business" or “corporate” is absent, suggesting a potential gap in the literature regarding the integration of business practices within the sustainability domain. These figures provide a snapshot of the current research landscape in sustainability, indicating which topics are most prevalent and potentially guiding future research directions and priorities.

3.2.3 Frameworks

The multitude of proposed frameworks for sustainability reporting suffers from a lack of consistency and standardisation, which hampers the effective implementation of a quantifiable sustainability framework. This issue is evident in various relevant articles, each presenting its unique framework. Despite this diversity, there are commonalities, particularly in the foundational aspects of these frameworks. Nine foundations were discovered within the articles namely, indicators, *life cycle assessment* (LCA), TBL, *sustainable development goals* (SDG), *environmental, social, and governance* (ESG), mathematical, use of experts, *balanced* *scorecard* (BSC), and Monte Carlo simulation. Each of these foundations are described in this section followed by showcasing a reference to which article corresponds to which foundation.

- Indicators are specific metrics used to measure and track progress towards sustainability goals, often referred to as *key performance indicators* (KPIs). KPIs provide measurable values that demonstrate the effectiveness with which a company is achieving its primary business objectives [13].
- LCA is a method used to evaluate the total environmental impacts of a product, process, or service throughout its life cycle, from raw material extraction to disposal or recycling[23]. LCA helps identify areas for improvement to optimise sustainability.
- As described previously the TBL's framework aims to put equal value on the economic, environmental, and social dimensions of sustainability [3].
- SDG are a set of 17 global goals agreed to by the United Nations to address pressing global challenges such as poverty, climate change, and inequality [45]. They provide a framework for organisations to align their sustainability efforts with broader international objectives [45].
- ESG is a framework used to evaluate an organisation's performance in environmental, social, and governance areas [40].
- Mathematical foundations are used in many forms, with weighted averages of indicators, linear programming, multi objective functions, and optimisation to derive a set of mathematical formulas that could describe the sustainability of the business [22], [24], [37].
- Use of experts relies on the involvement of experts to rate the sustainability on using a Likert scale (1: 'very low'; 2: 'low'; 3: 'average'; 4: 'high'; 5: 'very high') [30].
- BSC is a strategic management tool used to track and measure performance across multiple dimensions [25].
- Monte Carlo simulations are statistical methods used to analyse complex systems and estimate the probability of different outcomes [46]. They are often used in sustainability frameworks to model and predict the impacts of different scenarios or strategies.

The foundation of each article's framework and the corresponding references aim to discover trends in the proposed frameworks, as displayed in Table 5.

Table 5: Framework foundation and corresponding articles.

Foundation of the framework	References
Indicators	[13], [15], [16], [20], [21], [22], [23], [24], [28], [33], [34], [41]
LCA	[23], [32], [39], [42]
TBL	[13], [20], [28], [29]
SDG	[34], [39]
ESG	[38], [40]
Mathematical	[12], [17], [18], [21], [22], [24], [29], [32], [35], [36], [37], [40]
Using experts	[30]
BSC	[25], [26]
Monte Carlo simulations	[17]

Indicators and mathematical equations using weighted averages or optimisation functions are the most frequently used tools in creating a framework for quantifying sustainability.

3.2.4 Case studies

The case studies analysed in the various articles predominantly focused on the country of origin of the respective authors, with a few notable exceptions involving cross-country research. Two articles discussed sustainability within the context of the European Union as a whole, highlighting regional approaches and collaborative efforts. Additionally, one article provided a comprehensive analysis covering 34 different countries globally, offering a broad perspective on sustainability practices and challenges across diverse geographical and economic landscapes. This further highlights the global importance and interest as seen in Figure 4 in Section 3.1.4.

4 DISCUSSION

This paper explores the intersection and interplay between sustainability, quantification, and businesses, aiming to identify the latest trends and gaps in these fields on the basis of the foregoing analysis. To identify the relevance across the three factors, an approach of using the primary search strategy for Scopus, and systematically excluding one factor at a time to assess the relevance of each two-set intersection is used. The final intersection is the three-set intersection and hence is the number of articles that were accepted. This approach could identify which intersections have been well researched and where the potential gaps lie.

These intersections are illustrated in Figure 6 in the form of a Venn diagram where the number of relevant articles were then placed into the relevant intersection.

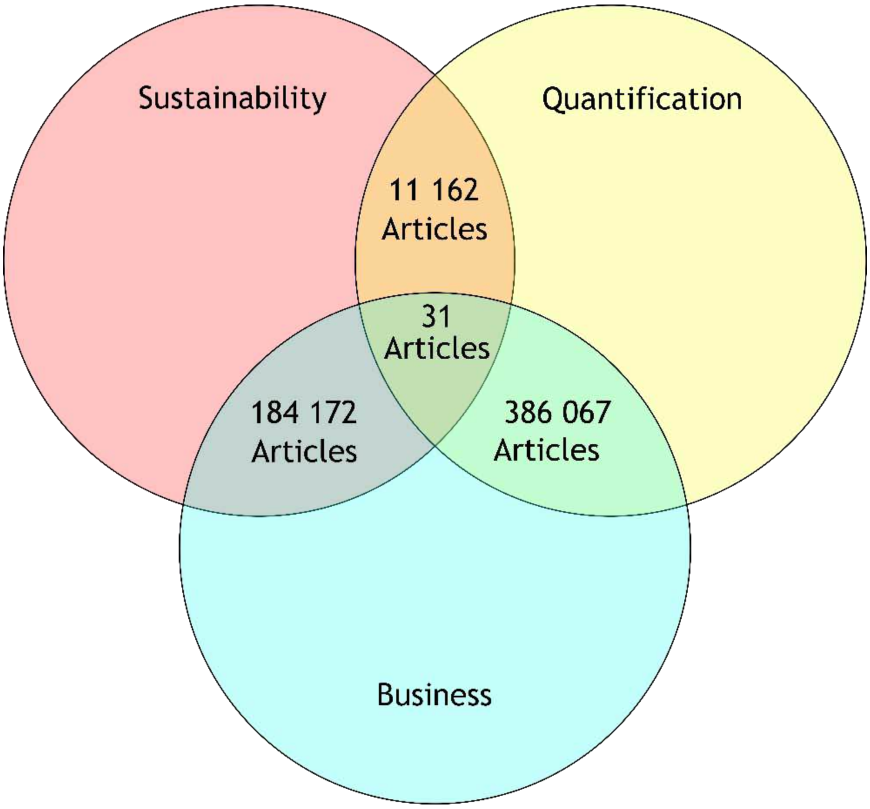

Figure 6: Venn diagram of the fields of interest and their intersections.

It was found that each of these three fields and their intersections are of high interest, however, the convergence of all three fields has not been thoroughly explored. Figure 6 illustrates the substantial number of sources Scopus contained within a two-set intersection, in contrast to the relevant field or three-set intersection which contained only 31 sources across the three databases. This indicates a potential gap that requires further research. The gap offers a chance for future research to explore the synergies and interdependencies among these fields more deeply, potentially leading to impactful findings that could enhance both understanding and practical applications in these areas.

From the results and analysis (Section 3) it was observed that there is a lack of consistency in the frameworks being utilised across studies. Additionally, there is significant global interest in the topic, as evident from the diverse locations of both the article publications and the case studies they discussed. This widespread interest, combined with the prominent themes identified and the current scarcity of research, indicates a gap in the literature. This gap suggests potential for future research to explore these themes more deeply and develop a more standardised approach to the frameworks used in this field.

Another significant gap identified in the analysis is the lack of practical guidelines for businesses. While all the articles discussed conceptual frameworks and many included case studies of their implementation, there is a notable absence of detailed instructions or practical steps for companies to integrate these frameworks into their operations. Specifically, businesses lack clear guidance on defining the boundaries for implementation, such as the scope of sustainability practices within different departments, the extent of changes required in existing processes, and the metrics for measuring success. This indicates that while the theoretical and evaluative aspects of sustainability are well-covered, there is a pressing need for actionable guidance that can assist businesses in effectively applying these concepts in real-world settings. This deficiency highlights an opportunity for future research to bridge the gap between theory and practice, providing companies with the tools they need to implement sustainability frameworks successfully, with clearly defined boundaries and measurable outcomes.

5 CONCLUSION

In this paper, a systematic literature review is conducted to examine the existing research on quantifying sustainability within businesses. The review explored the intersection of sustainability, quantification, and business practices, identifying the latest trends and gaps in these fields. Through the analysis, nine foundational frameworks were identified and synthesised, revealing that the topic is significantly under-researched, with a notable lack of consistency across studies. The review highlighted a substantial gap in the literature, indicating that there is a critical need for standardised approaches to sustainability frameworks. This gap suggests significant potential for future research to explore deeper into these themes and develop uniform methodologies that can enhance the accuracy and reliability of sustainability quantification. The insights gained from this review provide a theoretical foundation for future research, which could support the development of more effective sustainability practices in business. By addressing the identified gaps, future studies can contribute to a more coherent and standardised understanding of how to quantify sustainability, ultimately aiding businesses in their efforts to become more sustainable.

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THE ROLE OF UNIVERSITIES IN PREPARING INDUSTRY TO MENTOR WORK-INTEGRATED LEARNING STUDENTS

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ABSTRACT

Universities are increasingly offering Work Integrated Learning (WIL) programs to present students with real-world experience in their field of study. This study aims to answer the following research question, "How do Universities of Technology (UoTs) in South Africa prepare industry to mentor WIL students so that the outcomes are aligned with the learner guide's expectations?". A qualitative case study design, based on a semi-structured interview protocol was followed to collect data. The findings were compared against reviewed case studies to draw informed conclusions and recommendations. Findings relate to inefficient implementation of WIL that affects benefits for all stakeholders. For example, the inadequate duration of WIL, irregular interactions of university WIL coordinators, and lack of upfront guidance to companies. Universities must design WIL programs in line with credit allocation to establish a potent framework. These provide stakeholders with a comprehension of the expected outcomes of WIL guaranteeing optimal benefit for all.

Keywords: work integrated learning, universities of technologies

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1 INTRODUCTION

A discussion and debate are going on about the industry's perception of the content of the skills that are taught to engineering graduates such as the national strategy review on WIL in Australia by the tripartite of the government chamber of commerce, industry, and business council [1]. Statistics South Africa also argues that this is on the backdrop of high-paced changes brought about by several factors such as technological advancements, workplace role changes, and countries' different development goals [2]. These have impacted current Work Integrated Learning (WIL) models, and the need for both employers and universities to continuously improve on how best industry mentors WIL students [1].

Even though WIL research has been done, there are literature gaps on how Universities of Technology (UoTs) should formalize a program of preparing industry mentors to mentor WIL students so that the outcomes are aligned with the learner guide's expectations. This has brought divergent expectations on both UoTs and the industry. The paper will focus on how this can be best rectified by UoTs. Globally, for countries to compete they need to be intentional about producing students who can not only solve real-world challenges but also ensure that the university courses are more geared to producing career-ready graduates [3]**.** For example, in Australia both employers and universities have formalized this partnership by contributing to the development of the 2015 National Strategy on Work-Integrated Learning in higher education [1]. There is a view that developing countries are investing heavily in education to meet their developmental agendas while eradicating poverty which has necessitated the increase in UoTs to make it compulsory for WIL students to enrol in work-readiness modules [2]. Statistics SA argues that SA is not an exception to this as she struggles to meet the educational needs of her youth [2]. SA launched Work Integrated Learning South Africa (WILSA) at the Eleventh International Conference of the Technological Higher Education Network South Africa in March 2022 as a strategy to address new ways of working through universities by adopting technology in its teaching and learning - and ensuring students are engaged in the corporate or public sector to get relevant experience [4]. Ngonda et al [5], researched the occupational competency and self-efficacy for WIL students.

This paper reviews the definitions of WIL, WIL course structure in academia, recent case studies on developments of WIL in countries with cases pertinent to this paper, data analysis with findings, and recommendations

The aim of the research is to find out the best workable program for South African UoTs to prepare industry mentors to best mentor students to achieve learner guide expectations.

The research will probe the question on, "How do Universities of Technology (UoTs) in South Africa prepare the industry to mentor WIL students so that the outcomes are aligned with the learner guide's expectations?"

2 LITERATURE REVIEW

From The *South African* Qualifications Authority (*SAQA*) and the Engineering Council of South Africa, (ECSA), a Diploma in Engineering at NQF Level 6, with a minimum of 360 credits and well-defined graduate attributes, is made available for UoTs to consider ECSA-02-PN [6]. The purpose of the qualification is to build the necessary knowledge, understanding, abilities, and skills required for further learning towards becoming a competent practicing technician. SAQA [6] continues to state the minimum curriculum content by knowledge is outlined and it will have a WIL component with a minimum of 30 credits. To this effect, one UoT stated in their prospectus, "WIL (Applicable to Diploma Programmes only) [7]. To fulfill the requirements of some Diploma programmes, a student must complete a period of experiential learning, as described in the curriculum for the specific programme. A module guide outlining the requirements for the successful completion of this component of the curriculum is obtainable from the department" [8] . Referring to the purpose of the diploma, another UoT described it as a program where graduates will be able to integrate analytical and practical mechanical engineering techniques and mechanical engineering knowledge to solve engineering problems [9]. They will also be able to use given criteria to assess mechanical processes and outcomes. In SA some universities have engineering diplomas that have a WIL component in the curriculum. The qualifications are described in terms of learning outcomes, workload (credits), the NQF level, competencies, and profile [6]. Learner guide for WIL as a module, with a designated staff member, who would highlight the skills, knowledge, and attitudes that would be used to declare a graduate competent. The designing of learner guides, teaching, or training, learning activities, and assessment is the responsibility of the WIL coordinator. The duration of WIL would be determined by the UoTs [9].

The purpose of the WIL module is directly linked to the learning outcomes, which are primarily building into the skills development of the students as can be seen in Table 1 [10]. A learner guide is an appropriate tool to ensure that students are well prepared for the task that lies ahead of them in the industry.

Table 1: Minimum curriculum content by knowledge area

Knowledge Area	Minimum Credits
Mathematical Sciences	35
Natural Sciences	28
Engineering Sciences	140
Design and Synthesis	35
Complementary studies	14
Work-integrated learning	30

Figure 1 clarifies the components of a curriculum; it presents the programme structure. The structure starts with the purpose of the programme or qualification, which comes from National Accredited Technical Education Diploma (NATED)/SAQA/ECSA; followed by the objectives of the programme, the total credits of the qualification and breakdown into knowledge areas, the module content and modules, teaching and learning including assessment. It is against this background that the study is investigating the alignment of learner guides with industry expectations as WIL is the responsibility of the Universities.

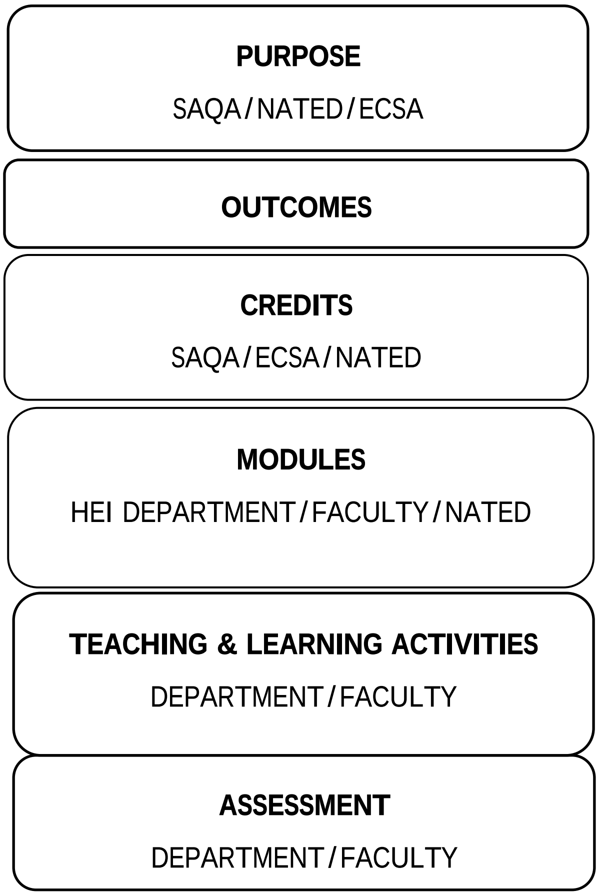

Figure 1: Steps in designing a programme and role players

WIL is defined as a purposeful, organized, supervised, and normally assessed educational activity whose primary purpose is to bridge theory and practice and prepare students for the world of work [11]. The Council on Higher Education (CHE) describes WIL as a curricular, pedagogic, and assessment practice, across a range of academic disciplines that integrate formal learning and workplace concerns [10]. According to the Higher Education Qualification Sub-Framework (HEQSF), WIL is defined as a characteristic of vocational and professionally oriented qualifications that may be incorporated into programs at all levels of all three sub-frameworks namely work-directed theoretical learning, project-based learning, and workplace-based learning [6]. According to the *Universities South Africa* (USAf), WIL entails a range of approaches, strategies, and methods used to meaningfully integrate theory with practices of the workplace within a purposefully designed curriculum [12]. For this study, WIL refers to a module with learning outcomes that are aligned with the requirements to attain a diploma qualification. The role players include the UoTs, industry, and students.

Outside of policy definitions of WIL, in academia, several definitions or models describe the concept of WIL. According to Du Pré [13], WIL is defined as a strategy of applied learning (integrated with work) that involves a structured educational program that combines productive relevant work experience with academic study and professional reflection. According to Heyler and Lee [14], WIL in the context of work placement is described as a planned period of learning in the industry that is intended to give students practical experience in their field, as well as meeting specified learning objectives [14].

The South African Qualifications Authority (SAQA) states that some qualifications' curricula will be designed to include both theory and practice by incorporating WIL. According to the HEQSF, WIL includes simulated learning, work-directed theoretical learning, problem-based learning, project-based learning, and workplace-based learning [12]. HEQSF further outlines that the selection of appropriate forms of WIL depends on the nature and purpose of the qualification type, programme objectives, and outcomes, the NQF level at which the WIL component is pegged, institutional capacity to provide WIL opportunities, and the structures and systems that are in place within professional settings and sites of practice to support student learning. Learning assessments should be designed and one most commonly used assessment models is Miller's (1990) Triangle/Model of Clinical Competence as shown in A Practical Guide for Work-integrated Learning (2016), it identifies the 4 components of competence namely knowledge, competence, performance, and action [3].

In HEQSF, the modalities of WIL are namely workplace or work-based learning (WBL) in the workplace, work-directed theoretical learning (WDTL), problem-based learning (PBL), Project-based learning (PjBL) as well as simulations [12]. WIL students are placed at organizations in either one department or rotated amongst the organization's engineering-oriented departments [9].

There are several lessons learned in WIL in both private and public education institutions. Jay et al [15], argue that innovative, sustainable, and scalable models of WIL are essential to enable universities to service a more diverse and larger student cohort [15]. Whilst Ojo [16], explains that the South African government has mandated and implemented a work-integrated learning policy in the educational sector to improve teaching and learning. The researcher further argues that class-delivery techniques should be considered, and academic supervisors put emphasis on students being taught employable skills to achieve sustained improvement of students' competencies. In his paper, he found there are different strategies engaged by academic supervisors to assist in preparing practice such as student guidance and mentorship [16]. Referring to lessons from the employability of graduates after WIL, Ngoda, Shaw, and Kloot explain, that the employability benefit of WIL is primarily due to competency development during work placement [9].

The challenges faced by higher education are perhaps more profound now than in recent years. The rapid advancement in technology, innovation, and the demand for high competency and specialization, have placed a huge demand on higher education [17, 18]. Gellerstedt [17], argues that higher education needs to focus on the formal aspect of education, while also intensifying its strategies towards the practical aspect of education through the effective implementation of programs such as WIL.

Universities are increasingly offering WIL programs to give students real-world experience in their field of study while they are still pursuing their academic degrees [19]. Internships, co-op placements, and other types of experiential learning are just a few of the many formats that these programs might take [20].

One of the main advantages of WIL programs is that they can support the alignment of the program's learning objectives with needs of university students to be ready for the industry when they graduate. WIL programs can aid in bridging the gap between theory and practice by giving students practical experience in their profession. This helps students gain a better understanding of how their academic knowledge can be utilized in the real world [5].

While Ajjawi et al [21], argue that it is not sufficient to merely assess WIL to meet the needs of the university, it is worth mentioning that a lot of what is believed to define effective learning experiences, the processes that enhance learning outcomes, such as concepts of curriculum and pedagogy, is predicated on the norms and practices of educational institutions [22]. However, [22] also makes the point that comprehending the processes and results of learning that occur through experiences outside of those institutions, as well as the development of curriculum models and pedagogies fit for practical settings, may be difficult or impossible using these premises.

Therefore, it is now necessary to take a new look at and evaluate what is known about practice settings, their contributions, and how these might be advanced to ensure beneficial outcomes for all stakeholders. To strengthen this point [23] has made the argument that a key advantage of cooperative education as a learning strategy, is that it provides students with a chance to learn both in the classroom and on the job and that these opportunities are inter-connected to create education that is rich and wholistic. It is clear from these arguments that the alignment of these aspects of education is of prime importance.

It has long been established that WIL is an integral component of most if not all engineering programs. It enhances the quality of engineering education and improves the employability of students upon graduation [24]. It is therefore imperative for all stakeholders to work together in the enhancement of WIL to ensure optimal benefit. In all forms of formalized education provided by educational institutions, the curricula are developed based on a predefined purpose statement, that influences the key competencies graduates must possess upon graduation, known as graduate attributes or cross-field outcomes [25]. These are outlined in the learner guide.

To ensure optimal benefit for all stakeholders regarding WIL, it is important to ensure the alignment of industry mentorship and these graduate attributes. With proper planning and collaborative effort between industry and universities, this can be achieved, and that is the focus of this research. To identify the role that universities can play to ensure the alignment of both these key components of engineering education, such that upon graduation, the students are not only competent regarding formal education but also the practical application of that formal aspect of education. To strengthen this observation, [26] observed from their study while investigating and contesting the goals of work-integrated learning, that all parties involved acknowledge that learning takes place both on campuses and in the workplace can be complimentary and, via integration, lead to new learning outcomes. They saw that none of the stakeholders expressly said that they believed one of these environments of learning to be more legitimate, reliable, or practically appropriate than the other. They concluded that the need for more research on the perspectives of all stakeholders is reinforced by the apparent uncertainties and discrepancies regarding what the concept of integration, regarding WIL might signify and how it might be fostered.

The section below will cover similar case studies relevant to this paper which will highlight developments of how WIL programs are ensured to be aligned with learner guide expectations.

2.1 Sweden

University West in Sweden has long practiced WIL as part of the curriculum in several of its degree programs. The university has a long history of the practice of WIL and provides a framework regarding the implementation of WIL in the Swedish context [17]. WIL in this context follows several models listed below as per the study by [17]. This category includes instructional strategies like role plays, practice-oriented simulations, and teaching situations. These could be exercises that are somewhat practice-related and could even be edited representations of real-world scenarios. This area includes the use of practice imprints as educational practice resources. Using information from existing organizations and professional disciplines, as well as inviting guest lecturers, are a few examples.

Training students to use professional tools of the trade could be software packages and many others depending on the profession for which they are being trained. Engaging in fieldwork or industry-based settings is a way of exposing the students to the real workplace. The challenge observed was that, since WIL depends mostly on educators, students, and the workplace environment, the relationship between university and industry may have a direct impact on the student's ability to learn. For instance, workplace culture may have a direct impact on the outcome of WIL. In this case study it was discovered that engineering, business management, and informatics practice WIL is part of their curriculum [17].

2.2 Australia

There are two models of WIL implemented in this case study following a study by [18]. The first model is where students spend a significant amount of time participating in industry activities in the third and fourth years of the degree. The second model follows a strategic incorporation of WIL into a semester subject and different subjects for the entirety of the degree. This means engaging industry for short durations of time for specific semester subjects that might have a practical component, or for short durations at specific times throughout the entire duration of the degree. The latter is termed Embedded Work Integrated Learning (EWIL) [17] The challenges outlined were that there was limited time spent by students; and roadshows to market WIL to industry, and therefore more time should be allocated to facilitate optimal benefit. Also, it was observed that there was not enough exposure to industry partners.

2.3 South Korea

The Southern Korean model of WIL follows regular or permanent, and non-regular employment commonly on a fixed two-year term contract according to a study [20]. Interns in these two categories often work side by side while performing similar tasks. However, the ones on a permanent contract often get preference over those on a non-permanent contract. It was observed that there is a misalignment between the supply of emerging graduates and the advancing Korean workplace. It was also discovered that it was difficult for universities to produce work-ready graduates, due to several factors including the focus of students on only prestigious organizations, and the competitiveness of the job graduate readiness.

2.4 United Kingdom

In the UK according to a study by [7], universities have three- or four-year undergraduate degrees that have an internship as a component of their curriculum, and credits are awarded to participating students. The students are responsible for finding placement for themselves, sometimes through connections. Students who fail to find placement may graduate without this crucial component of education. It was observed that sometimes students may even participate in internship programs that are not part of their curriculum, and this may cause a conflict or misalignment of outcomes.

3 FRAMING THE STUDY

3.1 Problem statement

WIL programs can support the alignment of engineering program's learning objectives with the requirements of learner guides. By providing students with real-world experience in their field, WIL programs can help close the knowledge gap between theory and practice [5]. Students benefit from having a greater understanding of how to apply their academic knowledge in real-world situations.

Literature shows that WIL is a key component in the curriculum for the Engineering Diploma: Mechanical and that there are credits attached to it. This implies that UoTs who offer this Diploma should have learning outcomes for WIL which are aligned with the overall purpose of the Diploma. Like all modules would have a learner guide and an academic staff member responsible, so should it be with WIL as well. WIL activities are performed in industry under the guidance of the program custodian who in this case is the University. Ideally, there should be active engagement between the university and industry so that WIL training accomplishes the desired learning outcomes as outlined in the learner guide. The training schedule should be drawn based on the learning outcomes as stipulated in the learner guide and the module lecturer should engage the industry partners to provide support and guidance for the training.

3.2 Purpose of the study

The purpose of the study is to investigate and explore how Universities of Technology (UoTs) in South Africa prepare industry to mentor WIL students so that the outcomes are aligned with the learner guide's expectations. This paper focuses on mechanical engineering diploma programs in South Africa.

4 RESEARCH METHODOLOGY

Qualitative research investigates the socially constructed nature of reality, the intimate relationship between the researcher and what is studied, and the situational constraints that shape inquiry [27]. Qualitative research design is exploratory, descriptive, interpretive, and contextual [28]. Qualitative research methods based on case studies and semi-structured questions will be used because they allow better exploring of the interaction between UoTs and industry in the preparation for WIL training. Case studies focusing on countries that have similar UoTs as in SA. The design of the semi-structured questions was to present patterns on the current challenges and success with future recommendations to better WIL programs. The sample included WIL coordinators at the University of Johannesburg (UJ), Walter Sisulu University, Central University of Technology, and Vaal University of Technology. Industry included four companies who participate in the WIL program WSU, and UJ.

The chosen approach is the most appropriate in this case, to establish a role that universities could play in ensuring that the outcomes of industry mentorship are well aligned with learner guide expectations. The choice of the method used was also influenced by the nature of the research questions. Ethical clearance from the University of Johannesburg was obtained. Three of the authors are lecturers for the Diploma and the degree in Mechanical Engineering Technology and one is also directly involved with WIL as a coordinator.

4.1 Data collection

A qualitative case study design based on a semi-structured interview protocol was followed [29]. Interviews were used as a data collection method through semi-structured questions because they allow for more in-depth responses with a clearer pattern in analysis that enables the researchers to make inferences. Appendix A and B show their structure of them. These questions were pertinent to help in achieving our aim, and research question. The responses from the participants were then transcribed to allow for easy analysis. The interview questions were formulated and guided by the research questions. The interviews were conducted via Microsoft Teams. The participants' responses were then transcribed and analyzed.

Data was also gathered from multiple case studies involving the practice of WIL in other institutions across the globe. Then a comparative study was performed to identify whether there are thematic similarities between South Africa’s approach regarding the execution of WIL and that of other countries.

4.2 Sampling strategies

Sampling in qualitative research can be categorized into three types namely random, convenience, and purposive [30]. The sampling of participants followed a convenient, purposive, and snowball approach [31]. These sampling strategies were influenced by the nature of the research questions and the aim of the research. The target participants were industry mentors in both SMMEs and established organisations, and WIL university co-ordinators. Four industry participants and four WIL coordinators were interviewed. The university coordinators were selected based on the purposive sampling method, influenced by the universities that offer WIL as part of the curriculum. The selection of industry participants was dependent on the snowball approach. The reason that the researchers chose both SMMEs and established corporations is that some of the students underwent their WIL training in SMMEs, while some did so in more established corporations. An invitation letter and consent form that was detailing the ethical rights of the participants were prepared.

After the participants were invited and agreed to participate, a date was set for the interviews, which were conducted via Microsoft Teams. The interviews were recorded, and the recordings were stored under a protected data storage device.

4.3 Data analysis

Qualitative content analysis was used to determine the presence of certain themes or concepts within the interview questions. This research tool was employed because it is beneficial during the planning of a qualitative study as is the case in our paper [32]. To further support choosing content analysis, the transcribed audio was to be analysed using latent content analysis as some participants were not as concise in their responses [33]. Audio recordings, and field-notes were selected as the best way to collect data to gain first-hand experiences of the participants. These were transcribed into protocols and transcripts, and coded [34]. Axial coding was applied to draw inferences and conclusions from the participants' responses, and to validate the data inter-coder reliability tests were used by three of the researchers to assess consistency. For example, themes were drawn based on the interview questions per category. Not all UoTs offer the National Diploma in Mechanical Engineering as some have now adopted the new Bachelor of Engineering in Technology (BEngTech).

5 RESEARCH FINDINGS

The findings revealed that UoT participants felt that it is not all universities that have a WIL component as part of their curriculum. It should be highlighted that some UoTs offer both Diploma in Engineering and BEngTech qualifications. From the case studies, some universities offer internships or WIL to 3rd or 4th year degree students.

Several challenges were raised by both WIL mentors and WIL coordinators.

Table 2: WIL Challenges

Group	**Challenges**
Students	Professional behaviour, attitude, and work readiness Scio-economic issues (Stipend & accommodation) Traveling logistics and dispersed geographic locations (Budget constraints) Work readiness/preparedness workshop certificate program
UoTs	Interaction with industry to establish the shortcomings of the student readiness regarding curriculum. Limitation of an HR personnel in UoTs who is not an engineer
Industry	Lack of ECSA registration for WIL mentors

Professional behaviour was a recorded challenge from all WIL mentors and WIL coordinators. One WIL mentor said, "Students' work ethic is wanting. As professionals we take home, but students are very reluctant to but still hope to meet competencies which is not possible." These highlight students have a challenge of moving from a culture of merely 'ticking a box' when they join WIL programs to adopting the respective host companies' cultures. He reiterated, "Students need to work on their presentation skills because those that can present well stand a better chance whilst they may not be the most deserving to be absorbed." He went on to say, "Students need to work on their presentation skills because those that can present well stand a better chance whilst they may not be the most deserving to be absorbed." The issue of socioeconomic factors of paying for accommodation and transport to and fro work is a major hurdle faced by students.

Regarding UoTs, a Participant from the industry raised the issue of 'laziness' from WIL coordinators to visit students while in training.

From the data analysis, the researchers found that both UoTs and the industry want WIL to continue and would like continuous improvement to be applied. One WIL coordinator, participant D, who's from a UoT removed WIL in their curriculum with new SAQA regulation providing that option. Participant D said, "Our UoT needs to reincorporate WIL to ensure increased students' employability, and relevancy of the BEngTech course." Whilst another WIL Coordinator, Participant E, argued, "UoTs should incorporate Work Preparedness Workshop and award qualifying students with certificates. This workshop must be compulsory and unsuccessful students should not apply for WIL." Below is a list of areas of improvement:

i. Interaction with industry to establish the shortcomings of the student readiness regarding curriculum.

ii. An active advisory board made up of stakeholders.

iii. Impact of socioeconomic factors more with previously disadvantaged students

iv. Work readiness - workshops run by UoT should be run by people from industry rather than academics to avoid the initiative being an academic exercise! For example, they could leverage the expertise of HR and engineers.

v. A WIL coordinator, suggested, "UoTs should incorporate Work Preparedness Workshop and award qualifying students with certificates. This workshop must be compulsory, and unsuccessful students should not apply for WIL.".

Below are the identified themes of this paper.

5.1 Procedure for WIL training

Three out of four industry participants said that the WIL training programme is generally prescribed by the university. They also indicated that the learning outcomes are outlined and aligned through the learner guide and logbook. This is aligned with the expectations whereas WIL is a module with a learner guide. The logbook is a manual where the learning outcomes are listed as a training schedule. This alignment should make it possible for the WIL coordinator to assess the preparedness of the company so that students can be sent through. It should be through the logbook that both industry mentors can assess the competency of the student.

5.2 Engineering or human resource personnel

From the industry's point of view, mentors are engineers or technologists who are ECSA registered with knowledge and understanding of the learner guide and logbook learning or training outcomes. The participants from UoT said that departmental academic staff are WIL coordinators. For the industry to use engineers and technologists who are ECSA registered and familiar with the learning outcomes, is welcomed feedback. It is however not clear whether the WIL coordinators from the UoTs are responsible for developing the learner guide and assessing the competency of the students. This was mainly due to the wide-ranging responsibilities which sometimes do not include assessing the work, particularly in instances where the WIL coordinator is from the HR function.

5.3 Communication on recruitment and assessments/visits

All the participants alluded to the fact that the recruitment of students is done through direct liaison with the universities. The adverts for WIL opportunities are made available through the cooperative office, departmental office, and the Internet. Industry participants claim that WIL coordinators visit students once in six months. The WIL coordinators referred to the WIL Policy and framework guides that at least one visit is expected. This is evidence that there is communication between industry and the universities.

5.4 Alignment of learner and industry expectations

Industry participants said that they are aware that UoTs have learner guides. It could not be established that for certain they are aligned with the logbooks in most companies. The WIL coordinator participants could not confirm this. This response is one-sided, the view of the WIL coordinators would be helpful.

5.5 Company WIL program

The industry's WIL is aligned with the learner guide, and they depend on the logbook from UoTs in formulating their program.

5.6 Feedback

Industry does have feedback mechanisms, however, UoT WIL coordinators could assist them in developing the process into a more meaningful process. These feedback mechanisms could also be used by UoTs as points for collecting progress reports. They alluded to mentor-to-student meetings and group sessions at well-planned intervals. However, the industry is concerned that UoT coordinators do not visit students. The WIL coordinators could not provide a methodology to find out to what extent students are prepared before WIL. A participant alluded to the preparatory course prepared for students before going for WIL placement but was quick to say that the attendance was poor.

6 CONCLUSION AND RECOMMENDATION FOR FUTURE RESEARCH

There is a general acknowledgment of the fact that WIL has learner guides and that from it logbooks are prepared. UoTs recognize that they are the custodians of WIL, however, some shortcomings are identified, namely: irregular interaction with companies when students are in the industry and lack of upfront guidance to companies. The duration of WIL was raised as a concern, that WIL in its current form seems not to be enough. To this end, UoTs should take it upon themselves to design the WIL program in line with credit allocation to establish a reasonable, meaningful, and effective duration. Challenges that are identified could engaged with by both industry and universities.

The following recommendations emerged from the study:

i. A dedicated WIL coordinator that facilitates communication between the university and industry is essential for the success of WIL.

ii. Involve WIL mentors in advisory boards so that they are well versed with the University operations.

iii. Planning for placement, visits of students, assessments, and budget should be part of the annual department activities.

iv. For future study, the following literature gaps could be researched further:

v. Learner guide learning outcomes, assessments, and logbooks could be quizzed further.

vi. A qualitative study on students' perceptions of how universities prepare them for WIL and further explore if in their view they acknowledge that WIL is handled as a module like all the other modules.

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APPENDIX A: INDUSTRY INTERVIEW QUESTIONS

Interview Questions for industry:

- Do you have a structured program for WIL?
- Is the person responsible for WIL in the engineering department or human resources?
- To what extent are students prepared for WIL?
- Do you have a specific training program for WIL students or you depend on what they learned in their respective tertiary institutions?
- What method do you use to gather information about how prepared the students were before coming for WIL?
- What method do you to gather information about student’s progress?
- Which challenges do you face in your WIL program?
- What opportunities are there to be looked into by both industry and universities?

APPENDIX B: WIL COORDINATOR INTERVIEW QUESTIONS

Interview Questions for WIL coordinator at tertiary institutions’ engineering department:

- Which programs incorporate WIL?
- Is the WIL coordinator a staff member within a department or faculty?
- How do you know which industry is looking for students?
- After identifying a company looking for WIL students, how do you prepare the students?
- What method do you use to place students in industry?
- How often do you visit the students doing WIL in industry?
- What method do you use to gather information about how prepared the students were before for WIL?
- How often do you visit the students doing WIL in industry?
- What method do you use to gather information about how prepared the students were before going for WIL?
- What method do the students use to give feedback when in industry?
- How do universities prepare industry to mentor WIL students so that the outcomes are aligned with learner guide’s expectations?

INVESTIGATING THE STATE-OF-THE-ART IMPACT ANALYSIS APPROACHES WITHIN THE CONTEXT OF BUILDING AUTOMATION AND CONTROL SYSTEMS FROM A FEASIBILITY PERSPECTIVE: A STRUCTURED LITERATURE REVIEW

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ABSTRACT

Automation and Internet of Things systems have emerged as a technology that provides organisations with a physically autonomous platform able to improve the effectiveness and efficiency of its operations across all domains, particularly in the building automation system space. However, an accurate analysis of the impact such automation systems have on key performance indicators such as sustainability and economic return remains a priority. This systematic literature review investigates the current landscape of building automation systems using a Preferred Reporting Items for Systematic Reviews and Meta-Analysis approach. Through synthesising existing literature, methodologies and case studies, the outcome of the analysis extracts the primary themes, trends and academic production origins of the industry. Resulting in highlighting the state-of-the-art of building automation as well as the primary impact measures linked to building automation systems.

Keywords: Building automation systems, Impact analysis, Sustainability, Energy management system, Building management system

1 INTRODUCTION

In an era marked by escalating concerns linked to environmental sustainability, the current social climate has seen a shift towards more sustainable based systems. As a result, the energy sector has seen a radical increase in funding linked to the industry, with renewable energy seeing a 22% increase in 2023's first quarter compared to 2022, highlighting an all-time high [1]. Also, there has been an increase of 3% from 2019 in corporate spending in energy R&D, linked to automotives, electrical generation, oil/gas, and networks [2].

As a result of the growing trend, various technologies have been developed by the private sector to fit the current paradigm. One of which is the adoption of *building automation systems* (BAS) or *building automation and control systems* (BACS's). Which aim to automate a space's equipment to sense, monitor and control buildings energy usage and carbon emissions, which trace back to the 1950's [3]. However, since the origin of the technology, the systems have developed radically, with microcontrollers being implemented in 1980's and wireless communication protocols following in the 2000's [3].

BACS units, operate using four distinctive levels [4]. Sensors, fitting the ground level are used to capture raw environmental data such as temperature, humidity, lumosity and occupancy [5]. The raw data is then fed to a network controller responsible for translating the separate data into a format readable by the supervisor, and then sent to the field controllers of the space, such as the electrical panel or *heating, ventilation and air conditioning* (HVAC) system to control the environment [4]. The final level pertains to the control panel or user interface which is handled by the systems supervisor.

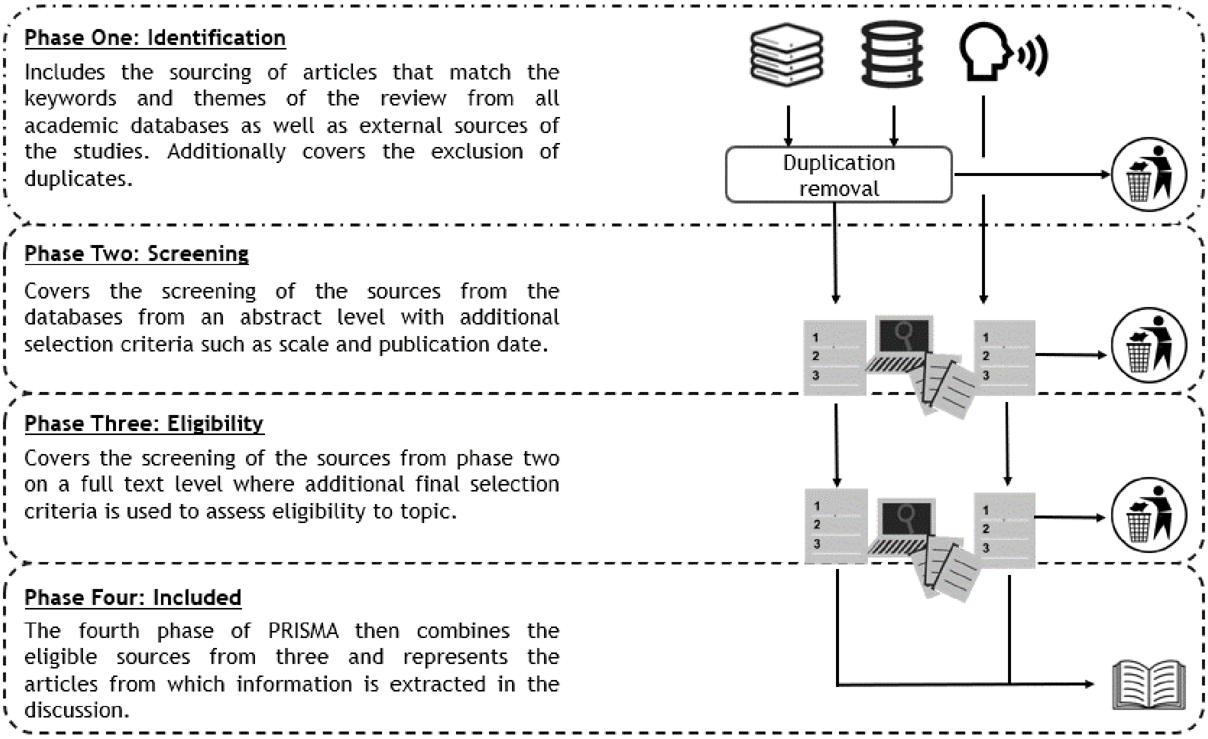
Due to the vast innovations within the field of BACS's, these units are able to accommodate a wide variety of operations to improve comfort and productivity, reduce costs from utility bills and reduce harmful environmental effects [3]. These operations include but not limited to lighting, HVAC and waterflow monitoring and control. As well as monitoring personnel access/occupancy, optimising maintenance schedules, and sensing emergency conditions to control building environments [3]. As a result of the diverse operations handled by BACS, these systems have generally been classified into four classes, namely: A, B, C and D. With D class resembling non energy efficient BACS, C and B for standard and advanced, and A class BACS for high energy performance systems [6]. As a result of the social pressure to adopt more environmentally friendly systems, more than a third of consumers are willing to pay an additional 25% premium charge for economically friendly products [7]. As such, the need for increased research within the space becomes essential to further explore the impacts and factors linked to building automation in order to aid the expansion of the technology [8].

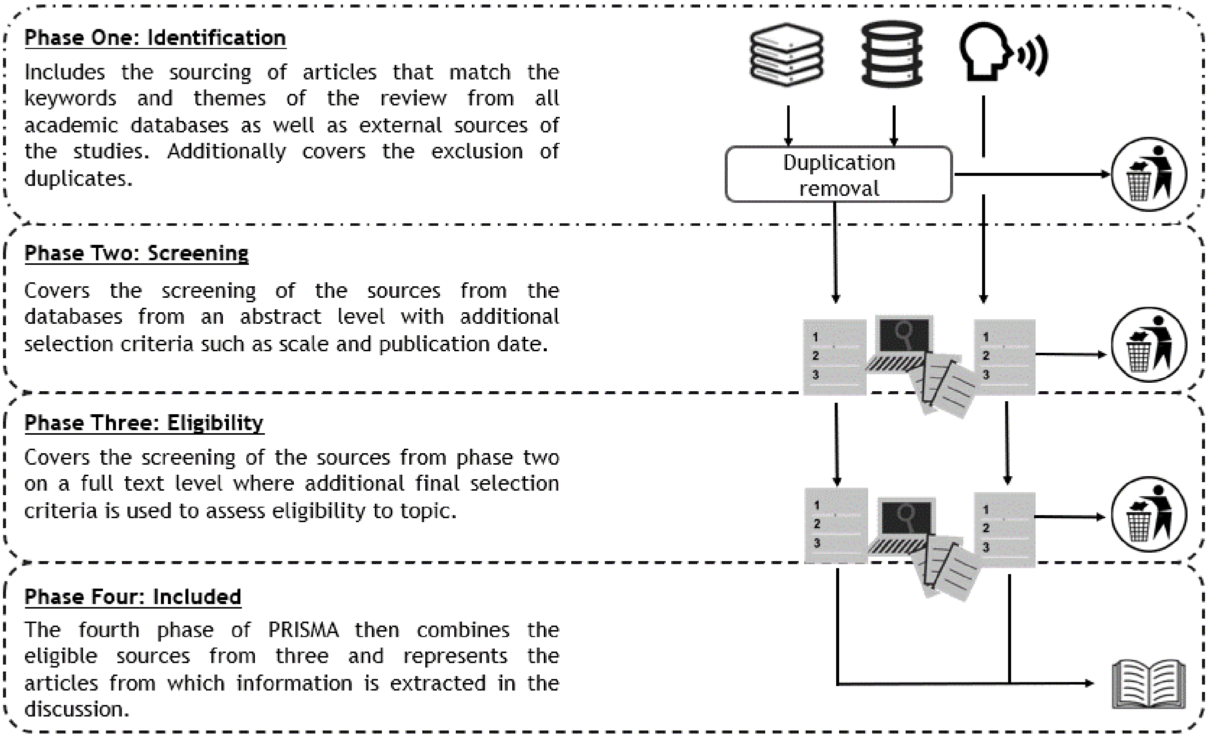
Following this climate, this paper presents a systematic literature review addressing the state of the art of BACS and tools used to analyse their impact on buildings. The systematic review focusses on evaluating the current state of the art of environmentally based or motivated BACS to gauge the current landscape associated with these devices. The paper aims to extract the themes and factors linked to building automation covering the environmental and financial aspects as well as the various frameworks established, covering the feasibility of a BACS. To achieve this, the review aims to achieve the following objectives: (i) To extract the relevant scientific literature linked to BACS and the various tools used to assess their feasibility using a pre-determined search process; (ii) To analyse the extracted literature according to the contents and origins associated with the publications to extract themes and trends currently emerging. (iii) To discuss the analysis results to examine the landscape and state of the art of BACS to uncover the gaps in literature.

2 APPROACH AND METHOD

The systematic literature review that follows is aimed at mapping out the current literature landscape and understanding depth regarding the impact of building automation and control systems from a sustainability and feasibility perspective. A systematic literature review is performed through investigating relevant research, systematically critiquing research reports, synthesising the findings of the investigation and finally concluding based on the findings of the research field [9]. These reviews are conducted following the conceptualisation of a research proposal before conducting the physical research [9]. The framework upon which the systematic literature review is build, follows the *Preferred Reporting Items for Systematic Reviews and Meta-Analysis* (PRISMA), conceptualised by Moher et al. [10] and expanded by Liberati et al. [11]. The PRISMA framework breaks down the various requirements and inclusions of a systematic literature review, and communicates them through a checklist, which was last updated by Page et al. [12]. The framework incorporates 27 content points required to conduct a thorough review, ranging from the title to the discussion of literature [10][12].

A distinctive feature of PRISMA literature reviews is the use of a pre-defined eligibility criteria for the sourcing of literature for the review, which covers four distinctive phases [10]. Moher et al. described the information flow phases as identification, screening, eligibility sorting and final inclusion [10] which is further described below in Figure 1 highlighting a visual breakdown of Moher et al.'s. steps.





Phase One: Identification

Includes the sourcing of articles that match the keywords and themes of the review from all academic databases as well as external sources of the studies. Additionally covers the exclusion of duplicates.

Phase Two: Screening

Covers the screening of the sources from the databases from an abstract level with additional selection criteria such as scale and publication date.

Phase Three: Eligibility

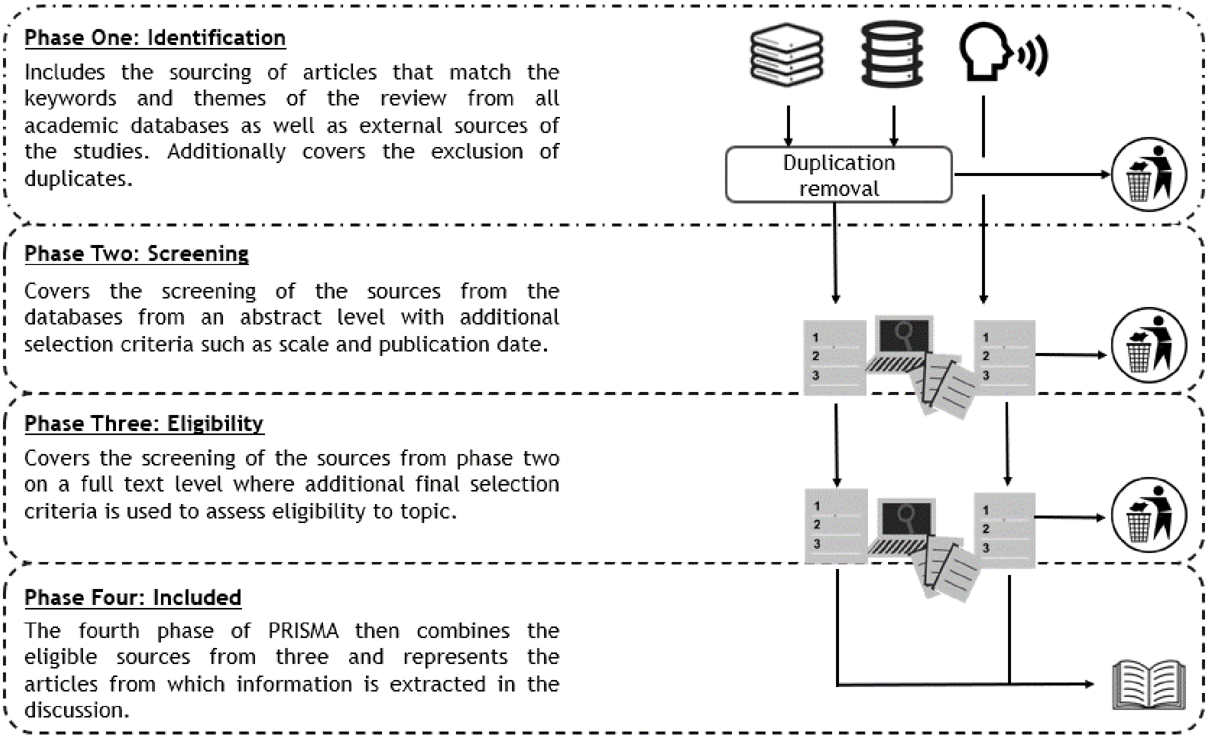
Covers the screening of the sources from phase two on a full text level where additional final selection criteria is used to assess eligibility to topic.

Phase Four: Included

The fourth phase of PRISMA then combines the eligible sources from three and represents the articles from which information is extracted in the discussion.

Figure 1: Flow breakdown of PRISMA systematic literature review process [13].

The first three phases cover the identification and screening aspects of the literature review seen in Figure 1. As a result, these phases are discussed below in Sections 1 and 1.2, which include the sourcing databases as well as eligibility criteria of the systematic literature review.



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2.1 Phase One: Source Identification

Phase one of the PRISMA review pertains to the extraction of literature from academia relevant to the topic. In alignment with this strategy, the first component of source identification covers the dataset selection. Which is then followed by the extraction of the relevant keywords used within each database to output relevant literature.

Of the various scientific databases, six are considered due to their range of literature relevant to engineering, energy, and science, namely: Scopus, IEEE, Science Direct, Google Scholar, Web of Science and Energia [14].

Of this initial list, three datasets are selected due to their collection of literature investigating building automation system impacts and assessment tools, access restrictions and advanced search tooling. The first of which was Scopus, used as the primary database used for extracting literature. Scopus houses the largest repository of peer-reviewed literature, currently holding 94 million records [15]. Following the primary search of Scopus, Google Scholar and Web of Science are used to access a wider spectrum of literature to ensure all relevant features and themes are captured. Google Scholar, is selected for this objective due to its vast range of academic literature, holding approximately 100 million studies as of 2015. This search engine makes use of multiple databases and accumulates the findings through one search entry [16]. However, as a result of Google Scholar extracting literature from a wide range of databases, a significant portion of the literature is unavailable due to access restriction and will need elevated screening through phase two. Lastly, Web of Science, is used as the third database, similar to Google Scholar, in an effort to ensure all relevant literate is extracted. Holding over 22 000 journals and over 92 million records, the database covers a wide range of science and engineering focused literature and is used to compliment the study as well as to validate to ensure all records are extracted [17].

The next component of source identification is the general search parameters used to limit the range of the search output. The following broad restrictions of the study are summarised below Table 1.

Table 1: Primary search limitations for source identification and initial screening [13].

Database	Type	Restriction	Rationale
Google Scholar, Scopus & Web of Science	Publication Year	2010 >	Avoid data bias due to innovation in technology which alter the efficiency of BACS units from a cost and sustainability perspective.
	Language	English	Language proficiency of author
	Source Type	No Thesis	Sources limited to articles, journals, and other ‘shorter’ publication to limit the size of output articles
	Access	Open Access	Google Scholar output limited to databases accessible to read full article entry as search outputs may be inaccessible.

The final component of source identification pertains to the physical search process used to extract the relevant literature used for screening. The search strategy used pertains to the keywords of the review and is illustrated in Table 2.

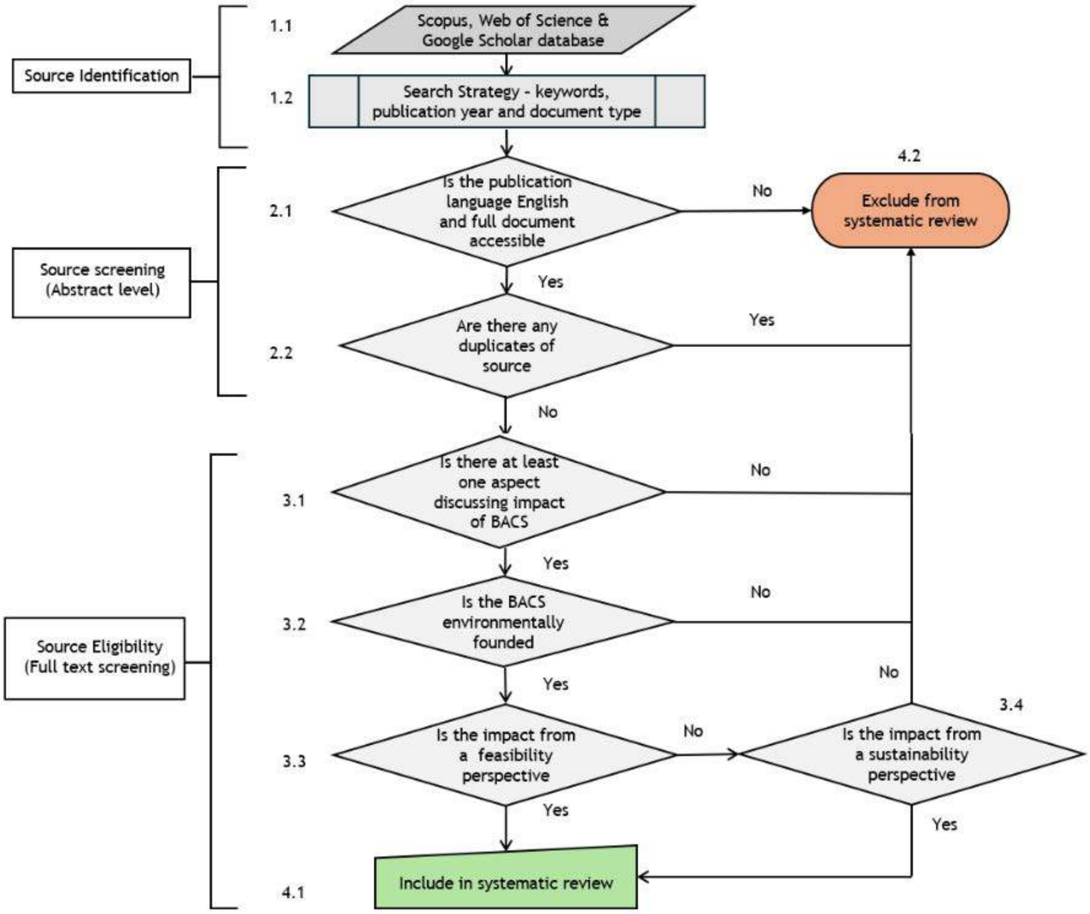
Table 2: The search strategy used to extract relevant literature [13].

Database	Search Procedure	Articles Extracted
Google Scholar (2010 - 2024)	“Building automation system” AND ("impact" OR "cost" OR "feasibility" OR “tool”) AND "EN 15232"	116
Scopus (2010 - 2024)	(TITLE-ABS-KEY ("Building automation" OR "Building automation and control" OR "Climate Control System") AND TITLE-ABS-KEY (feasib* OR cost* OR savin* OR emission* OR "Energ* Efficien*" OR "sustaina*”) AND ALL (“EN 15232”))	56
Web of Science (2010 - 2024)	“Impact assessment tool for building automation system”	36
Total Literature Extracted		**208**

The keywords in Table 2 are generated through the use of initial literature screening where relevant articles keywords are analysed and tested on the Scopus database until the results yielded relevant literature aligned with the objectives in Section 1. These keywords are then combined and used as the Scopus search procedure. As opposed to the primary search, the Web of Science search procedure differed in the sense that the database was incorporated to (i) validate the search results of Scopus and Google Scholar, and (ii) to cover unsaturated themes within the previous repositories. As a result, the search procedure for Web of Science is centred around the impact factor’s objective of Section 1.

2.2 Phase Two and Three: Screening and Eligibility

The next phase of the PRISMA methodology entails two intervals of analysis known as screening and eligibility. The first interval of the screening process covers the broad filtering of the sources, to remove duplicates, ensure access is open and exclude sources after the abstract screening process [18]. The second interval of the screening process follows a full examination analysis of the sources to remove articles based on contents, relationships, and relevance [19].



A visual representation of the screening and eligibility process is presented in

Figure 2, which depicts the exclusion criteria relevant to the extraction of sources for the discussion phase.

Figure 2: Screening and eligibility process flow chart [13].

The outcome of the screening process is shown in Table 3, highlighting the exclusion of literature relevant to each interval of the screening process.

Table 3: Outcome of screening and eligibility phase.

Interval number	Description	Impacted literature
2.1	Removal due to language restriction	18
2.2	Number of duplicate sources removed	19
3.1	Removal - no BAC consideration	36
3.2	Removal - BAC not environmentally founded	23
3.3 & 3.4	Removal due to not having key parameters	76

Phase one’s source identification produces a total of 208 sources in accordance with the search strategy Table 2, of which 37 articles were removed due to language and duplication rationale. The next phase of source extraction featured the abstract screening where an additional 111 sources were removed due to not being relevant to BACS. Upon completion of the abstract level screening the final 60 sources are analysed in the full text screening process where the final 36 are selected for further analysis and reporting.

3 RESULTS AND CONTENT ANALYSIS

The conclusion of phase two's source eligibility produced a total of 36 sources relevant to the investigation. These sources are examined through a bibliometric and content analysis to extract insight from the sources based on the literatures production, geographical origins, academic impact and credibility of the authors. Ensuing such, will follow a content analysis to extract the significant focal themes associated with the landscape of BACS literature in the using a thematic analysis approach.

3.1 Bibliometric Analysis

The bibliometric analysis is aimed at extracting the relevant features associated with the origins and format of the literature to assess the current scholarship of BACS within academia.

3.1.1 History of academic production

The first feature used for analysis of the extracted literature within the bibliometric analysis is the history of academic production. Within the context of assessing the state of the art of BACS, the historical academic production provides a degree of comprehension towards the evolution and maturity of the theme within academia [20]. As such, the history of academic production associated with the impact and feasibility of BACS is seen in Figure 3.

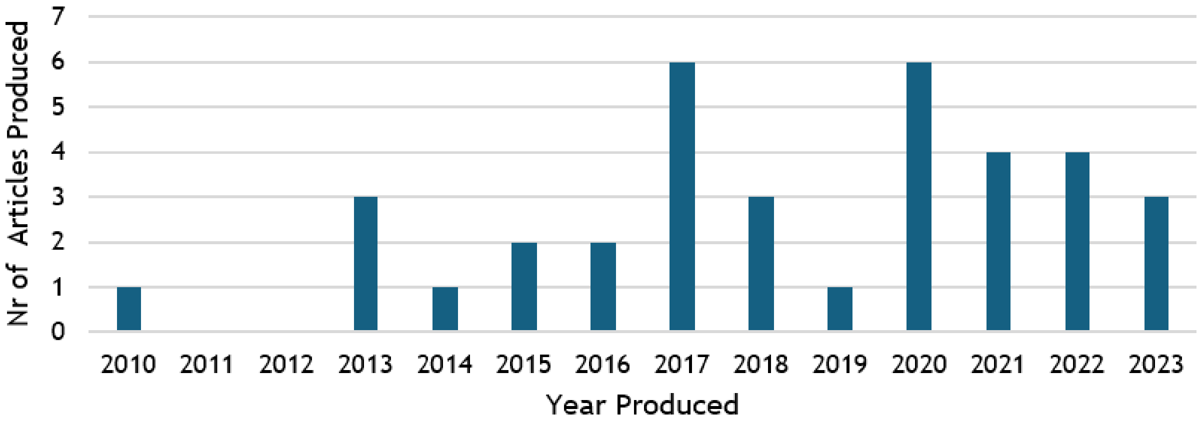


Figure 3: Chart highlighting the production of relevant academic literature within the context of BACS [13].

Figure 3 highlights an emerging trend within the academic space, with a significant increase seen from 2020 onwards. The presence of the trend reveals the recent increase in attention given to BACS and their installation within the world.

3.1.2 Geographical Origins of Literature

Following the analysis of the evolution of academic production within the field of BACS, follows an investigation of the geographical origins of the extracted documentation

Figure 4 4. Much like the production history of literature, the geographical origins of the literature may be used to extract insight. In the case of geographical origins, the literature may be analysed to examine the focal areas/dispersion of academic production to assess the saturation of a theme [21]. Furthermore, in addition to assessing the regional contribution of the literature, the geographical origin of the literature is used to assess the potential of bias being introduced into the synthesis due to the climate upon which the articles are produced [22].

Figure 4: representation of geographical origins of relevant literature [13].

As seen in Figure 4, the geographical origin of the relevant literature is primarily confined to the northern hemisphere, centred within Europe. These findings reveal the isolation upon which BACS are studied and implemented. Except for Columbia, the academic production has been limited to developed first world countries, where the standards and frameworks associated with the feasibility of BACS are based. Analysing the findings of Figure 4, there is a significant gap in the academic literature based in third world countries, with Africa in particular.

3.1.3 Academic influence of extracted literature

Following the geographical analysis of the extracted literature follows an examination of the academic weight the literature holds within the field's landscape. The first indicator commonly used to assess the eligibility and impact of the extracted literature is the citation count linked to the various sources. A common practice of gauging the impact a publication holds within a research environment is the citation count, where an elevated citation count is associated with an article being highly perceived within the research field [23].

In addition to citations being used to gauge the impact of a publication within the space, a common metric used to assess an author's expertise within a domain may be linked to the quantity of articles produced. In the same sense as the citations, the high academic production of an author can be used to gauge both a noteworthy impact and qualification within the field, and thus giving the articles produced a higher credibility [24].

Addressing the initial citation metric of assessing the impact associated with the extracted publications, the relevant citations linked to the literature are shown in Table 4, highlighting the documents holding the most weight or impact within the building automation space.

Table 4: Citation count of highest cited sources after screening [25].

Author, reference	Publication year	Citation count
Ippolito MG, [26]	2014	77
Marinakis V, [27]	2013	48
Kaminska A, [28]	2018	42
Mancini F, [29]	2019	37
Kamel E, [30]	2018	37
Vallati A, [31]	2016	24
OSMA G, [32]	2015	21
Schonenberger P, [33]	2015	17
Van Thillo L, [34]	2022	16

From Table 4, the highest cited article being produced by Ippolito in 2014, linked to 77 academic citations highlighting a substantial contribution to the automation space. Subsequently, the following 4 publications also indicate noteworthy citations, particularly when considering the 3rd and 4th articles publication release date. Overall, when considering the standard of literature, the publications highlight a significant impact within the field. Additionally, following from the citation metric, to assess the validity of the authors' work, the publications linked to the various authors of the literature are visualised in Table 5.

Table 5: Number of publications produced by top 10 authors [25].

Author	Number of articles produced
Jradi M	6
Zizzo G	5
Bonomolo M	3
Martirano L	3
Beccali M	2
Ciurluini L	2
Dessen F	2
Felius LC	2
Ferrari S	2
Flamini A	2

Table 5 shows a concentrated core of authors contributing to the field. The table shows the top 15 authors are responsible for generating at least two publications each, highlighting the limited number of individuals driving research in this field. This observation is further supported by Figure 4, which emphasises the central region around which the publications are produced. Notably, Jradi and Zizzo stand out among the top authors, contributing to 11 out of the 36 final documents. Their substantial influence in the extracted literature will prove evident in the analysis findings presented in Section 4, and thus shaping the core conclusions of the study.

3.2 Content Analysis

Following from the bibliometric study in Section 3.1 is the thematic analysis of the study, used to draw insights, trends and themes from the content of the sources. These themes are then used to build the discussion layout of Section 4. Through investigating the primary trends found within the extracted documentation, various factors stand out as prominent research themes of BACS.

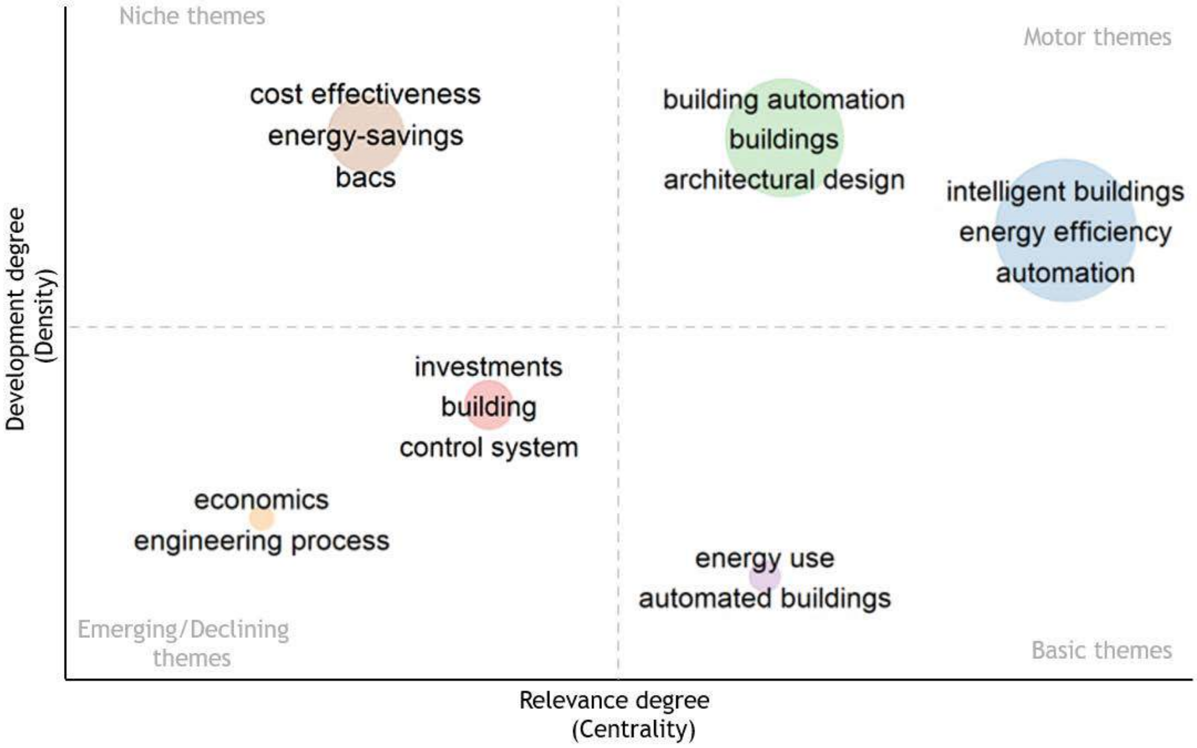


Figure 5: Graph highlighting the prominent themes extracted within literature [25].

Figure 5 highlights the various themes emerging within the literature, four primary categories are used to segregate the articles according to basic, emerging, niche and motor themes based on relevance and development. Addressing the basic and motor themes of the chart, describing the saturated research topics [35], energy use among building automation stands out as the primary discussion points of the literature, addressing the energy use aspects relevant to BACS. However, when considering the niche and emerging themes, describing the features as new and/or unique, the financial investment perspectives of building automation stand out.

In addition to the primary themes of the literature, analysis of the abstracts of the extracted publications presents various trends where the most significant terms are plotted against the literature's associated year as seen in Figure 6.

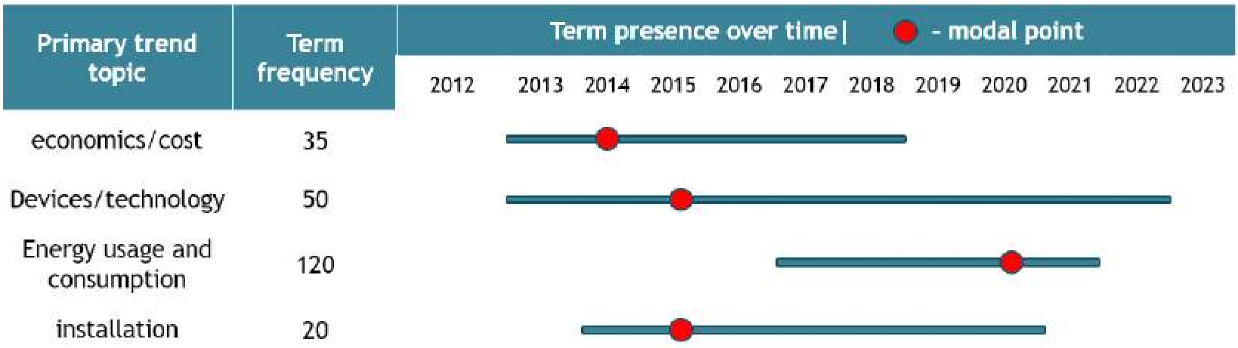


Figure 6: Graph highlighting the extracted primary trends from literature over the respective timeline [25].

Terms are be visualised over a timeline to identify trends growth over a period, as well as identifying gaps and opportunities within the research landscape. The first significant output of the graph is the economic and cost terms. With both terms addressing the financial aspects relevant to BACS, the significant portion of research was conducted early on and to a lesser degree, with the modal region set in 2014 indicating there has been a low saturation of financial research done on BACS in the recent history. This supports the findings of Figure 5. In addition to the financial identifiers, the devices term relating to the technology behind BACS, exhibits the most expansive range, indicating the continuous development of BACS technology. Lastly, looking at the energy aspects of building automation, the term displays the highest term frequency with a relatively recent modal region, indicating the term's focus within literature as well as the emerging nature of the technology.

3.3 Thematic Content Analysis

In addition to the themes extracted from the literature's abstracts, various significant factors are discussed within the publications linking to the state of the art of BACS research listed in Table 6.

Table 6: Identified factors that influence the state of the art of BACS [13].

Factor	Relevant list of publications	Nr of Publications
Electrical energy usage reduction	[36][37][38][39][40][41][32][42][43][44][31][45][46][47][48][29][49][50][51][33][52][53][54][26][55][56][28][57][34][58][59][60][30][61]	34
Thermal energy usage reduction	[36][37][40][41][43][44][46][48][29][53][56][57][34][58]	14
Internal BACS energy demand	[38][45]	2
Installation cost	[44][29][51][26]	4

Factor	Relevant list of publications	Nr of Publications
BACS cost effectiveness	[37][39][40][41][44][31][46][47][29][49][52][53][26][57][34][59]	16
Retrofitting alternative	[38][32][53][54][57][58]	6
BACS energy feasibility tools	[36][38][41][46][33][52][27][62][55][57][34][60][30][61]	14
BACS financial feasibility tools	[29][49]	2
Impact of Occupancy	[32][49][53][56][59]	5

3.3.1 Electrical and Thermal Energy Usage Reduction

Emerging as the most significant theme of the extracted literature, jointly discussed in 34 of the total 36 publications, electrical and thermal energy usage may be categorised as the leading factor behind the research of BACS. With 34 of the publications discussing electrical savings and 19 additionally covering thermal savings, the impact statistics varied drastically due to the array of case studies, where different BAS classes and instalment sites were studied. As such, the electrical savings of BACS instalment ranged from 7.6% to a significant 28%, compared to thermal savings where a range of 16 - 24% was observed. However, as opposed to the variation in energy savings, various trends did emerge throughout the literature. Firstly, when examining the energy sources that BACS target for reduction, the thermal component of energy usage stands out as the most significant source compared to others, as illustrated below.

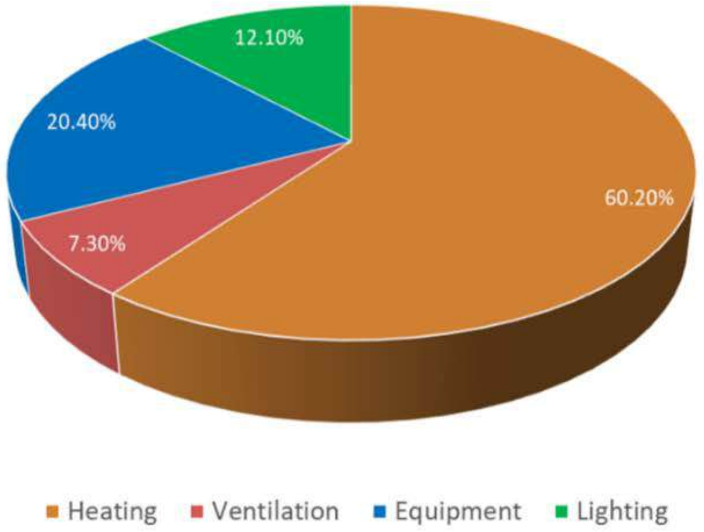


Figure 7: Chart highlighting the various energy demand origins of a building [58].

3.3.2 *Internal BACS Energy Demand*

As opposed to the energy usage savings theme of the literature, the internal BACS energy demand was only discussed in two of the 36 publications. However, despite the low recognition within literature, the internal energy demand placed on the system does hold significance in various cases. On average, the internal energy demand of BACS ranges from 0.6% to 1% of the total energy demand of a site. This percentage varies depending on the class of the BACS, with more advanced classes consuming more energy. As such, in larger sites this can represent a substantial energy quantity. Additionally, much like the effectiveness of the BACS, the internal demand varies based on the geographical placement of the unit. Where the consumption increases with latitude above the equator, described in the case study based in Abu Dhabi, where the internal consumption increases from 0.51W to 0.68W as the latitude increases across the border.

3.3.3 *Installation Cost*

Much like the internal energy demand of BACS, the installation cost of BAC Systems was discussed in only 4 of the publications. As a minor theme within the literature, the installation cost of a BACS varied due to the discrepancies of the case studies, however when removing office and university cases, a common trend places BACS system installation costs in the region of 6000 EUR for a single residential home. Where the cost of these systems may be broken down into three phases; Equipment procurement, installation costs and lastly the indirect costs due to the downtime required for the installation period.

3.3.4 *BACS Cost Effectiveness*

As opposed to the above, the cost effectiveness of BACS was discussed in 16 of the articles. Addressing the effectiveness of these systems to reduce costs based on the financial input, the effectiveness of the BACS systems was heavily dependent on the class of the system. In line with the standards laid out by EN15232, D-class BACS systems (base level BACS) feature a *discounted payback period* (DPP) of 2-8 years. Additionally, the C & B BACS class followed suit with a DPP of 10-13 years as opposed to an A class BACS (intelligent automation system) requiring a DPP of 18 up to 29 years depending on the case. However, as with the themes above, the DPP is largely variable depending on the location and starting class of the building, occupancy per square meter and geographical placement. Lastly, a significant and recurring factor within the literature stated the effectiveness of BAC Systems is heavily dependent on the starting class of the buildings and technology within. Where BACS systems are significantly more effective when installed in buildings originally placed in a low energy efficiency class, as opposed to originally green sites where the *return-on-investment* (ROI) is lower.

3.3.5 *Retrofitting Alternative*

When addressing the theme of retrofitting, referring to the replacement of devices within a space. The theme was discussed within 6 of the articles where the effects of retrofitting was ranked against the installation of a BAC system to assess the effectiveness of each. The assessments were achieved using various case studies which yielded diversified findings. The first of which was the significant effectiveness of retrofitting on lighting systems which yielded a 30-70% reduction in energy demand. Secondly, unlike the case in lighting, the initial costs associated with retrofitting in contrast to BACS is case dependent and more effective in the lower energy class buildings. However, as stated in literature, the instalment of BACS systems is commonly associated with the retrofitting of the internal technology to raise the energy class of a building where the effectiveness is maximised.

3.3.6 BACS Energy Feasibility Tools

Addressing the BACS feasibility tools and frameworks identified within the literature, 14 of the publications refer to approaches used to monitor, describe and assess the feasibility of installing/monitoring a BAC System. The most significant framework of the publications stands out as the EN15232 classification standard, aimed at addressing the minimum energy efficiency standard of newly constructed buildings within the EU. As discussed in Section 1 of the study, EN15232 categorises BACS into four identifiable classes, labelled as D, C, B or A class. In addition to such, the standard includes two methods used for assessing the impact of BACS systems within a site. The first of which is the BAC factor method, used for initial feasibility assessments of a building based on estimations, and a second detailed method used to assess impacts based on extensive device characteristics. By various case studies within the relevant literature, the EN15232 framework deviates in accuracy and exhibits various limitations. In multiple case studies the BAC factor method presents error deviations of over 10% in energy saving parameters, which is heavily influenced by seasonal and weather conditions. A second limitation identified through the literature discusses the gaps of the framework in covering outdoor lighting systems and seasonal effects on the assessment. In addition to the EN15232 framework, various standards are discussed such as the *Smart Readiness Indicator* (SRI), EU.BAC framework and the *Interactive tool for building automation and control systems auditing* (IBACSA). As in the case of the EN15232 framework, these systems all express similarities in methods of classifying buildings and BACS according to a class system, but are limited to presenting a comprehensive, accurate feasibility assessment of BACS installation, and largely focus on assessing the smartness of existing BACS.

3.3.7 BACS Financial Feasibility Tools

As opposed to the feasibility tools linked to assessing the impact of BACS on energy, only two publications briefly describe financially based feasibility assessment tools. The two tools both feature similar evaluation techniques where the energy demand is assessed according to the various BAC devices before linking the demand to costs. However, much like the above, the tools exhibit limitations. Firstly, both frameworks are presented in case specific scenarios and applied primarily to their individual case study, and secondly, as opposed to being feasibility assessment tools, the frameworks are largely used to monitor already functioning BAC Systems.

3.3.8 Impact of Occupancy

The last factor identified linking to the impact of BAC systems is the influence of occupants on the energy demand of a building. Discussed in 5 of the publications, the impact of occupancy on the performance of BACS is significant. Using case studies, the effect of occupants is observed to decrease with increasing BACS classes due to the elevated degree of automation within the space, ultimately removing the manual interaction of occupants between the energy services of the space. However, in the case of lower automation such as C class systems, occupants are described as having a 43% impact on heating, 34% on lighting and 22,8% on HVAC usage when comparing energy efficient occupant’s vs standard occupant behaviour.

4 DISCUSSION

Addressing the findings of Section 3's content analysis, various trends and themes were analysed according to the extracted sources publication origins, geographical placement, keyword significance and factors linked to the impact and feasibility of BAC Systems. To highlight the state of the art of BACS systems and the various impact factors, Section 4's discussion breaks down the various gaps found within literature relevant to the landscape of BACS research. The first gap revolves around the isolation of BACS literature within the European region, highlighted in Figure 4. Observing the origins of the literature, there exists a gap in literature covering the instalment, monitoring and assessment of BAC Systems within the Southern hemisphere and particularly also in African. This gap is furthered by the absence of frameworks and standards aimed at providing the minimum levels of automation required in newly constructed buildings, as well as sustainable practices relevant to the installation of building automation. Furthermore, another evident gap found throughout the study is that the literature is predominantly produced by a limited number of authors based in Europe, mirroring the trend observed with the first gap. As a result of such, the case studies discussed and analysed within literature are all founded within the European region and thus excludes context specificities that relate to elements such as African climate which creates an area of uncertainty surrounding the performance of BACS systems under the African weather system. However, the most significant gaps found within literature surround the limitations and absence of an expansive feasibility tool used to assess the impact of installing a BACS system in the early construction phase of a building. As seen in Section 3's content analysis, there exist multiple limitations in the current frameworks used to assess BACS. The first of which is the absence of an economic feasibility assessment where the current tools are limited to factors not addressing costs, and instead using energy, comfortability and efficiency factors to assess the impact of BACS. While there exist economic feasibility assessments, the methods used to assess the cost impacts surrounding the installation are case specific as opposed to a general framework. Additionally, the current frameworks fail to include seasonal change effects within their assessment. Shown through the factor analysis, the geographical placement of the building has significant effects on the efficiency of building automation, however, none of the current frameworks and tools account for seasonal changes, nor the longitudinal and latitude placement. Lastly, an additional limitation of BACS assessment tools covers the reporting of all energy systems where the widely adopted EN15232 framework fails to include outdoor lighting within the report amongst other energy losses which as a result, limits the ability of assessing an extensive BAC system. Synthesising the above gaps found within literature, there exists a need for an extensive, geographically based, economic feasibility tool capable of accurately predicting the impact of installing a BAC system and furthermore, there is a need for such an economic feasibility tool to be customised to take context specificities into account.

5 CONCLUSION

This paper presents the state of the art of building automation systems and investigates the various factors linked to the impact and efficiency of BACs and the feasibility tools used to assess the impacts of installation. The paper made use of a PRISMA based literature review to extract the relevant publications linked to the impact of BACS. Following this approach the relevant literature was screened and analysed through a bibliometric study and content analysis where the various factors linked to the impact of BACS were extracted. The outcome of the content analysis and bibliometric study was then used to assess the various gaps found within literature and to discuss and highlight the limitations linked to the literature of building automation. This paper can therefore be used as a stepping stone to guide future work.

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STRATEGIC INTEGRATION OF PLANT MAINTENANCE SYSTEMS: A SYSTEMS THINKING APPROACH FOR ENHANCED PERFORMANCE AND SUSTAINABILITY

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ABSTRACT

The modern industrial landscape demands optimal plant performance, presenting challenges for maintenance management. This research focuses on strategically integrating plant maintenance systems using a systems thinking approach to improve performance and sustainability. The study advocates a shift from reactive to proactive models, emphasising technology-driven advancements and a holistic understanding of maintenance practices. Examining the transformative journey of plant maintenance, the research underscores the significance of adopting a systems-thinking perspective. This approach provides a comprehensive view of maintenance systems, enabling a thorough examination of interconnected components and relationships. Aligned with the theme of strategic integration, the study systematically explores how systems thinking enhances performance and sustainability in plant maintenance. By analysing systems thinking principles and their application, the research offers insights into maintenance practices and addresses technological advancements, human factors, and organisational dynamics. The outcomes contribute to advancing maintenance strategies, fostering efficiency, and promoting sustainability in modern industrial operations.

Keywords: systems thinking, maintenance management, performance improvement, sustainability, human factors, holistic understanding, strategic integration

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1 INTRODUCTION

In the dynamic landscape of industrial operations, the strategic integration of plant maintenance systems is critical, fostering an evolution from conventional practices to a comprehensive approach aligned with systems thinking principles [1]. This research endeavours to navigate the complexities of plant maintenance, offering transformative insights into how a strategic integration rooted in systems thinking can significantly enhance plant performance and sustainability.

In the context of this research, the term "strategic integration" implies a holistic and purposeful amalgamation of various facets of plant maintenance systems, aligning them with overarching organisational objectives. This approach requires a paradigm shift towards systems thinking, recognising maintenance systems as interconnected entities [1]. This theoretical foundation addresses the intricate challenges of developing plant maintenance systems.

The core research problem revolves around the difficulties confronted by plant maintenance systems in achieving optimal performance and sustainability. In plant maintenance, sustainability involves integrating proactive strategies and environmentally responsible practices to ensure long-term operational viability while minimising adverse impacts [2]. It aims to balance stakeholder needs by optimising resource utilisation and fostering a culture of continuous improvement and innovation [2]. The absence of a comprehensive framework hampers efficiency, adaptability, and long-term sustainability, posing a barrier to innovative enhancements in operational effectiveness [3].

Several maintenance frameworks have been developed to enhance organisational competitiveness and cost-effectiveness [4]. Developing a maintenance framework begins with identifying maintenance objectives and strategies aligned with the corporate vision, goals, and stakeholder expectations [4]. This process leads to the formulation of maintenance policies, organisational structures, resources, and capabilities required to support the framework [4]. However, existing maintenance frameworks face significant gaps, including concerns about their relevance, interpretability, timeliness, reliability, validity, cost and time effectiveness, and ease of implementation [4]. Parida and Kumar [4] argue that an effective maintenance framework must link operational-level maintenance outcomes to corporate strategic objectives. The primary gap in traditional maintenance frameworks is the lack of integration between strategy, processes, and outcomes, necessitating a holistic approach that aligns maintenance with business goals to enhance profitability and sustainability [5]. This integration ensures that maintenance activities contribute to the organisation's overall strategic goals, highlighting the need for robust and adaptable maintenance frameworks that address these multifaceted challenges [4].

The research seeks to identify the theoretical underpinnings of strategic integration and derive practical models and methodologies within this framework to enhance plant maintenance systems' safety, reliability, and overall equipment effectiveness [6]. By addressing the identified gaps and integrating systems thinking principles with conventional paradigms, the research aims to contribute transformative insights, laying the groundwork for a strategic integration that enhances operational effectiveness and sustainability in plant maintenance.

The research will provide a novel approach to plant maintenance and improve efficiency, adaptability, and sustainability in industrial operations by bridging theory with practice. The holistic framework proposed (Figure 2) empowers maintenance practitioners and industry leaders with the necessary knowledge and tools. This innovative approach aligns with the principles of systems thinking, which is essential for understanding the complex interactions within maintenance systems and ensuring effective decision-making and resource allocation [7], [8].

The findings could drive transformative change, fostering improved performance and long-term success in the competitive industrial landscape. Furthermore, the research scrutinises the significant influence of organisational and managerial factors on the efficacy of maintenance practices, specifically focusing on leadership styles, organisational culture, workforce competencies, and performance indicators. By synthesising insights from various scholarly viewpoints, it proposes methodologies for optimising these factors to attain superior maintenance results. Through meticulous examination, the research endeavours to enrich the academic dialogue surrounding maintenance management by introducing innovative frameworks and actionable suggestions to bolster operational efficiency and sustainability. This inquiry aims to unveil the transformative capacity of strategic organisational and managerial interventions within the industrial landscape.

2 LITERATURE REVIEW

2.1 Systems thinking in plant maintenance

Pintelon and Gelders [9] highlight the evolution of plant maintenance from a mere technical necessity to a strategic organisational component, indicating a significant paradigm shift in industrial operations. This transformation underscores the recognition that maintenance management requires more than just engineering expertise—it necessitates integration into broader business frameworks. This integration is explored through the lens of systems thinking, aligning with the theme of strategic integration for enhanced performance and sustainability in plant maintenance.

Foundational works by Senge [7] and Sterman [8] emphasise the holistic perspective of systems thinking, highlighting its relevance in uncovering complex relationships within maintenance systems. Monat and Gannon [10] elaborate on systems thinking as a holistic viewpoint, recognising the significance of relationships among system components, akin to Bertalanffy's General Systems Theory [11], providing a foundational understanding across various disciplines. Betley et al. [12] classify systems into simple, complicated, and complex, providing a framework for tailoring problem-solving approaches. Kim [13] argues that systems thinking offers a suite of tools, including archetypes, categorised into brainstorming, dynamic thinking, structural thinking, and computer-based tools, fostering deeper insights into dynamic behaviour.

Despite a century of literature promoting systems thinking in organisational management, its mainstream implementation in plant maintenance still needs to be improved [14]. Arnold and Wade [15] highlight that despite the significant impact of systems thinking, its utilisation still needs to be enhanced due to insufficient clarity in definition and understanding. This gap could stem from a need for practical regulations derived from advanced systems thinking principles [14]. In plant maintenance, systems thinking breaks down barriers between maintenance and operations [16], fostering a more integrated approach. Önder [17] emphasises proactive, long-term strategies, while Lung and Levrat [18] highlight maintenance's role in advancing sustainability. Agresti [19] underscores the importance of systems thinking in comprehensively examining cause-and-effect links in maintenance processes.

Plant maintenance is a multifaceted system that requires coordinated activities such as preventive, predictive, and corrective measures to maintain industrial machinery and systems in optimal condition [20]. This complexity necessitates a systems thinking approach, which views maintenance processes as interconnected and interdependent. This allows for better managing dynamic interactions and feedback loops [5], [6]. This approach ensures maintenance strategies align with broader organisational goals and fosters sustainable practices through continuous improvement [18], [21].

2.2 Technological advancements in plant maintenance

The evolution of technology has reshaped plant maintenance, introducing tools to enhance efficiency, reliability, and safety [22]. This study investigates the latest developments in predictive maintenance, condition monitoring, and maintenance management, aiming to elucidate strategic approaches for leveraging technology to augment plant maintenance practices.

Plant maintenance aims to optimise reliability and minimise downtime [23]. The digital revolution has progressed maintenance strategies from reactive (M1.0) to predictive (M4.0), drawing on big data analytics and the Internet of Things (IoT) [24]. Under Industry 4.0, "Smart Maintenance" is gaining scholarly and practical attention to enhance maintenance practices [25]. Rogers [26] argues that embracing a proactive stance is crucial in adopting Maintenance 4.0 to sustain competitiveness. Maintenance 4.0 empowers companies through big data analytics and IoT, reducing costs and enhancing efficiency [27]. The practical implementation of Maintenance 4.0 requires sophisticated digital technology and policy support [28]. Smart Maintenance, as an organisational structure integrating digital technologies, fosters effective decision-making [25].

By embracing technological innovations and a systems thinking approach, organisations can optimise maintenance practices, ensuring efficiency and sustainability in industrial landscapes. “Smart machines" represent a fusion of new technologies into equipment, emphasising adaptability and efficiency [27]. Connectivity facilitates data exchange, extending services beyond physical machines, underscoring the importance of regular maintenance concept reviews to adapt to technological advancements [29]. Smart infrastructure, integrating data and digital twins, reshapes infrastructure management [30].

The convergence of technological advancements in plant maintenance, alongside principles from Industry 4.0 and smart maintenance strategies, signifies a shift towards proactive, data-driven approaches. By utilising big data analytics, IoT, and smart technologies, organisations can transition from reactive to predictive maintenance paradigms, optimising reliability and efficiency. Successful implementation requires sophisticated digital technology and a holistic systems-thinking approach, enabling organisations to navigate industrial complexities with foresight. This discourse emphasises organisations' need to foster a culture of innovation and adaptability, positioning themselves at the forefront of the evolving maintenance landscape.

2.3 Innovative processes within plant maintenance

De Felice, Petrillo, and Autorino [31] emphasise the need for comprehensive data in maintenance management despite challenges in aligning production and maintenance objectives. On the other hand, Modgil and Sharma [32] highlight organisations' efforts to optimise maintenance operations amidst the convergence of physical and digital domains.

Senge [7] and Grant [33] stress the importance of organisational knowledge-based theory and continuous learning for enhancing maintenance efficiency. Lee et al. [34] note the transformative potential of technological advancements in maintaining and integrating management information systems (MIS). Lee et al. [35] observe a shift from reactive to proactive maintenance approaches driven by computing advancements. In the context of Industry 4.0, they discuss collaborative machine interconnection and predictive tools for minimising downtime and optimising maintenance scheduling [35]. Pitt et al. [36] underscore the importance of structured approaches and case studies in exploring and understanding innovation in maintenance. Strategies for overcoming obstacles to innovation include fostering a supportive organisational culture and adopting a systems-thinking approach [37], [38].

In the dynamic landscape of plant maintenance innovation, synthesising research findings from diverse scholars illuminates a multifaceted approach towards optimising operational efficiency and sustainability. From the emphasis on comprehensive data by De Felice et al. [31] to the transformative potential of technological advancements highlighted by Lee et al. [34], each contribution offers a unique perspective on the evolution of maintenance practices. Furthermore, the discourse on organisational knowledge-based theory by Senge [7] and Grant [33] underscores the critical role of continuous learning in enhancing maintenance efficiency. These insights collectively underscore the intricate interplay between technological innovation, organisational learning, and strategic management in shaping the future of plant maintenance.

Building upon this foundation, integrating management information systems (MIS) and collaborative machine interconnection, as discussed by Lee et al. [35], emerges as a pivotal strategy in transitioning from reactive to proactive maintenance approaches. Moreover, the emphasis on structured approaches and case studies by Pitt et al. [36] provides valuable guidance for organisations seeking to navigate the complexities of innovation in maintenance. By fostering a supportive organisational culture and adopting a systems-thinking approach, as advocated by Vargo et al.[38] organisations can overcome innovation obstacles and unlock their maintenance operations' full potential. This synthesis of research findings offers practical insights for industry practitioners. It contributes to the scholarly discourse on innovation processes in plant maintenance, positioning this academic journal as a beacon of knowledge and guidance.

The discourse on innovation in plant maintenance highlights its multifaceted nature, influenced by technological progress, organisational learning, and the integration of physical and digital realms. Despite challenges, embracing innovation is crucial for organisations to adapt to the evolving industrial landscape and foster long-term success.

2.4 Strategic framework development

In developing maintenance management frameworks, accurately gauging the current state of equipment degradation is paramount for formulating effective system operation plans and scheduling maintenance activities [39]. The research delves into the intricacies of crafting a strategic framework for plant maintenance, highlighting the necessity of aligning maintenance objectives with broader organisational goals to avoid suboptimisation [9]. Various approaches to strategic framework development are explored, encompassing maintenance management strategies, planning methodologies, scheduling techniques, and risk-based methodologies [40]. Maintenance strategies are critical in augmenting operational efficiency, reliability, and resource utilisation [41], [42].

The maintenance strategic framework proposed by Muchiri et al. [20] provides a comprehensive roadmap for driving maintenance activities towards achieving organisational performance objectives. It underscores the importance of aligning maintenance goals with broader organisational objectives to optimise performance outcomes and enhance operational efficiency [20]. The three main sections, as shown in Figure 1 below, are maintenance alignment with organisational goals, maintenance effort/process analysis, and maintenance results performance analysis. This framework directs maintenance efforts towards attaining requisite performance levels and fostering continuous improvement in production equipment performance [20]. Moreover, it highlights the significance of two integral phases—formulation and implementation—within the strategic maintenance process, with each phase carrying substantial implications for organisational success [43].

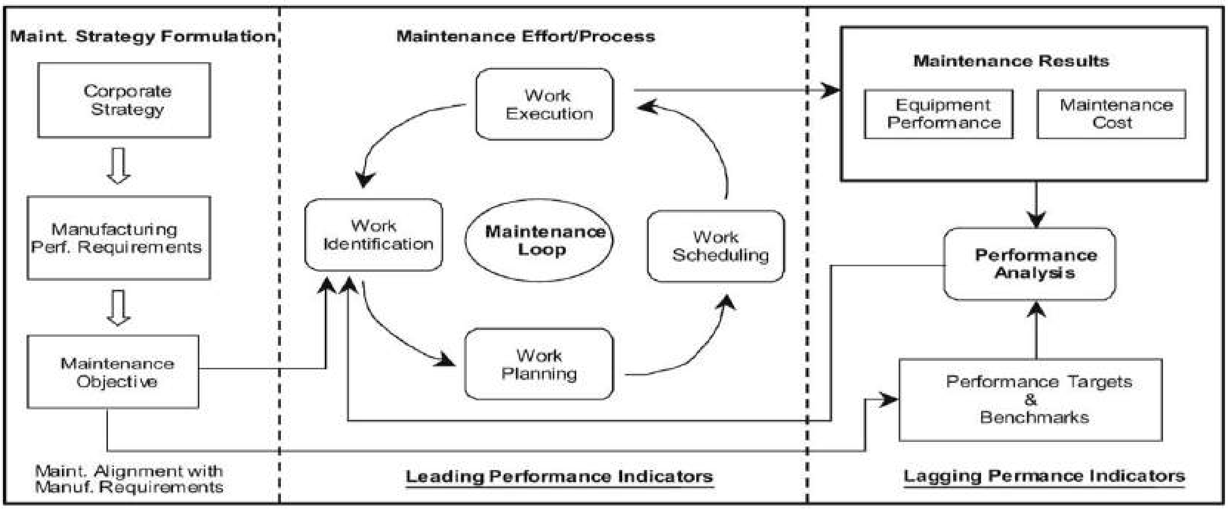

Figure 1: A maintenance framework as proposed by Muchiri et al. 2011

The selection and execution of maintenance strategies are complex decision-making processes that require careful consideration of various factors, including organisational objectives, resource availability, and system complexity [44]. Al-Najjar and Alsyouf [45] highlight the cost-effectiveness and reliability of maintenance strategic frameworks in achieving plant objectives such as availability, product quality, and safety. Systems thinking emerges as a foundational approach for constructing maintenance frameworks, offering insights into dynamic interactions within maintenance ecosystems [8], [46]. This perspective enables holistic integration of organisational goals and maintenance requisites, fostering proactive decision-making and continuous improvement [47], [29].

By integrating systems thinking principles, organisations can optimise maintenance management, mitigate risks, and maximise asset value [48]. This systemic approach enhances operational efficiency and fosters resilience and sustainability amidst evolving industrial landscapes [49].

2.5 Organisational and managerial factors

Change management literature underscores the importance of effective leadership and adaptive organisational cultures in integrating systems thinking into maintenance practices [7]. Decision-makers within maintenance management face challenges in comprehending interconnected cause-and-effect relationships, highlighting the need for a comprehensive understanding facilitated by systems thinking methodologies [50], [51]. Empirical evidence suggests the significant impact of systems thinking on organisational effectiveness, promoting innovation and practical problem-solving [52], [53].

Leadership styles, particularly transformational and participative approaches, are crucial in influencing maintenance outcomes by inspiring motivation and fostering a sense of ownership among team members [54]. Organisational culture, characterised by continuous learning and openness to change, shapes behaviour and attitudes towards maintenance practices, impacting innovation and adaptability [55]. Workforce skills, including technical proficiency and problem-solving abilities, are essential for maintaining proficiency in evolving technologies [56]. Finally, performance metrics aligned with maintenance objectives provide valuable insights into operational efficiency, reliability, and cost-effectiveness, enabling organisations to refine their strategies for continuous improvement [57].

Organisational and managerial factors, such as leadership styles, organisational culture, workforce skills, and performance metrics, play a crucial role in maintenance practices. Systems thinking provides an approach to tackle the complex challenges of optimising maintenance and achieving sustainable outcomes. The literature also stresses the need for interdisciplinary collaboration to align maintenance strategies with broader operational goals. Continuous evaluation and adaptation of maintenance practices are essential to keep up with changing organisational goals and industry trends.

2.6 Enduring effects on performance and sustainability

Integrating systems thinking into maintenance practices is critical to the discussion highlighted by Utterback's [56] longitudinal study on the impact of technological innovation. It emphasises the importance of aligning maintenance systems with broader corporate plans and manufacturing strategies [20]. Furthermore, sustainable maintenance practices will be explored, focusing on minimising environmental impact and maximising resource efficiency [58]. These practices lead to environmental benefits and contribute to financial savings and operational efficiency [58].

The enduring effects of maintenance initiatives extend beyond operational metrics to encompass broader organisational goals, including customer satisfaction and employee engagement [59]. Moreover, the role of leadership in shaping enduring maintenance practices is emphasised, with a focus on fostering a culture of innovation and strategic alignment between leadership vision and maintenance objectives [60].

Integrating sustainability principles into maintenance practices is explored, highlighting the importance of corporate social responsibility and its impact on stakeholder relationships [61]. Organisations prioritising ethical and socially responsible approaches in maintenance operations are better positioned to build resilient supply chains and navigate industry disruptions [61].

The literature highlights maintenance practices' complex and lasting impacts, advocating for a comprehensive approach that combines technological adaptation, leadership excellence, and sustainability. By embracing innovation, fostering a positive organisational culture, and prioritising sustainability, organisations can build a resilient foundation for sustained excellence in maintenance operations. The research examines how leadership styles, technological innovation, sustainability integration, and organisational culture affect organisational performance and sustainability. Synthesis of these academic perspectives and empirical studies identifies critical drivers of successful maintenance and explores ways to implement sustainable practices through a framework.

3 METHOD

3.1 Theoretical framework

Current maintenance management frameworks, such as those proposed by Muchiri et al. [45], Tsang [62] and Al-Turki [63], emphasise the interconnectedness of maintenance strategy formulation, the maintenance process and maintenance outcomes within organisational systems. Despite numerous authors highlighting the interdependence of maintenance strategy formulation, process, and outcomes, a significant gap exists in their effective integration, often leading to fragmented management and inefficient resource allocation [64], [65], [66]. This fragmentation hinders the ability to optimise maintenance activities in alignment with broader corporate strategies, leading to inefficiencies and reduced effectiveness in maintenance practices.

Systems thinking tools such as Systemigrams offer a holistic perspective that can bridge this gap. These systems thinking tool is handy for identifying areas of inefficiency, potential improvements, and strategic decision-making by clearly representing the entire system's structure and behaviour [67], [15]. It is a powerful tool for integrating various models from maintenance and systems thinking to create a cohesive framework for strategic maintenance management. The Systemigram facilitates a holistic approach to maintenance management, enabling a clear understanding of how these elements interact and influence each other within the broader organisational context. This visualisation helps identify feedback mechanisms, non-linear relationships, and dynamic behaviours, supporting informed decision-making and continuous improvement in maintenance practices.

According to Arnold and Wade [15], a Systemigram is a visual representation that maps out the interconnected components of a system, highlighting dynamic interactions and feedback loops. The Systemigram consists of nodes representing different components or elements and arrows depicting the relationships and flows between these nodes [15]. Systemigrams provide a comprehensive view of the system, emphasising the need for integrated decision-making and resource allocation. Systemigrams also help identify areas where integration is lacking or inefficient, guiding organisations in developing strategies aligned with broader goals and operational requirements, thereby enhancing overall effectiveness [15].

The Systemigram in Figure 2 is proposed to mitigate the challenge of fragmented maintenance management systems often seen in traditional frameworks. The framework effectively addresses the inherent complexities in maintenance management by illustrating the interconnectedness of the various components that drive a maintenance management framework's effectiveness. The framework integrates corporate strategy, production requirements, maintenance objectives, and sustainability practices to ensure a comprehensive approach that aligns with organisational goals. By leveraging systems thinking principles, the framework provides a holistic view that enhances decision-making, resource allocation, and overall maintenance efficiency. This integrative approach is crucial for developing adaptive and sustainable maintenance strategies that can respond to the dynamic nature of industrial operations [7], [8], [20], [18].

The proposed framework visualises maintenance activities' complexity, interdependencies, and dynamic nature, providing a unique and innovative contribution to maintenance management. This approach aligns with the principles of systems thinking, which emphasise understanding and managing the interconnections within a system [7], [8]. Consequently, the framework enhances the organisation’s ability to adapt to changing circumstances and achieve long-term success by developing informed strategies that drive performance and sustainability in a competitive industrial landscape [20], [18].

The maintenance framework proposed in Figure 2 provides a holistic and integrated approach to managing plant maintenance systems, emphasising the interplay between corporate strategy, production requirements, resource allocation, work management, and maintenance strategies. Managerial influence shapes strategic direction, decision-making, and resource prioritisation. This extends to developing work orders and using digital tools like digital twinning and blockchain for maintenance records.

Central to the framework is aligning corporate strategy with production requirements and maintenance objectives, ensuring maintenance strategies reflect broader organisational goals. The work management loop is essential for driving maintenance activities and enhancing efficiency, supported by technology integration and innovative initiatives like predictive maintenance with AI and condition-based maintenance. Maintenance KPIs are crucial for measuring the effectiveness of maintenance strategies and guiding continuous improvement. The framework also integrates sustainable maintenance practices, linking energy efficiency, waste reduction, and green procurement to maintenance objectives.

The novelty of this framework lies in its holistic, systemic approach, which integrates diverse elements of maintenance management into a cohesive structure [68], [69], [70], [71]. It aims to enhance efficiency, adaptability, and sustainability in industrial operations by aligning maintenance strategies with corporate objectives and leveraging advanced technologies. This integrated approach empowers maintenance practitioners and industry leaders to develop informed strategies that drive performance and long-term success in a competitive landscape.

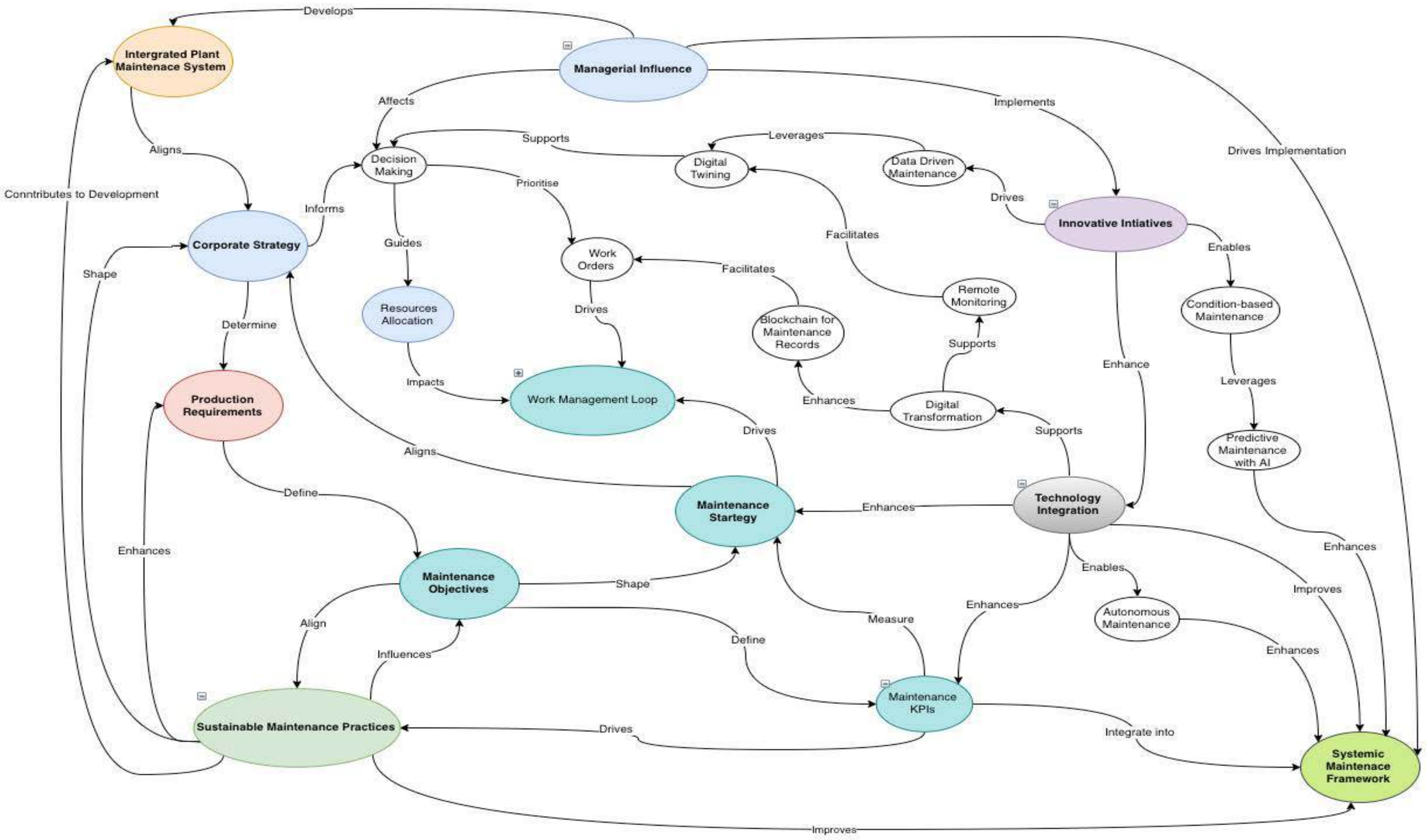

Figure 2: Proposed theoretical framework

The proposed framework uses systems thinking principles to address gaps in fragmented frameworks and enhance understanding of maintenance activities' complexity, interdependencies, and dynamic nature. It incorporates technology, innovation, and managerial influence, creating a novel model that balances traditional maintenance principles with emerging trends like sustainability goals, stakeholder engagement, and resilience planning. This forward-thinking framework enhances organisational adaptability and long-term success, uniquely contributing to maintenance management.

3.2 Framework Evaluation

The methodology to test and enhance the framework will implement a mixed-methods research design to explore the strategic integration of plant maintenance systems comprehensively. It incorporates qualitative methods like interviews and document analysis alongside quantitative measures such as surveys and key performance indicators (KPIs) to converge findings on systems thinking principles, operational performance, and sustainability practices in plant maintenance. Sampling techniques will involve the purposive selection of maintenance practitioners experienced in implementing systems thinking and prioritising ethical considerations throughout the research process. Data analysis will encompass statistical tools for quantitative data and thematic analysis for qualitative data, aiming to provide actionable insights into optimising maintenance practices. Expected results include:

1. Improvement in Operational Efficiency: Statistical analyses comparing integrated and non-integrated systems to demonstrate higher operational efficiency in integrated systems.
2. Enhanced Adaptability: Assessment of increased adaptability in integrated systems through qualitative and quantitative evaluations.
3. Contribution to Long-Term Sustainability: Identification of the positive correlation between strategic integration and long-term sustainability.
4. Systems Thinking Adoption: Insights into the integration and impact of systems thinking principles in maintenance frameworks.
5. Identification of Best Practices: Examination of existing maintenance systems to identify best practices in strategic integration.
6. Validation of Hypotheses: Empirical evidence supporting relationships between strategic integration, operational efficiency, adaptability, and sustainability, contributing to academic discourse and industry practices.

These anticipated results will inform decision-making, shape industry practices, and drive innovation in maintenance management. Statistical and analytical techniques like regression analysis, machine learning algorithms, thematic coding, and structural equation modelling will be employed to comprehensively model and analyse the expected results.

4 CONCLUSION

In the evolving landscape of industrial operations, the strategic integration of plant maintenance systems is imperative for achieving heightened operational efficiency, adaptability, and sustainability [19], [21], [72]. This research underscores the transformative potential of systems thinking in bridging the existing gaps within traditional maintenance frameworks. By aligning maintenance strategies with overarching organisational goals and incorporating advanced technological innovations, organisations can transcend the limitations of fragmented management practices, fostering a cohesive and adaptive maintenance environment.

The literature review within this research emphasises the necessity of adopting a systems thinking approach, as delineated by foundational scholars such as Senge [7], Sterman [8], and

Arnold and Wade [15]. This approach enables a comprehensive understanding of maintenance systems' dynamic interactions and feedback loops, facilitating informed decision-making and continuous improvement. Integrating technological advancements, notably predictive maintenance, IoT, and digital twins, further amplifies the capacity for proactive maintenance strategies, reducing downtime and optimising resource utilisation.

A critical contribution of this research is the proposed theoretical framework for maintenance management, grounded in systems thinking principles. The framework, illustrated through a Systemigram, provides a visual and conceptual representation of the interconnected components of maintenance systems. It underscores the importance of understanding feedback mechanisms, non-linear relationships, and dynamic behaviours, enhancing the efficacy of maintenance processes and outcomes.

The empirical investigation, employing a mixed-methods research design, will evaluate the theoretical framework and provide actionable insights into optimising maintenance practices. The anticipated results, including improvements in operational efficiency, enhanced adaptability, and contributions to long-term sustainability, are poised to inform decision-making processes and significantly shape industry practices. Furthermore, identifying best practices and validating hypotheses through robust statistical and analytical techniques will contribute to the academic discourse and offer a solid foundation for future research in maintenance management.

The research offers a novel and comprehensive approach to plant maintenance management, addressing the critical need for strategic integration and systems thinking. Organisations can enhance their operational effectiveness and sustainability by fostering a holistic understanding of maintenance systems and leveraging technological advancements. This forward-thinking framework bridges the gap between theory and practice and paves the way for continuous innovation and resilience in the competitive industrial landscape. The insights garnered from this study hold the potential to drive transformative change, ensuring long-term success and sustainability in maintenance management.

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IMPROVING THE QUALITY OF CONSTRUCTION PROJECTS IN SOUTH AFRICA USING BUILDING INFORMATION MODELLING

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ABSTRACT

The quality of the construction industry has been diminishing for the past years owing to factors not limited to reduced funding for infrastructure development and corruption. These quality issues were prevalent before the COVID-19 pandemic, and studies have explored the construction industry's performance in South Africa beyond the COVID-19 effects. This study, therefore, seeks to examine the five factors and dynamics that affect the South African construction industry as per the 2022 study titled “Reflections on the Performance of South Africa’s Construction Industry: Hope Beyond Covid-19 Effects” and evaluate the potential of Building Information Modelling (BIM) to improve detrimental effects arising from these factors. The five dynamics and factors are Policy regulation and governance, Investor interest and confidence, productivity and challenges of construction firms, Investing in sustainable construction and Construction corruption.

Keywords: Quality, Building Information Modelling (BIM), Construction Industry Performance in South Africa

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1 INTRODUCTION

Quality is a vital factor in every component of construction projects. The study by Ashkanani and Franzoi [1] emphasises that quality management of any project is crucial in achieving the expected results, and all the elements of construction projects depend on quality. As a result, companies have recently begun to emphasise quality by developing quality management systems and industrial project management systems that are currently concentrating on quality drivers because they impact every phase and component of the project, and high quality should be the core goal of the entire decision-making process [1].

According to Babatunde and Aigbavboa [2], quality is a product's expected characteristics and features, encompassing its ability to meet the needs and adhere to the specifications. A study by Jain [3] provides an iron triangle of project management, as illustrated in Figure 1, outlining the quality constraints.

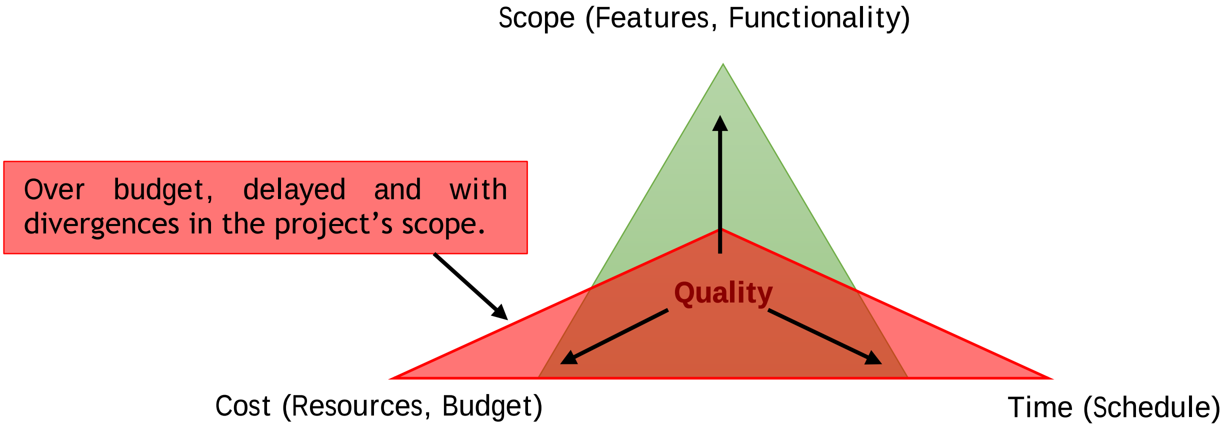

Figure 1: Project Management Iron Triangle (Adapted from Jain [3])

Figure 1 illustrates that quality is generally constrained by scope, cost and time. It also emphasises that reduced quality results from divergences in the project's scope, exceeding the budget and delays. Hence, Jain [3] emphasises the need for project managers to master the appropriate balance of the three constraints to ensure that adjusting these factors does not compromise the overall project efficiency.

Furthermore, Rever [4] provides project managers with suggestions on incorporating quality concepts and tools for each process during a project to ensure its success. The study's overview of the project quality management concepts and tools is illustrated in Appendix A, which outlines the inputs, outputs, and tools for each concept.

The quality management concepts identified by Rever [4] are quality planning, quality assurance and quality control. According to Ashkanani and Franzoi [1] and Rever [4], quality planning involves creating the quality metrics of a project, while quality assurance is a strategic and logical procedure required to guarantee that a product or service meets requirements. Quality control ensures that the product or service complies with the requirement.

Despite all these efforts to assist project managers in enhancing quality, the South African construction industry still needs to work on quality and performance issues [5]. Projects like the Medupi power station, which experienced cost escalation, lengthy project schedules, and significant defects, raise concerns about the quality of construction produced.

However, some studies, like Luo et al. [6], explore digital technology for quality management in construction and find that there is a need to adopt digital technology in the aspects of quality management to enhance defect management, prevent pre-construction defects, improve post-completion product function testing, and explore research on a construction compliance inspection. As a result, this study investigates how digital technology through BIM adoption can help the South African construction industry strive during the post-COVID-19 era by evaluating the potential of BIM to improve quality and performance issues. BIM is an enabler of digital transformation, which changes the value path creation of structures by adopting digital technology [7].

2 LITERATURE REVIEW

The South African construction industry has been struggling lately, and its contribution to economic growth has not been positive, leading to issues in the delivery and maintenance of infrastructure [5]. Among the numerous challenges in the industry is the failure of contractors to meet quality requirements, including adherence to project schedules and budgets. Consequently, projects often incur increased costs and delays due to the need to rectify errors, resulting in cost and time escalations. The primary dynamics and factors affecting the progress of the construction industry include policy regulation and governance, investor interest and confidence, productivity and challenges of construction firms, investing in sustainable construction and construction corruption.

2.1 Policy regulation and governance

Policy regulations and governance shape the relationship between the state, citizens, and corporations to promote the constitutional framework and economic growth [8]. According to Dithebe et al. [5], construction industry regulations must include insurance requirements that set minimum standards for competency and financial security guidelines for defect liability periods and health and safety requirements. These regulations impact business processes, including hiring and firing practices, supervision, training permissions, and contracting procedures [9].

Since 1994, the South African government has established over 1 000 regulations, creating an impression of overregulation, which results in numerous regulatory requirements [5]. This overregulation has led to opportunities for companies to fail to comply, either intentionally or unintentionally. The study emphasises that overregulation introduces complexities, confusion, administrative burdens, and unrealistic expectations of standards, leading to a challenging business environment with opportunities for non-compliance, especially in local regulations, legislation governing business operations, employment, taxation, and health and safety issues.

Consequently, overregulation and non-compliance issues give rise to other problems, such as zoning delays, ineffective formation of Public-Private Partnerships (PPP) which are partnerships between the public and private sectors to deliver and manage infrastructure projects, and inaccessible private land [5]. Zoning delays originate from complex local regulation processes, while inaccessible private land results from legal land claim disputes, zoning concerns, and heritage site regulations. This makes the supply of private land low, thus contributing to the price of existing land becoming unaffordable and slowing down development activities.

The challenge in forming effective PPPs lies in the enormous regulations negatively impacted by the public sector's inadequate skills, resources, and technology to execute projects [9]. This deficiency hinders the public sector's ability to structure and negotiate complex deals with the private sector, weakening its bargaining power and often favouring private sector partners.

2.2 Investor interest and confidence

The interest and confidence of investors depend on economic stability, which is further influenced by other factors like the country's governance and policy certainty [5]. Investors are primarily interested in the projections of the business financial information, considering financial metrics not limited to Return on Investment (ROI) and its related measures [10]. They want to see optimistic predictions that show a positive result for each unit of money invested. The business projections must emphasise good productivity and a great return on investment, which gives investors more confidence. As a result, investors tend to spend money on business-viable projects, which enhances economic growth through increased job creation, production and products or services.

However, South Africa needs more investor interest and confidence in infrastructure development [11]. This is due to declining economic growth, multiple reshuffling of cabinet ministers, unfavourable existing political conditions, and poor decision-making of parastatals like Eskom, with projects like Medupi being good examples of poor decision-making in parastatals [5]. This situation causes distress in the construction industry business sector, affects social responsibility initiatives, and leads to a further decline in the South African economy [5]. As a result, economic forecasts for the construction industry do not emphasise good productivity or strong returns on investment, causing many investors to lose confidence and interest in South African infrastructure projects.

To change this trend, immense efforts are required to restore investor confidence and interest, especially from foreign investors. Specific measures for improving political stability will be crucial for revitalising the construction industry and contributing to the country's economic recovery by restoring the confidence and interest of other investors.

2.3 Productivity and challenges of construction firms

The construction industry is lagging in labour productivity by approximately 20-25% [12]. The study by Dithebe et al. [5] outlines various methods of realising the company's productivity. These include implementing advanced technology, restructuring, and diversifying the procurement system, which has highly skilled workers. All these approaches protect the business while improving product and service quality.

In South Africa, reduced productivity and challenges in construction firms are mainly due to insufficient digitalisation and advanced technology [5]. The slow adoption of advanced technology is partly due to government policies encouraging construction companies to hire more people to grow the economy and reduce poverty rather than wholly embracing advanced technology [5]. As a result, some construction industry companies are discouraged from investing in technologies that can improve efficiency, owing to the need for more understanding in balancing technological adoption and job creation.

Hence, the productivity of the South African construction industry needs to improve due to a lack of balanced government policies that support both job creation and technological advancement. This has led to poor labour productivity caused by the slow adoption of new technologies that improve efficiencies. Synek [12] concurs that reduced labour productivity in the construction industry is generally due to insufficient digitalisation. Therefore, Synek [12] highlights that digitalisation significantly improves the evaluation of effectiveness based on project objectives to increase efficiency and analyse risk management of processes by detecting and eliminating the cause so that project quality may be increased. The study further explains that digitalisation simplifies and speeds up construction processes and reduces costs by minimising errors and losses. It also enhances project quality management, particularly quality assurance and control measures.

Other contributing factors to the reduced Productivity in South Africa include a lack of skilled workers, strikes, and a current procurement method that does not foster the growth of small enterprises [5]. The study emphasises that small companies in South Africa often need more capabilities and resources to implement these digital innovations, and the shortage of skilled workers worsens the problem. According to the Construction Industry Board [9], the construction sector employs 70% unskilled and semi-skilled labourers. With this, the gap between required and existing expertise is so large that skilled foreigners are often preferred over less skilled South African citizens [5]. Hence, this skill shortage is a significant barrier to the development of the construction sector and is also evident in parastatals like Eskom, where service delivery is declining. Addressing the skills shortage is essential, yet current solutions could be more effective. Many graduates remain unemployed due to a lack of necessary skills, and insufficient efforts are made to bridge the skills gap.

Small and medium enterprises (SMEs) are mostly affected by the skills shortage, as they often cannot afford highly skilled workers. SMEs play a crucial role in employing and training workers, but once these workers gain the necessary skills, they are often lured by larger firms offering higher salaries and benefits. This dynamic hinders the development of SMEs, reducing their productivity and efficiency.

Furthermore, the current procurement system in South Africa needs to be revised. It is susceptible to unethical behaviour like corruption and manipulation by large companies, thus hindering the development of SMEs even further [5]. A refined procurement system that promotes transparency and fairness is needed to improve the Productivity of SMEs and the entire construction industry. This system should ensure all procurement information is publicly available and enforce fair and competitive bidding processes. Additionally, it could mandate short-term project partnerships between SMEs and large firms to promote SME development.

Moreover, Strikes further affect the construction industry by causing infrastructure vandalism, leading to significant financial losses, as seen during the 2021 Zuma unrest, which resulted in damages worthy of billions of rands [13] and [5]. According to the Construction Industry Development Board [9], strikes lead to loss of productivity, wages and billions of Rands. As a result, strikes reduce profit margins, force companies to restructure, retrench employees, file for bankruptcy, increase unemployment, and contribute to economic decline. They also create uncertainties for investors, leading to reduced interest and confidence.

As a result, the productivity issues and challenges in construction firms have resulted in increased project failures, highlighting the need for solutions. Projects like the Medupi power station demonstrate the impact of strikes, delays, cost escalations, lack of expertise, and poor productivity [14]. Addressing these productivity challenges is imperative for the sustainable growth of the South African construction industry.

2.4 Investing in sustainable construction

The construction industry has significantly increased its focus on sustainability in response to global concerns about climate change, global warming, and environmental degradation. According to Widyatmoko [15], the construction industry is responsible for 30% of waste generation and materials consumption and contributes to 70% of global greenhouse gas emissions. These gas emissions significantly contribute to climate change and global warming. The study highlights an urgent need to reduce carbon dioxide emissions, materials consumption, and waste generation across all construction phases, particularly post-construction.

Aligned with global efforts, the South African government actively promotes sustainable construction to enhance the quality of life. This initiative aims to conserve natural resources such as water, reduce energy consumption, and mitigate environmental pollution [5]. Consequently, South Africa has the potential to explore strategies highlighted by Widyatmoko [15] to diminish its dependency on raw materials. These strategies include boosting recycling efforts and managing real estate asset depreciation triggered by climate change impacts, such as rising temperatures and intensified rainfall.

The South African construction industry has also been working towards creating a sustainable environment. However, progress has been slower than developed countries, partly due to the slow adoption of digital technologies. Their progress is evident in the strategic initiatives they intend to implement, including adopting lean construction and digital transformation [16].

Fitchett [17] reveals that the Gauteng province in South Africa has a high level of awareness of lean construction and its benefits in terms of waste reduction. This awareness can be a good starting point for implementing lean construction practices. Additionally, South Africa can reduce its dependency on raw materials by using digital twins technology, which creates a virtual representation of constructed assets as a repository for materials data. This technology and self-healing materials could increase the use of recycled materials [15].

Furthermore, Dithebe et al. [5] emphasises that sustainability in construction extends beyond environmental considerations. It also encompasses the health and safety of construction workers, end-users, and individuals residing or working near construction sites. Panteli et al. [18] stress that the construction industry has vastly poor health and safety performances globally, which results in increased injuries, accidents, and deaths on site. The Occupational Health and Safety Act of 1993 is pivotal in enforcing health and safety standards. With this, decisions made throughout project development significantly influence the health and safety of individuals affected by construction activities and indoor environment quality [5].

As a result, integrating Building Information Modelling (BIM), particularly its sustainability dimension, provides a comprehensive solution to address sustainability drivers and negative impacts. BIM facilitates the analysis of indoor environments, energy consumption, carbon dioxide emissions, waste management, and information storage for recyclable materials [18] and [15]. It also incorporates weather information to help manage real estate depreciation risks caused by climate-related factors. By choosing weather-resilient materials, BIM helps reduce weather-related depreciation. In essence, BIM adoption represents a strategic investment in sustainable construction practices.

2.5 Construction corruption

Corruption is unethical conduct that affects the construction industry immensely [5]. This is due to the nature of the construction business, which creates opportunities for unethical conduct. The procurement system creates possibilities for manipulation and corruption when selecting contractors and suppliers for construction projects because employees in the company (as well as in the government officials if it is a project for public infrastructure) may impact the choice [5]. The study by Aigbavboa et al. [19] highlights that a significant barrier to a contribution to the expansion of the South African economy is a need for more commitment to ethical principles that support accountability and transparency within the construction industry. Dithebe et al. [5] approves this by identifying the drives for corruption as a lack of trust in the legal system to handle corruption cases, weak governance and a lack of accountability and transparency. All these contribute to the persistence of corruption and other unethical behaviour.

The most common unethical conduct in the construction sector identified by Aigbavboa et al. [19] is not limited to bribery, fraud, falsification of experience, nepotism, and illegal tender awards. Some companies pay the individuals responsible for selecting contractors and suppliers to manipulate the final choice. This constitutes illegal tender awards and bribes. Also, some companies commit fraud by substituting superior quality materials and equipment with cheap and poor materials. Similarly, companies inflate costs for materials and labour to increase their profit margins. All this contributes to fraudulent activities in the construction industry. The Medupi power station is an excellent example of a contractor's fraudulent activities. These fraudulent activities were highly sophisticated and found in construction and welding activities, resulting in faulty quality control and incorrect manufacturing of some equipment [14].

On the contrary, nepotism involves favouritism in the construction sector, owing to employing and awarding tenders to friends and relatives. This unethical behaviour allows underqualified people and companies to do some work. As a result, this affects productivity and quality, which largely depend on the resources and capabilities of individuals and the company. An example of nepotism in tender awards is the irregular tender award to Lubbe Construction in 2015 for constructing K46 William Nicol Drive in Johannesburg. Due to irregularly awarded tender, five officials from the Gauteng Department of Roads and Transport were suspended upon the termination of the contract [20]. This project has suffered from missed deadlines, cost escalation, and failure to maintain a valid performance guarantee since November 2017.

Moreover, most of these conducts are a result of greed and poverty. The rich people who commit bribery, fraud, nepotism, and illegal tender awards are not satisfied with what they have, and they always want more. Hence, they always find ways of making things work in their favour, even if it means spending significant amounts of money to get more money. Conversely, the poor struggle to make ends meet. As a result, they find ways to survive by doing unacceptable things like exaggerating their experience to increase their chances of being hired. The legal consequences of such issues are not severe. Therefore, these unethical conducts are still prevalent.

The weak justice system and governance amplify corruption issues in the South African construction industry [5]. Instead, the justice system brings the economy to its knees by participating in unethical conduct by taking bribes and allowing people who commit these crimes to walk freely without saving their sentences. More strict consequences may lessen these discussed unethical conducts in the construction industry since their impact on the construction industry is unbearable. It is sensible to ensure that the consequences of such crimes are equivalent to their effect on the economy and the entire construction industry.

These crimes have resulted in increased project failures, poor quality and productivity, reduced construction industry growth, a decline in the South African economy and deterioration in professionalism, further affecting people's reputation and trust [19]. The study also identified critical measures that can help enhance ethical conduct in the construction industry. These include, but are not limited to, effective communication; acting when an ethical violation occurs; reviewing, monitoring, and reporting ethical behaviour; creating a culture of honesty and ethics in the construction industry; putting ethical rules and policies into place; starting routine and random ethics checks; being transparent and accountable in contract administration, and hiring the appropriate personnel who value ethical conducts.

As a result, construction businesses may strengthen their ethical conduct culture, cultivate stakeholder trust, and protect their success and reputation by implementing these measures. By doing so, BIM could be used to enforce transparency and accountability [21]. With this, BIM can be considered the future for improving the quality of construction projects by alleviating some of the discussed issues arising from a lack of transparency and accountability owing to corruption.

Several quality issues discussed in the literature review are due to insufficient digitalisation and the use of advanced technology that may start with BIM implementation. Hence, the need to improve the quality of construction projects using BIM can help solve some detrimental effects within the dynamics and challenges of the construction industry in South Africa. Therefore, this study uses the information gathered in the literature to explore the detrimental effects and evaluates the potential of implementing BIM in alleviating them.

3 METHODOLOGY

The study employed a mixed-methods approach, integrating both quantitative and qualitative analysis. The secondary data from the Google Scholar database identified the dynamics and factors affecting the South African construction industry. Subsequently, the driving factors for these dynamics and their detrimental effects were easily identified. The primary data from the people working in the construction industry with BIM experience was collected using a survey questionnaire as the primary data collection instrument to gather data regarding the detrimental effects.

The respondents' selection from the LinkedIn platform employed a purposeful sampling method with a sample size of 35 participants. This helped promote the validity and reliability of the study by allowing only potential participants with BIM expertise to respond to the survey questionnaire. The ethics committee also checked the questionnaire to ensure that it was formulated appropriately and could be shared with subject experts to collect primary data. Subsequently, the questionnaire results were compared with relevant literature from other scholars to support the arguments.

Furthermore, this study promoted ethical conduct since the participants' identities were kept anonymous, participation was entirely voluntary, and participants could skip any questions they felt violated their privacy. Overall, anonymity and voluntary participation helped mitigate response biases, while the option to skip sensitive questions reduced the risk of inaccurate data. These measures collectively enhanced the robustness and credibility of the research findings.

The survey asked participants whether the detrimental effects could be directly controlled using BIM, with "yes" or "no" response options. The resulting frequency illustrated in Table 1 was then considered the outcome of whether BIM directly resolved the detrimental effect, thus contributing to the study's quantitative analysis. The participants also gave a final comment to support their choices by providing some qualitative input to their responses.

4 RESULTS DISCUSSION

This section discusses the survey questionnaire results shown in Table 1, which outline the detrimental effects that can be directly controlled by implementing BIM. Subsequent sections discuss how BIM addresses these issues and explore additional measures to enhance its effectiveness in mitigating problems not directly controlled by BIM implementation.

Table 1: Can BIM directly resolve these detrimental effects, Yes or No?

	Dynamics affecting the SA construction industry	**Driving factors**	**Detrimental effects**	**Yes**	**No**
1	**Policy regulation and governance**	• Overregulation • Non-compliance	Delays in zoning processes of local authorities	12	16
			Challenges in forming PPPs	8	20
			Unaffordable private land	6	21
2	**Investor interest and confidence**	• Unfavourable existing political conditions • Multiple reshuffling of cabinet ministers	Reduced funding for infrastructure	14	14
			Distressing construction industry business sector and social responsibility	14	14

		• Poor decision-making of parastatals like Eskom • Declining economic growth	Further decline of the economy	9	19
3	**Productivity and challenges of construction firms**	• Insufficient digitalisation and use of advanced technology • Lack of unskilled workers • Strikes • Current procurement methods that can be significantly manipulated	Increased project failures due to quality issues	18	10
			Reduced profit margins	18	10
			Hindered development of small enterprises	9	19
			Slow Productivity	21	7
			Increased unemployment rate due to retrenchments	9	19
			Restructuring and filing for bankruptcy	10	18
4	**Investing in sustainable construction**	• The nature of construction projects. Particularly, being large consumers of natural resources and energy while producing extensive waste. • Health and Safety	Increased pollution	7	21
			Increased energy consumption	15	13
			Degradation of the environment and limited natural resources like water	11	17
			Climate change and global warming	10	18
			Poor health and safety	11	17
5	**Corruption**	• Poor justice system • Poor governance • Lack of accountability and transparency • Nature of the procurement system of the SA construction industry • Greed and poverty	Project failures	18	9
			Poor quality and Productivity	19	8
			Deterioration in professionalism, reputation and trust among people	14	13
			Reduced construction industry growth	11	16
			Economy decline	7	20

4.1 Detrimental effects that can be resolved by implementing BIM

The survey questionnaire results, summarised in Table 1, indicate that implementing BIM can directly control seven detrimental effects. These include increased project failures due to quality issues, reduced profit margins, slow productivity, increased energy consumption, poor quality, and deterioration in professionalism, reputation, and trust. These findings emphasise that BIM plays a vital role in addressing these detrimental effects faced by the South African construction industry. As a result, its role in improving the quality of construction projects is enormous.

Several studies concur with these findings. According to Dowsett and Harty [22], BIM-based sustainability software can directly, semi-directly, or indirectly document up to 17 LEED (Leadership in Energy and Environmental Design) credits, significantly saving time and resources compared to traditional methods. LEED is a green building rating system guideline for the USA. This highlights that BIM-based sustainability directly addresses some sustainability issues, such as increased energy consumption, while other sustainability matters are not directly resolved by implementing BIM, as identified by participants. Furthermore, the time and resource savings from using sustainability software directly impact profit margins, aligning with the participants' observations that BIM can resolve reduced profit margins.

Also, time reduction positively impacts quality, as illustrated in Figure 1. This highlights that BIM can mitigate increased project failures due to quality issues and poor quality, as Luo et al. [6] and Synek [12] noted. Additionally, Ghaffarianhoseini et al. [23] emphasise that BIM models for planning and scheduling can enhance productivity by leveraging just-in-time delivery of building materials and components. Just-in-time delivery of building materials ensures that materials and components are delivered when needed for the construction process rather than keeping extensive inventories on-site. This helps reduce waste and increase efficiency.

While no publications explicitly state that BIM directly improves professionalism, reputation, and trust, numerous studies emphasise BIM's role in enhancing quality. Hence, it can be inferred that improvements in quality through BIM can directly support these aspects since maintaining high quality is essential for customer trust and company reputation [16].

On the contrary, the survey questionnaire has two indecisive detrimental effects, namely reduced funding for infrastructure and distressing construction industry business sector and social responsibility due to having an equal number of "yes" and "no" responses. This emphasises the complexity of these two detrimental effects and highlights that other external factors beyond BIM implementation immensely influence these effects. While BIM can substantially improve these effects, these effects would require control and resolution beyond BIM implementation.

As a result, further research is essential to explore how BIM can be integrated with broader external factors, like political aspects, to effectively address the funding and social responsibility issues. Understanding the interplay between BIM and these external influences will be crucial in fully leveraging BIM's potential to mitigate these complex challenges. Future studies could identify specific external factors and develop comprehensive frameworks that integrate BIM with other industry practices and policies.

4.2 Considerations for improving the efficiency of BIM implementation in mitigating problems not directly controlled by BIM implementation

The participants highlight that BIM implementation will not directly amend many detrimental effects, as shown in Table 1. BIM can, however, assist with mitigating some issues by offering ways in which data can be appropriately managed and made available for future decision-making processes. With this, the survey questionnaire results illustrate that BIM implementation does not directly control 13 issues. These include delays in zoning processes of local authorities, challenges in forming PPPs, unaffordable private land, further decline of the economy, hindered development of small enterprises, increased unemployment rate due to retrenchments, restructuring and filing for bankruptcy, increased pollution, degradation of the environment and limited natural resources like water, climate change and global warming, poor health and safety, reduced construction industry growth, and economy decline.

As a result, the participants identified eight systems that need to be integrated to improve BIM's efficiency and refine the processes to address some detrimental effects not directly controlled by implementing BIM. The integration would be for different BIM technologies for the smooth exchange of digital information and policies to provide a structured way of incorporating some processes into the BIM implementation for effective digitalisation of construction projects. The systems include collaboration and communication platforms, risk management systems, change management procedures, training and education, continuous improvement initiatives, post-occupancy evaluation, sustainability assessment tools, and integration with facility management systems.

4.2.1 Collaboration and communication platforms

Platforms for collaboration and communication utilise advanced tools to enhance coordination among project stakeholders. These platforms facilitate seamless information exchange, decision-making, and issue resolution. Therefore, BIM software must be highly effective in improving the overall performance of construction projects by leveraging these collaboration and communication platforms.

Such platforms are crucial in improving communication between involved parties, contributing to proper planning, efficient projects, and streamlined processes and activities. As a result, they can positively impact delays in zoning processes by facilitating streamlined workflows with local authorities. They can also address challenges in forming PPPs by promoting seamless information exchange, issue resolution, trust and transparency between the private and public sectors. Furthermore, these platforms support the development of small enterprises by enabling effective collaboration with larger firms on potential partnership opportunities.

4.2.2 Risk management systems

A robust risk management system identifies, assesses, and mitigates risks, including those related to detrimental issues not directly resolved by implementing BIM. Therefore, a risk management system within BIM implementation must be encouraged to control and manage all potential risks. The system must understand that risks may evolve and change as time progresses. Hence, regular reviews and updates are required to address potential risks proactively.

A robust risk management system can identify and analyse potential risks to provide proactive mitigation measures for projects. This helps stabilise projects and promote economic viability. As a result, risks connected to forming effective PPPs, zoning delays from local authorities and potential project risks that lead to company failures and job losses, such as issues around retrenchments, restructuring and filing for bankruptcy, will be identified early to establish proactive mitigation measures to control these risks. Additionally, this system can identify potential health and safety risks within the project, enabling the anticipation and early mitigation of hazards.

4.2.3 Change management procedures

Change management procedures are vital to ensure that imperative changes to control risks are managed effectively. As a result, the change management system is vital in handling modifications and updates occurring throughout the project lifecycle. This may require a protocol definition for evaluating and implementing changes to mitigate the impact on project timelines, scope, and costs.

The change management procedure may also address the changes in the responsibilities of professionals involved in carrying out tasks to help them adapt to their new roles and responsibilities, thus reducing the chances of them losing their jobs. This lays a good foundation for training and educating the professionals to help them adapt to their new roles.

4.2.4 *Training and education*

Some participants argue that implementing systems like BIM is essential, but at the core of everything is the development of practising professionals. There is a need to invest in engineers before developing sophisticated systems. With this, BIM awareness and continuous professional development around BIM are vital in ensuring that professionals adapt to BIM and its related technologies. This will enable professionals to grow and learn continuously, thus keeping their skills current and valuable. By doing this, professionals will be up to date with BIM technology, including software, hardware and industry standards.

Moreover, training and education improve the organisation's need for more relevant skills. This has a positive impact on the hindered development of small enterprises and the public sector’s inadequate skills to form PPPs since they are immensely affected by skills deficits. Also, ongoing education and training in BIM implementation would improve the skills capacity in the construction industry, thus contributing to industry competency, growth, and economic development.

The training may include educating the professionals about the sustainability assessment tools, thus training them on the 6D BIM dimension since professionals generally need more expertise in this department. The theory of what BIM can do regarding sustainability assessment is accessible. However, the knowledge and awareness that fosters professionals' knowing how to achieve sustainability and makes them believe they can use sustainability assessment tools are limited.

4.2.5 *Sustainability assessment tools*

The sustainability tools may incorporate the tools for lean construction, energy analysis, environmental assessment and integrated project delivery (IPD) that is motivated by the lean theory, a concept for reducing waste and increasing efficiency and value in the entire project. The IPD approach promotes early collaboration, shared risk, and shared rewards among project participants, thus motivating everyone to work hard so that they can reap the benefits and avoid acquiring any losses. Also, this approach can help address issues arising from fragmented processes and encourage a more holistic project perspective.

Hence, sustainability tools can help reduce waste production, including harmful gasses contributing to global warming and climate change during construction projects. They also have a positive impact on conserving natural resources through promoting a circular economy. As a result, sustainability assessment tools yield positive results on increased pollution, degradation of the environment, limited natural resources, climate change, and global warming.

4.2.6 *Integration with facility management systems*

Integrating BIM with facility management systems complements the adoption of sustainability assessment tools, making the post-construction phase more efficient by bridging the gaps between the delivery and post-construction phases. This integration helps acquire valuable data for facility managers, such as asset information on infrastructure components, materials, equipment, systems and spatial data. It also ensures that operations and maintenance data that aids in decision-making, optimising building performance, planning maintenance, and enhancing the end-user experience is captured.

Considering all these systems when implementing BIM can address detrimental effects not directly resolved by BIM alone, such as increased pollution, climate change, and global warming in the post-construction phase.

4.2.7 Continuous improvement initiatives

For an organisation to generally do well, continuous improvement initiatives are required, establishing a culture of continuous improvement. Initiatives like encouraging feedback from team members and stakeholders to identify opportunities for refining BIM processes and addressing non-BIM-related issues would be required. This enables lessons learned to be identified and documented in a structured manner, thus creating a lessons learnt repository that incorporates the positive and negative experiences from projects. Additionally, this fosters regular reviews and analysis of the feedback to identify recurring issues and develop strategies to mitigate them in future projects. By implementing these initiatives, project teams can address effects that are not directly resolved by implementing BIM better. Therefore, this provides a proactive approach to learn and grow from past mistakes, thus fostering continuous improvement throughout the project lifecycle.

4.2.8 Post-occupancy evaluation

The continuous improvement initiatives may include post-occupancy evaluation, which is the process of acquiring feedback from the final users of the built infrastructure regarding its features, functionality, performance, and sustainability. Additionally, this creates room for implementing systems to monitor and analyse project performance metrics. By tracking key performance indicators following the end-user's feedback, project teams can identify areas for improvement and take corrective actions.

5 CONCLUSION

The study analysed the detrimental effects within the South African construction industry arising from five primary dynamics and the factors driving them. It explored the potential of BIM in directly resolving these effects. The findings revealed that implementing BIM can directly control increased project failures, poor quality issues, reduced profit margins, slow productivity, increased energy consumption, and deterioration in professionalism, reputation, and trust. Additionally, the study identified eight systems that need to be integrated within BIM implementation to enhance its overall efficiency and mitigate the detrimental effects not directly controlled by BIM.

While BIM positively impacts various detrimental effects in the construction industry, there is no evidence to suggest that it effectively addresses the issue of unaffordable private land. For future work, the study recommends providing more technical details about the tools and methods used within each system, such as specific software or frameworks. The framework would incorporate information standards, information management processes, digital technologies, and enhanced collaboration with project team members to deliver the required project and asset information that the client has specified for their construction project. This study also suggests conducting case study analyses as future work to illustrate real-world examples of how these systems work together to improve BIM's efficiency in resolving quality issues.

6 ACKNOWLEDGEMENTS

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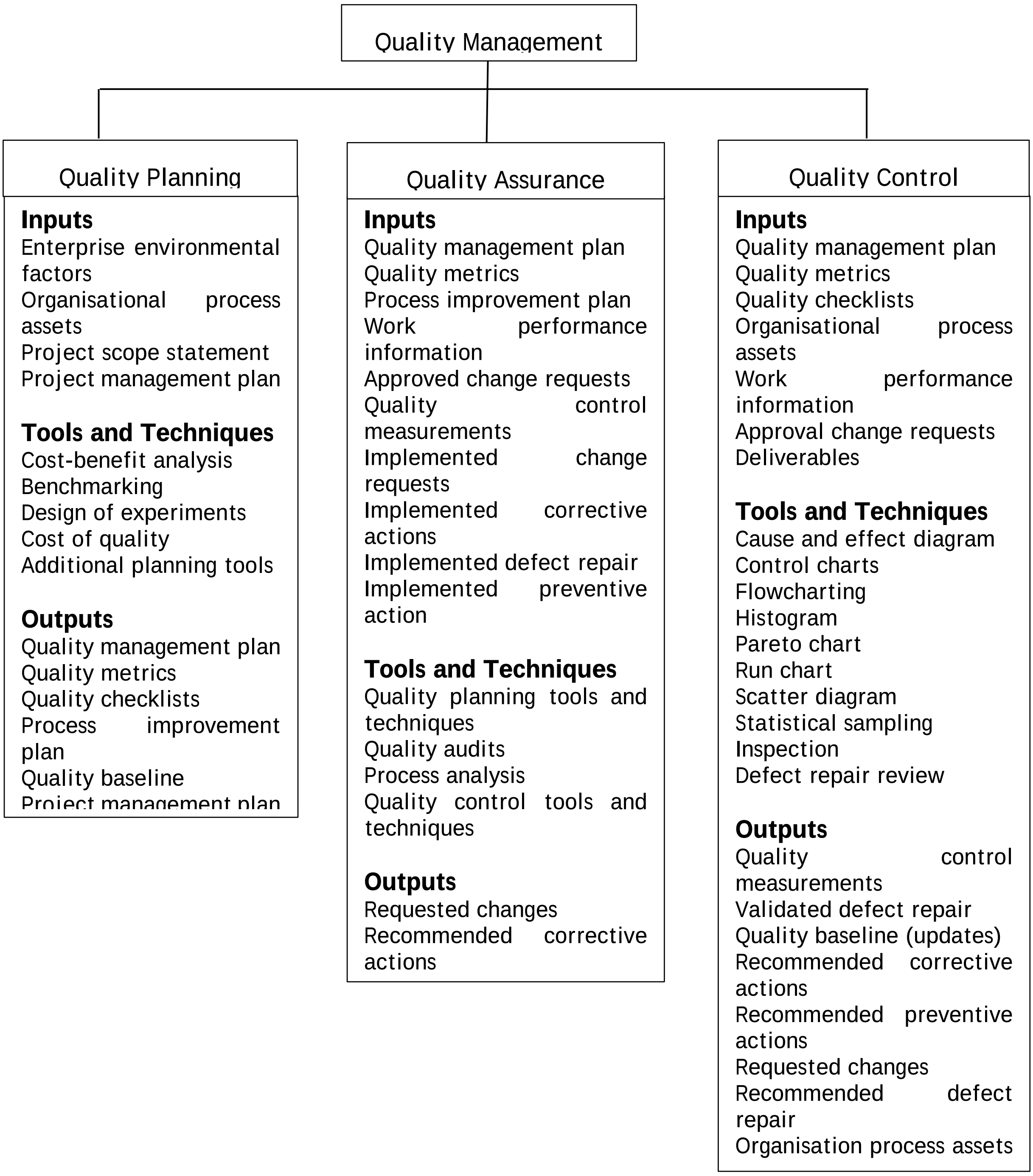
8 APPENDIX A: PROJECT QUALITY MANAGEMENT OVERVIEW (ADAPTED FROM REVER [4])



Quality Management

Quality Planning

Inputs
- Enterprise environmental factors
- Organisational process assets
- Project scope statement
- Project management plan

Tools and Techniques
- Cost-benefit analysis
- Benchmarking
- Design of experiments
- Cost of quality
- Additional planning tools

Outputs
- Quality management plan
- Quality metrics
- Quality checklists
- Process improvement plan
- Quality baseline
- Project management plan

Quality Assurance

Inputs
- Quality management plan
- Quality metrics
- Process improvement plan
- Work performance information
- Approved change requests
- Quality control measurements
- Implemented change requests
- Implemented corrective actions
- Implemented defect repair
- Implemented preventive action

Tools and Techniques
- Quality planning tools and techniques
- Quality audits
- Process analysis
- Quality control tools and techniques

Outputs
- Requested changes
- Recommended corrective actions

Quality Control

Inputs
- Quality management plan
- Quality metrics
- Quality checklists
- Organisational process assets
- Work performance information
- Approval change requests
- Deliverables

Tools and Techniques
- Cause and effect diagram
- Control charts
- Flowcharting
- Histogram
- Pareto chart
- Run chart
- Scatter diagram
- Statistical sampling
- Inspection
- Defect repair review

Outputs
- Quality control measurements
- Validated defect repair
- Quality baseline (updates)
- Recommended corrective actions
- Recommended preventive actions
- Requested changes
- Recommended defect repair
- Organisation process assets

SUSTAINABILITY OF LEAN IN SOUTH AFRICAN PUBLIC HOSPITALS

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ABSTRACT

One of the initiatives by South African public hospitals to improve the level of service was the introduction of Lean. The introduction of Lean in South Africa followed the global trend of Lean applications in healthcare, which has been steadily climbing since 2000. Several public hospitals have implemented Lean in specific areas or sections, and these implementations have shown early positive results. However, the Lean implementations have faced a higher failure rate over time. This failure rate could be attributed to a lack of information or a knowledge gap on what causes Lean implementations not to be sustainable. This paper aims to explore information on what affects the sustainability of Lean in public hospitals. Interviews were conducted with practitioners involved with Lean in public hospitals. Through interviews, 44 factors were explored and synthesised into 13 themes.

Keywords: Lean, factors, public hospital, sustainability, healthcare, interviews, themes

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1 INTRODUCTION

1.1 Background

The South African government introduced National Health Coverage in 1997 as a new reform to deal with the bad state of the country's public healthcare [1]. The district health system model was introduced as part of National Health Coverage where through it, primary healthcare became the foundation of healthcare policy [2]. Primary healthcare, as a social justice philosophy, together with legislative, policy and resource-allocation measures were aimed at achieving transformation and improving population health [2]. These new policies and initiatives have not made a significant improvement in the overall performance of the country's health system [2]. Skills gaps in management, leadership and stewardship have led to poor implementation of these good policies that are meant to transform the public health system [3]. As healthcare institutions realise the necessity of improving quality and eliminating waste, Lean healthcare became a strong initiative to adopt [4].

Healthcare entities have adopted Lean as an operations management model that can simultaneously improve quality and productivity, provided that the tools and concepts are successfully applied [5]. The implementation of Lean healthcare in South Africa is still in its early stages and underdeveloped [6]. The majority of the literature only mentions the use of Lean healthcare and its early successes without providing empirical evidence to evaluate its long-term effectiveness and sustainability [7]. This lack of empirical evidence is not unique to South Africa but it is an international concern as mentioned by Henrique et al [8] that Lean has been widely adopted and reported in healthcare however there is a scarcity of literature that reports on Lean sustainability in the long term even though the low success rate of Lean implementation in healthcare is widely reported. Costa and Godinho Filho [9] mention the shortage of Lean healthcare literature that explores the barriers and lessons learned to sustain the process changes through a Lean journey in healthcare.

1.2 **Purpose of the study**

This paper seeks to use interview processes to gather information from practitioners in South Africa on factors affecting the sustainability of Lean healthcare in South African public hospitals. This paper addresses the research question: What is the practitioner's perspective on factors affecting the sustainability of Lean healthcare in South African hospitals?

2 LITERATURE REVIEW

2.1 Lean Healthcare in South Africa

The organisational structures and culture entrenched in the public healthcare system pose challenges to Lean implementation in public hospitals [10]. According to Nwobodo-Anyadiegwu [11], corporate governance, mismanagement, lack of visible leadership, inadequate support, and limited resources are the main challenges faced by Lean Healthcare.

Available literature mentions some challenges related to Lean implementations in public healthcare. Kruger [12] encountered resistance from staff during the implementation of Lean. Staff perceived Lean to be invasive and lacking significance to them individually. Additionally, there was a lack of belief in Lean methods, and unions believed that Lean would lead to job loss [12]. Price [13] implemented Lean in a hospital to reduce waiting times and improve patient satisfaction. The project revealed that the average visit took 4 hours and 44 minutes, with only 41 minutes spent on value-added activities.

However, Lean has proven effective in improving the performance of selected areas and has the potential to do even more [13]. Lean implementation in one South African hospital demonstrated that Lean can improve staff morale, patient flow, and waiting times [11]. Price [13] proposed an alternative solution to better manage the flow of patients in hospitals during her Lean implementation project. By levelling the demand throughout the day, waiting times were reduced by 18% to solely based on the commitment of staff and stakeholders, without any additional funds [13]. Naidoo [14] discovered that Lean implementation led to improved staff satisfaction and motivation. Staff felt that things were improving in their department, communication improved, and attitudes toward teamwork significantly improved. Practical Lean training, support and incentives for staff participation, an internal resource dedicated to Lean, a computerised record management system, addressing clinical staff shortages, and infrastructural maintenance are some of the interventions necessary for successful Lean implementation [11]. Literature mentions challenges, and success stories associated with implementing Lean in South African public hospitals. There is, therefore, a definite argument for pursuing Lean healthcare in South Africa to address the increasing demand and requirements for improved quality with constrained resources and circumstances.

2.2 Sustainability of Lean Healthcare in South Africa

Lean Implementation is senseless without including long-term sustainability goals [15]. Lack of sustained improvements wastes resources, creates stakeholder resentment, and demotivates staff [16]. There are no official or trusted reports on the success and failure rates of Lean implementations in South African healthcare organisations [17]. Furthermore, there is a lack of empirical data to demonstrate how Lean implementation can be preserved and sustained in the long term [10]. This lack of evidence highlights the need for more research on Lean management in healthcare, particularly in underdeveloped countries like South Africa, which face unique challenges compared to developed countries [10]. Given the current local challenges of limited resources and poor prospects for economic growth, efforts must be made to improve healthcare management based on the philosophy of achieving more with less [18].

The future of Lean in healthcare is to develop structures, mindsets and systems which ensure that the significant existing investment in Lean is sustained. To achieve long-term sustainability, management must be committed to a determined Lean journey [11]. A planned approach should be taken to formulate sustainability goals and strategies that align with the organisation's strategic objectives [6]. Sustainability should not be seen as a final destination, as this approach can hinder early or sufficient sustainability planning but should be prioritised earlier in the adoption process [17]. Routinisation and institutionalisation are fundamental processes for sustainability [17]. However, to make sustainability a routine component, there is a need for greater clarity on the hindrances to sustainability and their causes [17].

3 RESEARCH METHODOLOGY

This study’s research focus is to explore the factors affecting the sustainability of Lean healthcare in South African public hospitals. A constructivism paradigm was used to understand the phenomenon through interaction with the research participants [17]. This study followed a phenomenological approach, focusing on understanding the meaning of people's experiences [19].

A qualitative research method in a form of semi-structured interviews was used to explore participants' social and cultural perspectives by providing freedom to express themselves without limitations [19]. This method also facilitated the discovery or elaboration of information deemed important by participants, but may not have been previously considered relevant by the research team [20]. The semi-structured interview protocol involved asking key questions to determine the areas to be explored but also allowed the interviewer or interviewee to deviate and delve deeper into an idea or response [20].

3.1 Data Sampling

In this study, purposeful sampling was employed using a set of inclusion criteria. Additionally, snowball sampling was utilised to expand the participant pool. Interviews were conducted until the point of saturation was reached, meaning that no new information was being provided and the researcher was satisfied that the data collected was sufficient to achieve the study's objectives.

Participants had to satisfy the following inclusion criteria:

- Academics, consultants, and practitioners involved with Lean healthcare in South African public hospitals.
- Must know and understand Lean healthcare, and Lean implementation in healthcare.
- Must have first-hand experience and information on Lean healthcare
- Must have been personally and practically involved in Lean healthcare in South African public hospitals

In total, nine participants were interviewed. Table 1 displays the profession and experience of each interview participant.

Table 1: List of interview participants' profession and experience

Interviewee No.	Profession	Field	Lean healthcare Experience	
1	Consultant	Engineering	15 years	Has implemented Lean in both private and public hospitals
2	Healthcare	Medical	10 years	Government employee who has been involved with Lean implementation in Gauteng province public hospitals
3	Academic/ Consultant	Engineering	10 years	Lecturer who has implemented Lean in more than 5 public hospitals
4	Academic	Engineering	6 years	Lecturer who has provided classes about Lean and consulted with public hospitals on Lean implementations
5	Academic	Engineering	5 years	Lecturer who has provided classes about Lean and consulted with public hospitals on Lean implementations
6	Consultant/ Healthcare	Medical	20 years	Has implemented Lean in both public and private hospitals, obtained master's degree in Lean healthcare

7	Healthcare	Medical	10 years	CEO of the hospital, been involved with one hospital, has received international training and exposure to Lean healthcare
8	Academic/ Consultant	Business Management	20 years	Pioneer of Lean implementations in South Africa implemented Lean in more than 5 public hospitals, internationally recognised Lean specialist
9	Consultant	Business management	15 years	Has implemented Lean in both public and private hospitals, obtained PhD in Lean healthcare

The healthcare experience of all interview participants ranges between 5 and 20 years with an average of 12 years. All participants have a minimum of a master's degree in their field of study which includes medical, engineering and business administration fields. The participants met the inclusion criteria set for the study and their professional diversity helps to enrich the findings for this study.

3.2 Reliability and Validity

The interview questions, process, and analysis were clearly outlined to avoid interviewer bias. Interview questions (refer to Appendix 1) were open-ended and shared with interviewees in advance. During the interview process, the interactions with participants were standardised and recorded. After each interview, the researcher reflected on the data collected to evaluate the quality of information received. Each interview data was coded independently. The interviewer spent sufficient time engaging with the data before coding. Findings were described in detail with evidence provided to support any claims made. To eliminate participant bias, all participants were invited in their respective capacities and spoke on their behalf. The extensive engagement of participants in the field also helped address concerns about validity. The sample of participants adequately represented different sectors involved in Lean healthcare. All participants worked for different employers or ran independent and unrelated consulting companies.

3.3 Analysis

In this study, the thematic coding analysis approach was utilised. Statements related to sustainability issues were identified from each interview data and assigned codes. All the coded statements or lines were extracted into a spreadsheet. Each similar coded lines were grouped, repetition was eliminated, and 118 distinct coded lines remained. The 118 coded lines were aligned according to their meaning and language and rephrased into a total of 44 factors. The 44 factors were synthesised and grouped related to the common subject they are addressing, resulting in 13 analytical themes as shown in Table 2.

Table 2: Synthesised interview themes with corresponding participants

No.	Theme	Extracted Factors	Participants
1	Long-term philosophy	Continuous process	1, 5, 6
		Lean thinking	1
		Lean understanding	4, 5, 6
2	Lean alignment	Lean adaptation	3, 4, 7, 9
		Lean Integration	5, 6, 8, 9
		Language adaptation	1, 3, 4, 7, 9
		Organisational readiness	3, 4, 5, 6, 7
		Strategic alignment	3, 5, 9
3	Implementation Phase	Staff engagement	3, 4
		Implementation plan	1, 2
		Implementation process	1, 2, 4, 6, 9
4	Leadership	Change management	3, 4, 6, 7
		Gemba walk	2, 3,4, 6, 7,8
		Leadership involvement	6, 8
		Leadership quality	2, 7, 8, 9
5	Commitment	Leadership commitment	2, 3, 4, 5, 6, 8, 9
		Long term commitment	1, 2
		Personnel commitment	1, 2, 4, 5, 6, 7, 8, 9
6	Training	Coaching and guidance	5, 6, 7
		Lean training	1, 2, 6, 8, 9
		Personnel training	2, 3, 4, 7
7	Teamwork	Collaboration	3, 6, 7, 8, 9
		Integrated teams	3, 4, 6, 9
		Multi-disciplinary approach	2
		Personnel involvement	2
8	Support	External support	1
		Lean champions	1, 4, 6, 7, 8
		Personnel support	2, 5, 6, 7
		Resources	2, 5, 7, 9
9	Motivation	Acknowledgement and recognition	2, 6
		Perception	7, 9
		Personnel benefits	2, 3, 4, 5, 6 8, 9

		Personnel involvement	**2, 6**
		Staff morale	**2**
		Success stories	**3, 6, 7, 9**
10	**Communication**	**Open communication**	**5, 6, 9**
		Visual Communication	**6**
11	**Management**	**Lean tools**	**3, 5, 6, 7, 8**
		Management competence	**3**
		Performance management	**2, 3 5, 6, 7, 8**
		Staff engagement	**2, 3, 6, 7, 8**
12	**Empowerment**	**Staff empowerment**	**2, 5, 6, 7, 8**
13	**Healthy competition**	**Creating competition**	**6, 7**
		Benchmarking	**2,7,8**

4 FINDINGS

The thirteen themes with corresponding 44 factors as per Table 2 are analysed individually in this section.

4.1 Long-term Philosophy

Long-term philosophy is at the core of Lean's objectives. It is important for hospitals to fully understand and embrace the long-term philosophy before implementing Lean (P4, P5, P6). By doing so, they can avoid treating Lean as a quick-fix project with a short-term endpoint (P1, P6). Instead, Lean should be seen as a continuous improvement process that enhances performance over an extended period (P5). This long-term philosophy cultivates a Lean thinking mindset (P1), which encourages the maintenance and continuous improvement of achieved fixes. The goal is to establish a new current state and baseline, enabling the organisation to strive to reach even higher performance levels. This creates an ongoing cycle of improvements, leading to the sustainability of Lean. The application of Lean as a long-term philosophy transforms the entity's vision and strategic planning, strongly emphasising the continuous improvement process. This process, driven by Lean thinking, is what ultimately leads to sustainability [8].

4.2 Lean Alignment

Lean alignment broadly encompasses the incorporation of Lean philosophy and principles into a healthcare organisation's activities, visions, and strategies. Lean alignment establishes an environment conducive to institutionalising Lean and fostering a new Lean-based organisational culture (OC) (P5). Lean, a concept originating from the Japanese automotive industry, needs to be adapted to fit the healthcare context during the implementation phase (P1, P3, P4, P7). Before implementing Lean, it is important to thoroughly understand the hospital environment and culture (P3, P4, P5, P7). Lean alignment entails aligning the hospital and its culture, preparing them for the significant organisational and process changes that Lean implementation brings. Aligning the OC with the Lean-based strategic plan is crucial for the hospital to achieve its sustainability goals and objectives (P3, P5, P9).

Lean organisation needs to be dynamic and be able to adjust accordingly (P3, P7) because Lean alignment should be continuous to ensure ongoing success and effectiveness (P3, P7). Lean alignment is essential during the implementation phase and the ongoing adaptation to new Lean developments (P7). By successfully aligning Lean with the organisational structure, and defining new strategic directions, goals, and objectives, the implementation process becomes more successful and the long-term sustainability of Lean is ensured.

4.3 Implementation Phase

During the implementation phase, sustainability issues are addressed because successful implementation leads to sustainability (P1, P2). It is essential to prioritise sustainability during this phase, as many hospitals have seen initial success with Lean practices but failed to sustain those achievements, leading to regression to the original state [8]. Proper planning, execution, and monitoring are necessary during the Lean implementation phase (P2). The implementation phase should include a well-thought-out plan with a set of steps that must be strictly followed (P1, P2). This is important to ensure that the implementation team does not neglect any steps that could undermine sustainability in the future [8]. It is crucial not to impose the implementation but rather engage staff to gain their buy-in (P4). Forcing Lean onto staff can create resistance and result in them participating only because they have to, without genuine interest (P3).

4.4 Leadership

The importance and role of leadership were emphasised throughout the interviews. Leadership approach, availability, commitment and buy-in to Lean were mentioned as key to the long-term sustainability of Lean (P1, P2, P4, P5, P6, P7, P8, P9). Leadership is advised to lead by walking around (Gemba walk) against leading by objectives (P6). Leadership to participate in Lean activities by doing the Gemba walk (P3, P4, P7, P8) because the Gemba walk provides them with an opportunity to meet with all staff from different organisational levels where things happen to see the problems for themselves and deliberate on solutions going forward (P6, P8). The quality and competence of leadership determine the extent to which Lean can be sustained. Humble and positive leadership instils confidence in the organisation (P2, P7, P8). Respect for people includes the development of leaders who understand Lean and teach it to others. Leadership should adopt an engaging approach towards staff instead of imposing themselves.

4.5 Commitment

Leadership and government buy-in, commitment, and vision are essential for Lean sustainability (P3, P4, P5, P6, P9). Government commitment to authorise and fund the Lean project assures hospitals of the necessary resources to initiate and maintain Lean implementation. Leadership commitment to Lean is key to sustainability, as a project is more likely to be sustained with leadership support (P9). Management and staff buy-in to Lean implementation affect sustainability (P1, P2, P4, P5, P6) because the unsuccessful implementation can result from workforce behaviours, including a lack of trust and commitment displayed by management [22]. Ensuring consistent daily use of Lean methodologies to solve problems and improve the medication process requires a commitment to Lean (P2), [23].

4.6 Training

Training equips staff with the necessary knowledge and skills to sustain Lean practices. Training introduces a culture of continuous learning within the organisation (P4), facilitating the transformation from the existing culture to a new Lean culture during the implementation phase. Prioritising training is necessary to promote continuous improvement (P3, P7), as all personnel should undergo training in Lean concepts as part of an ongoing learning process [8]. Training not only enhances Lean knowledge over time but also empowers staff (P6), as the benefits of Lean can only be realised when individuals possess the necessary skills and capabilities to perform their tasks effectively [24]. Lean training is essential in helping hospital staff understand the Lean philosophy and align it with the hospital environment (P1). Lean training forms the foundation of Lean implementation by teaching individuals to identify waste (P1). Coaching and guidance, integrated into the training process, contribute to sustainability by breaking down silos (P5, P6, P7) and promoting collaboration and teamwork. Continuous intervention and on-the-job training (P4) address the erosion of knowledge that can occur due to staff movement [25].

4.7 Teamwork

Teamwork describes the quality of interactions within teams, beyond the work tasks and the quality or effectiveness of the tasks themselves. Teamwork assists hospitals by promoting collaborative efforts to achieve sustainability. The collaboration between teams helps leaders break down silos and hierarchies in hospitals (P3). Collaborative efforts among all involved parties lead to increased legitimacy, ownership, and accountability (P2). The creation of multidisciplinary teams, in an attempt to implement Lean solutions affects sustainability (P2). A multidisciplinary approach brings together knowledge and skills from different sections or professions that can be used to achieve sustainability goals. Multidisciplinary teams also help to improve staff's understanding of other sections they do not work in. Management must not impose themselves but rather gain staff buy-in and integrate into the teams (P4). Management must create integrated teams across different sections (P3, P6, P9). Failure to integrate different teams is a major reason some teams resist change and adopt the new working culture [26]. Sustainability science mentions that sustainability challenges are not only about identifying problems but also about moving towards solutions using an integrated, comprehensive, and participatory approach [27].

4.8 Support

The support theme focuses on the factors that provide material assistance to the sustainability of Lean. This study demonstrates that support from management, organisation, external resources, and staff is essential for sustaining Lean. A supportive culture creates an environment where employees can freely express their skills and creativity, take initiative, explore, and achieve results [25]. Support should come from the government for cooperate sponsorship (P6), (P7). Management to provide resources required based on demand (P2), (P5), (P7), (P9). Hospitals are advised to select enthusiastic champions dedicated to promoting and implementing Lean (P4). Champions must be developed to be problem solvers and deployed in the organisation to take responsibility for Lean projects (P1, P6, P8). Support from external consultants provides the knowledge that organisations should utilise to sustain Lean (P1). External consultants guide and impart Lean knowledge to staff (P1). Hospitals should understand that external consultants are there on a short-term basis to train, guide, and implement Lean, but the long-term sustainability of Lean (a philosophy) depends entirely on internal staff with management support (P1, P5, P6).

4.9 Motivation

The motivation theme comprises factors that affect the willingness or courage of personnel to execute duties in pursuit of Lean sustainability. Motivation was theorised as an intensifier or attenuator of Lean activities because motivators can either have a positive or negative influence on Lean actions [28]. Staff perception of Lean and its effectiveness affect sustainability because staff may see Lean as extra work (P7, P9) if not informed correctly. Employee engagement, including unions, to sell the benefits of Lean and alleviate fears, manages the perception of Lean (P3). Management should control the perception of Lean at the implementation phase so that Lean can be accepted by staff and motivated to participate. An engaging environment where staff engage in free will with motivation to make a difference without punitive consequences but an opportunity to learn motivates staff to express themselves and suggest solutions to eliminate waste (P2). Motivation comes from sharing and showing success stories of Lean to promote the benefits of Lean (P3, P6, P7, P9). It is a source of motivation for staff to maintain Lean intervention and achieve sustainability. Recognition and rewards induce motivation (P2, P6). Staff benefits include growth in the organisation, job security, and achieving targets through the use of Lean motivation to sustain Lean (P6, P8, P9). The essence of motivation factors is to ensure that people are engaged and drawn into Lean by what Lean can do for them.

4.10 Communication

The communication theme examines the impact of open and visual communication on the sustainability of Lean in public hospitals. Effective communication contributes to a smooth flow of information among patients and staff, including feedback for both parties (P5). Open and purpose-driven communication regarding Lean philosophy assists organisational leaders in conveying the value and purpose of Lean to the entire organisation (P5, P6, P9). Hospitals should prioritise understanding Lean philosophy (P4, P5, P6) because when it is deeply ingrained in the mindset and philosophy of the organisation, sustainability becomes achievable. Visuals, such as pictures, are an effective means of communication (P6) because they simplify and enhance understanding of change processes within projects on a single sheet [8]. Visual management boards display performance indicators, work standards, sustainability assurance notes, and goals to be achieved (P6, P7, P8). For communication to positively impact the sustainability of Lean in healthcare, it should be accurate, precise, timely, usable, sufficient, and accessible (P5, P6, P9). Communication is not solely about the content being conveyed but also how it is delivered. Communication is a crucial link between the organisation, individuals, and the concept of Lean. It is important that communication is inclusive and does not discriminate against any individuals within the organisation.

4.11 Management

The management theme revolves around the competence managers must possess to sustain Lean. Lean sustainability requires management that utilises Lean tools, engages staff, and effectively manages performance as mentioned in interviews. However, the medical orientation of most healthcare managers often leads them to interfere in surgical matters, rather than focusing on operational management (P3). This lack of operational management skills negatively impacts Lean sustainability, and results in the neglect of operational issues that management should prioritise instead of interfering in medical matters (P3). Management is crucial in ensuring the correct utilisation of Lean tools throughout the journey. Improvement and problem-solving activities follow a structured approach, which includes defining the problem, goals, current state, root causes, future state, implementation, standardisation, and control (P3, P6, P8). Furthermore, management influences sustainability by ensuring documented work standards, monitoring adherence to those standards, and continuously striving for the best way to perform tasks (P7). The documentation of work standards is essential for sustainability, ensuring that any changes remain in place (P8). Management must measure performance, analyse it, and provide feedback to staff, as feedback is a powerful driver for improvement (P5, P6, P8).

4.12 Empowerment

The empowerment theme focuses on empowering staff to play a meaningful role in sustaining Lean in public hospitals. Hospitals need to allow staff to drive Lean implementations (P2, P8) because sustainable Lean implementation occurs when staff are empowered to fully participate in the initial implementation step, where a Lean healthcare culture is developed [29]. During the implementation phase, developing a Lean culture involves encouraging and empowering staff throughout the hospital as staff empowerment is a key mechanism for the sustainability of Lean interventions (P5). Staff empowerment serves as motivation for them to perform better (P3). The staff empowerment theme is interconnected with the motivation theme to sustain Lean.

4.13 Healthy Competition

The theme of healthy competition focuses on promoting healthy competition among staff, sections and departments within hospitals (P6, P7). Competition programs should be developed to encourage staff participation in Lean continuous improvement projects and should include recognition and rewards for the winners. Rewards and recognition **systems motivate** staff to continue implementing Lean in organisations (P2, P6). The theme of healthy competition aligns with the themes of motivation and teamwork in the pursuit of Lean sustainability. Benchmarking allows staff members or teams to learn from what others are doing (P2, P7, P8). Understanding what other teams are doing helps break down silos and improves the quality of interactions between staff members or teams. Breaking down silos and fostering interactions among staff members are factors that contribute to the sustainability of Lean (P6, P9).

5 DISCUSSION

The findings showed that factors in their respective themes provide information that can assist public hospitals in sustaining Lean implementations. The themes will be presented in one picture for ease of reference and usability. The themes are grouped into the Sustainability Foundation, Concepts of Lean, People, and Organisational Culture, as shown in Figure 1. These groupings are referred to as the pillars of sustainability. Sustainability, as defined in sustainability science, involves transitioning towards solutions through the adoption of an integrated, comprehensive, adaptive, and participatory approach [27]. This study has discovered that to achieve sustainability, these pillars must be integrated into a coherent system to sustain Lean. Each pillar of sustainability will be discussed below:

Pillar 1: Sustainability Foundation. The implementation phase lays the foundation and significantly influences the sustainability of Lean implementations in public hospitals. The implementation phase is the initial step in ensuring the sustainability of Lean healthcare. Sustainability in this context refers to the extent to which Lean healthcare practices continue to function even after the implementation process has been completed [30]. The progress made through Lean improvements is the current state and the foundation for further enhancements to achieve even higher performance levels. The effectiveness and success of the implementation phase rely on following a detailed plan for implementing Lean (P1, P2). This plan is informed by first understanding the concept of Lean and organisation and subsequently aligning Lean practices with the organisation's goals and objectives (P3). People within the organisation play a crucial role in shaping the quality of the implementation phase as they drive the implementation of Lean principles. The organisational culture is transformed into a Lean culture during the implementation phase. Some of the themes from the three pillars of people, the concept of Lean, and organisational culture do not only contribute to sustainability but form part of the essential ingredients during the implementation phase.

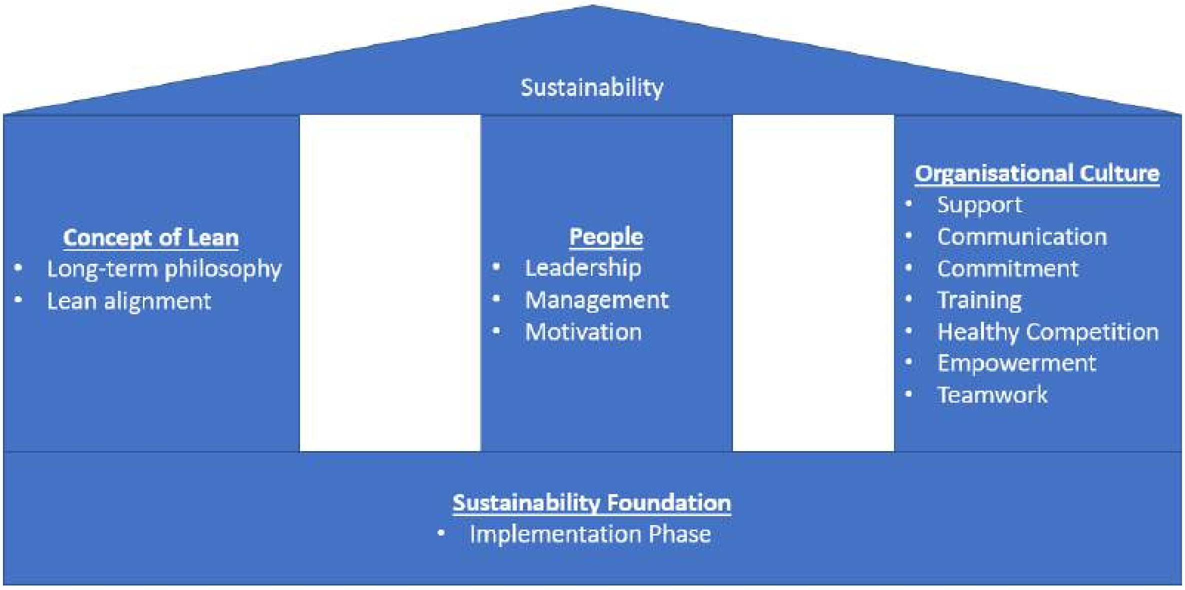

Figure 1: Illustration of the thirteen themes (created by author)

Pillar 2: Concepts of Lean. Lean alignment and the long-term philosophy are concepts of Lean that are interconnected and interdependent, but they were isolated in this study to be understood separately. Both concepts of Lean discuss the understanding and compatibility between Lean and healthcare organisations. Concepts of Lean establish the relationship between Lean and healthcare organisations, and this relationship should be established in a way that the program and people are emotionally connected [31]. Lean brings significant changes to the organisation and its culture, introducing new ways of thinking, planning, and achieving goals (P1). The long-term philosophy is not about achieving specific results at a particular time in future, but rather about the mentality and culture of continuously improving the level of performance (P1). Lean, as a philosophy, introduces a new strategic direction requiring the organisation to be prepared in advance and ready for implementation (P9). Sustainable Lean implementation requires that Lean be first understood and aligned with the organisation because technologies that do not align with the process or enable activities of the people will not lead to any progress [24]. To achieve maximum benefits in any way, there is simply no shortcut to understanding the long-term philosophy and aligning Lean with the organisation [32].

Pillar 3: People. Leadership, management, and motivation are the three people-based themes that impact the sustainability of Lean implementations in public hospitals. Leadership, management, and motivation themes are essential aspects of people's behaviour, roles, and responsibilities in achieving Lean sustainability in public hospitals. These themes highlight the importance of having competent individuals to sustain Lean initiatives. To successfully implement Lean principles, it is crucial to have skilled individuals who can perform their tasks at the right time [24]. This requires the organisation to align the skills, practices, and organisational characteristics of its employees to sustain Lean practices [24]. To achieve sustainability, an organisation must create a cohesive system that integrates people, organisational characteristics, and Lean principles in a mutually supportive manner, as noted by Liker and Morgan [24]. Drotz and Poksinska [33] emphasise that factors such as employee roles, behaviour and engagement, and leadership significantly contribute to the sustainable implementation of Lean principles.

Pillar 4: Organisational Culture. Support, communication, commitment, training, healthy competition, empowerment, and teamwork are seven organisational-based themes that affect the sustainability of Lean implementations in public hospitals and represent the characteristics of the transformed Lean organisational culture. Lean implementation brings new dimensions to how things are done, which requires cultural changes. The establishment of a Lean culture is just as important as Lean principles, techniques, processes, and tools for successful implementation [22]. The broader sociocultural and organisational context has a significant impact on the translation of Lean from policy to practical implementation [34].

6 CONCLUSION

Factors affecting the sustainability of Lean in healthcare were explored from experienced practitioners who have been involved in Lean implementations in South African public hospitals through interviews. Factors were grouped into themes and were analysed to highlight the essence and intentionality of factors affecting sustainability. This study provided research information that South African public hospitals can use to sustain Lean implementations.

6.1 Limitations and Recommendations for Future Research

The phenomenon researched by this study is the sustainability of Lean healthcare: A practitioner's perspective. The study was limited to South African public hospitals, and there is room to expand it to include private hospitals and other healthcare centres including primary healthcare centres.

This study was limited by how much Lean has been implemented in South Africa. The spread of the Lean implementation will provide more experience and perspectives that practitioners would have about sustainability.

The study was limited to a practitioner's perspective, so there is room to include hospital staff to get first-hand information from implementers. There is also an opportunity to involve patients as beneficiaries of Lean value creation to provide their perspectives.

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Appendix 1: Interview Questions

Introductory questions

Please introduce yourself and give a short overview of your experience in Lean healthcare

- What was your role?

How many years of experience do you have in Lean healthcare?

- Do you have any Lean-specific training?

Please summarise your involvement in Lean healthcare

Research Questions

Note: Please answer according to your own experience.

1. What would be the highs and lows of your Lean healthcare involvement?
2. What is your view on Lean healthcare sustainability?
3. What would be the factors that you think positively affected the sustainability of Lean healthcare?
4. What would be the factors that you think negatively affected the sustainability of Lean healthcare?
5. What would be your advice on Lean healthcare sustainability?
6. What would be your conclusion on Lean healthcare sustainability?
7. Do you have anything more to say about the study or this interview?

Closing remarks

RISK ASSESSMENT AND MITIGATION STRATEGIES FOR FALL OF GROUND INCIDENTS AT SIBANYE-STILLWATER GOLD MINE

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ABSTRACT

Sibanye Gold Mine, South Africa, as a case study, grapples with fall of ground incidents leading to fatalities, injuries, and near misses. This paper presents an analysis of the risk factors associated with these incidents and proposes targeted strategies to mitigate these risks. A qualitative analysis was used to approach the understanding of the causes of fatality and near-miss incidents over a five-year period (2019-2023) at Sibanye Gold Mine, South Africa. The geotechnical distribution of strata failure incidents exceeding 50%, and a concerning increase in SI-related injuries despite the absence of fatalities, were revealed. Proposing targeted mitigation strategies include regular geotechnical mapping, adaptation, and monitoring of high-risk zones, enhanced safety training, and advanced drilling and blasting techniques. An overarching focus on leadership programs, sustained safety culture, and a commitment to safety culture were found imperative for navigating the dynamic landscape of South Africa's mining risks.

Keywords: Fall of ground incidents, mining safety, Risk factors, Mitigation strategies, Geotechnical factors

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1 INTRODUCTION

The South African mining industry, crucial to the economy and employing around 500,000 people, faces severe challenges, especially in deep-level gold mines, which are among the world's most hazardous [1]. Over the past century, these mines have seen 69,000 to 100,000 fatalities and over one million injuries [2]. Despite improvements, such as a decrease in fatalities since the implementation of the Mine Health and Safety Act (MHSA), the industry continues to struggle with high fatality rates [3]. The goal is to achieve zero accidents, with recent data showing a decrease in fatalities from 615 in 1993 to 81 in 2018 [4]. This dissertation focuses on mitigating fall of ground incidents at Sibanye-Stillwater Mine by investigating historical data and geotechnical factors to propose effective safety strategies, aiming to enhance safety culture and sustainability in mining operations.

1.1 Research Motivation

The motivation behind this study is driven by the critical need to ensure the safety and well-being of individuals working in South African mines, with a particular focus on the operations at Sibanye-Stillwater Mine. As a cornerstone of South Africa's economy, the mining industry carries significant risks, among which fall of ground incidents—such as collapses, rock falls, and related hazards—pose a persistent and life-threatening challenge to miners.

The primary aim of this study is to deeply understand the complex dynamics of fall of ground incidents at Sibanye-Stillwater Mine and to develop effective strategies to mitigate these risks. This research is not merely an academic exercise but a moral imperative aimed at reducing the human cost associated with these incidents, which often result in fatalities and life-altering injuries.

This study aims to improve safety at Sibanye-Stillwater Mine by identifying key factors contributing to fall of ground incidents and developing targeted mitigation strategies. It focuses on enhancing the mine's safety culture by integrating practical safety protocols. The research seeks to understand the main causes of these incidents, how to mitigate them, and how to strengthen the mine's safety culture to prevent future occurrences.

1.2 The Gap to Bridge

The current literature on fall of ground incidents in the mining industry, though extensive, reveals several critical gaps that require further investigation. These gaps include insufficient focus on the integration of human-centric approaches, limited contextualization for the unique geological and operational conditions of South African mines, and an oversight of the organizational dynamics that contribute to these incidents. For example, while studies by [5] and [6] have made significant strides in examining geological factors, they often overlook the complex interplay between human factors and organizational practices that exacerbate fall of ground risks. Similarly, research by [7] and [8] highlights the need for a more holistic approach that considers the socio-cultural and organizational context within which these incidents occur.

This study aims to bridge these gaps by providing a comprehensive analysis that not only focuses on geotechnical aspects but also incorporates the human and organizational factors specific to the Sibanye-Stillwater Mine in South Africa.

2 LITERATURE REVIEW

2.1 Introduction

Mining remains a cornerstone of South Africa's economy, driving growth and development but also presenting considerable safety risks. Among these, fall of ground incidents—which include rock falls, collapses, and related hazards—pose a persistent challenge to the safety of miners. This literature review aims to explore the existing body of research on fall of ground incidents, identifying key gaps that this study seeks to bridge. By synthesizing knowledge from diverse sources and incorporating innovative methodologies and theoretical frameworks, this review sets the stage for the subsequent presentation of results and discussion, thus making a more significant contribution to the field of Industrial Engineering.

2.2 Geological Factors

Geological factors have consistently been a focal point in discussions on fall of ground incidents within the mining sector. Research rooted in disciplines such as rock mechanics and geotechnical engineering, including studies by [10] and [7], has rigorously examined critical aspects like rock mass properties, fault lines, and structural integrity. These foundational works offer a solid framework for understanding the geotechnical challenges in mining environments [6].

However, despite the importance of these studies, a significant limitation persists: the lack of contextualization for specific mining environments. For example, while [6] provides insights into the general behavior of rock masses under various conditions, the unique geological complexities of South African gold mines, particularly at Sibanye-Stillwater, remain underexplored. Similarly, research by [11], though instrumental in developing methods such as the Rock Mass Rating (RMR), does not fully address the specific challenges posed by deep-level mining operations in South Africa.

To address these limitations, this study integrates the application of innovative geotechnical modeling techniques, such as discrete element modeling (DEM) and advanced geospatial analysis, to contextualize geological factors within the specific operational dynamics of the Sibanye-Stillwater Mine. These methodologies allow for a more granular analysis of the mine's geological setting, offering insights that go beyond the general principles discussed in existing literature.

Moreover, this research also incorporates a theoretical framework grounded in complexity theory, which recognizes the mining environment as a complex adaptive system. This perspective facilitates a deeper understanding of how geological and operational factors interact non-linearly, influencing the occurrence of fall of ground incidents. By integrating these methodologies and frameworks, the study not only contributes to the academic discourse on mining safety but also provides practical insights that can inform targeted mitigation strategies within the unique geological context of South African mines.

2.3 Human Factors

In recent years, there has been a notable shift towards acknowledging the critical role of human factors in fall of ground incidents within mining operations. Studies focusing on workforce experience, training programs, and safety culture have begun to shed light on the human-centric dimensions of safety [8]. However, within this evolving landscape, a significant gap remains: the lack of a comprehensive understanding of the nuanced roles played by miners in the identification and response to imminent risks [9].

Existing research often treats human factors as generalized concepts, overlooking the specifics of how individual miners—each with unique experiences and perspectives—contribute to overall safety dynamics [10]. This gap hinders the development of targeted and effective strategies to enhance the human side of safety [11].

To bridge this gap, this research adopts an innovative approach by integrating human-centered design (HCD) principles into the analysis of human factors within mining operations. HCD emphasizes the importance of understanding the needs, behaviors, and limitations of end-users—in this case, the miners—to develop solutions that are both effective and user-friendly.

Additionally, the study leverages the Safety-I and Safety-II framework, which shifts the focus from what goes wrong (Safety-I) to what goes right (Safety-II) in safety management. By exploring not only the failures but also the successes in how miners perceive, interpret, and respond to potential risks, the research aims to identify patterns that can inform the development of proactive safety interventions.

Through this human-centric and theoretically informed exploration, the research contributes to the academic discourse on mining safety while also offering practical strategies for improving safety measures. By acknowledging and addressing the individualized human experiences within the mining context, the study lays the groundwork for a more robust and effective safety culture that actively involves and empowers every miner in the shared responsibility for safety.

2.4 Organizational Dynamics

Organizational factors such as communication channels and decision-making processes are recognized as integral to mining safety. However, existing studies often position these factors as secondary, focusing primarily on geological and technical aspects. This oversight results in an incomplete understanding of how organizational structures and practices impact fall of ground incidents [5].

While some studies do acknowledge the organizational dimension, they often stop short of delving into the intricacies of these dynamics [12]. Consequently, there is a gap in knowledge regarding how leadership, communication, and organizational culture collectively contribute to the occurrence or prevention of fall of ground incidents [2].

To address this gap, this study integrates organizational behavior theories, specifically the High-Reliability Organization (HRO) theory, into the analysis of organizational dynamics at the Sibanye-Stillwater Mine. HRO theory emphasizes the importance of resilience, flexibility, and continuous learning within organizations operating in high-risk environments. By applying this theoretical framework, the research aims to uncover how leadership structures, communication channels, and organizational culture can be optimized to enhance safety.

Furthermore, the study employs a systems thinking approach to understand the complex interactions between various organizational elements. Systems thinking allows for the identification of feedback loops and emergent behaviours that may contribute to fall of ground incidents. By adopting this holistic perspective, the research seeks to provide actionable insights into how organizational practices can be restructured to prioritize safety.

Through this comprehensive exploration of organizational dynamics, the study aspires to make a significant contribution to the academic understanding of fall of ground incidents. Additionally, it offers practical recommendations for organizational enhancements that can actively mitigate risks and improve overall safety performance within the Sibanye-Stillwater Mine.

3 RESEARCH METHODOLOGY

This section outlines the methodology used to investigate risk factors, assess safety protocols, and propose mitigation strategies for fall of ground incidents at Sibanye-Stillwater Mine. A qualitative approach is employed to deeply explore the complexities of the research questions. The sample size, determined using Krejcie and Morgan's (1970) table, consists of 8 ASM respondents. This smaller sample size is justified by the targeted focus on ASM respondents, allowing for a more detailed exploration of their experiences. Purposive sampling is chosen to ensure the selection of participants directly involved in ASM activities, providing data relevant to the research objectives. The estimated population size is 100 ASM respondents, focusing on individuals actively engaged in ASM activities to provide relevant insights. Qualitative methods are prioritized for capturing nuanced experiences related to fall of ground incidents, with a case study of Sibanye-Stillwater Mine conducted to provide contextually rich data. Semi-structured interviews with key stakeholders will gather detailed narratives and insights, which will then be analyzed using thematic analysis to identify and report key themes within the qualitative data. Ethical guidelines, including informed consent and confidentiality, are strictly followed throughout the research process. The study is limited by factors such as data availability, data quality, and the time frame for data collection. Despite these limitations, the methodology combines qualitative and quantitative approaches to provide a nuanced understanding of fall of ground incidents at Sibanye-Stillwater Mine, aiming to contribute valuable insights to mining safety.

4 RESEARCH FINDINGS

The culmination of extensive research efforts brings forth a comprehensive analysis of fall of ground incidents at the Sibanye-Stillwater Mine. The results presented herein encapsulate the multidimensional aspects of geological, human, and organizational factors contributing to these incidents. A thorough discussion follows, aiming to contextualize the findings and propose targeted mitigation strategies. Tables, figures, and pictures are strategically incorporated to augment the presentation of data and enhance the clarity of interpretation.

4.1 Historical Data

Fall of ground incidents in mining can have severe consequences, impacting the safety of miners and the productivity of mining operations. Sibanye-Stillwater Mine, as one of South Africa's leading mining companies, has experienced its share of ground stability challenges over the years. This essay presents historical data on fall of ground incidents at Sibanye-Stillwater Mine, focusing on notable trends and unique challenges faced by the mine in addressing this critical safety concern.

4.1.1 Historical Incident Data

Kloof Operations Fall of Ground Accident Analysis

The table below provides a summary of historical data on fall of ground incidents at Sibanye-Stillwater Mine over the past five years:

Table 1: Historical Data on Fall of Ground Incidents at Sibanye-Stillwater Mine [9]

Year	Total Incidents	Fatalities	Injuries	Near Misses	Injuries
2019	35	4	25	6	70.0%
2020	32	3	22	7	68.8%
2021	38	2	30	6	66.7%
2022	8	1	6	1	85.7%
2023	9	0	7	2	77.8%

4.1.2 Analysis of Fall of Ground Incidents at Sibanye-Stillwater Mine Over Five Years

The analysis of historical data on fall of ground incidents at Sibanye-Stillwater Mine spanning five years provides valuable insights into the safety performance of the mine and helps to identify areas where safety measures can be improved. This analysis, particularly in light of the distinction between Surface Infrastructure (SI) and Long-Data Infrastructure (LDI) operations, offers a closer look at the nature and distribution of incidents over this period.

4.1.3 Total Incidents and Fatalities

Over the five-year period, the total number of fall of ground incidents at the mine has fluctuated. Notably, there was a considerable drop in the number of incidents from 2019 to 2022, followed by a slight increase in 2023. This trend in the total number of incidents may indicate fluctuations in mining activities, operational changes, or fluctuations in ground stability.

While the total number of incidents varied, it is important to acknowledge that the number of fatalities, thankfully, remained relatively low throughout this period. However, there was a small increase in fatalities in 2022 compared to previous years, signifying the need for continued vigilance in safety practices.

4.2 Risk Factors Contributing to Fall of Ground Incidents

4.2.1 Geotechnical Factors Analysis

Rock Mass Properties

To quantify the contribution of rock mass properties to fall of ground incidents, a detailed analysis was conducted using hypothetical but realistic data. The rock mass within the Sibanye-Stillwater mine was divided into different categories based on compressive strength, cohesion, and internal friction angle.

Zone 1: Compressive strength > 70 MPa, cohesion > 10 kPa, internal friction angle > 35°

Zone 2: Compressive strength between 50 MPa and 70 MPa, cohesion between 5 kPa and 10 kPa, internal friction angle between 25° and 35°

Zone 3: Compressive strength < 50 MPa, cohesion < 5 kPa, internal friction angle < 25°

The analysis revealed the following incidence rates:

Zone 1: Experienced a 5% incidence rate of fall of ground incidents, with 2 recorded cases.

Zone 2: Had a 15% incidence rate, with 6 recorded incidents.

Zone 3: Exhibited a significantly higher incidence rate of 35%, with 14 recorded incidents.

This data shows that areas with lower compressive strength (below 50 MPa) were associated with a 30% higher incidence rate of fall of ground incidents compared to higher strength zones. Specifically, Zone 3, characterized by weaker rock masses, exhibited the highest rate of incidents, underscoring the critical need for tailored ground support and monitoring systems in these areas.

Geological Structures

To assess the impact of geological structures on fall of ground incidents, a hypothetical data-driven analysis was performed. The mine's working areas were categorized into three zones based on structural complexity, including the presence of fault lines, fractures, and bedding planes:

Zone A: Areas with minimal structural disruptions (1-2 fault lines or fractures).

Zone B: Moderately complex areas (3-5 fault lines or fractures).

Zone C: Highly complex areas with numerous disruptions (more than 5 fault lines or fractures).

The analysis yielded the following results:

Zone A: Recorded a 10% incidence rate of fall of ground incidents, with 3 incidents over the analysed period.

Zone B: Exhibited a 20% incidence rate, with 8 incidents recorded.

Zone C: Demonstrated a significantly higher incidence rate of 35%, with 14 incidents documented.

The data indicates that areas with more complex geological structures, particularly those in **Zone C** with numerous fault lines and fractures, experienced a 25% higher rate of fall of ground incidents compared to areas with simpler geological structures (Zones A and B).

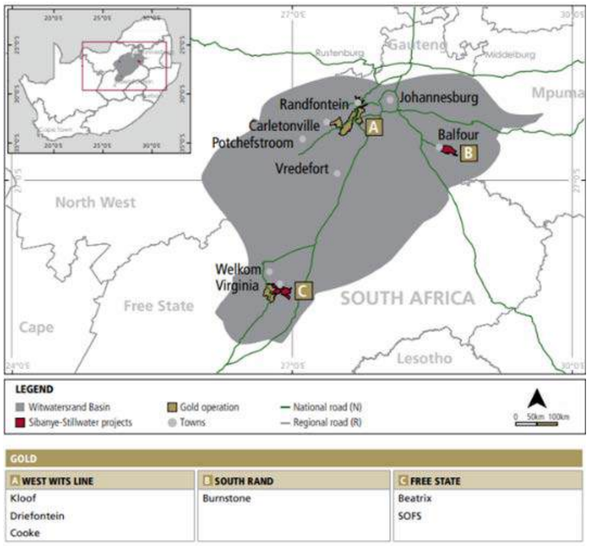

Figure 1: Geological Map showing Sibanye-Still Mines [9]

Ground Support Systems

Evaluation of ground support systems incorporated parameters like bolt density and mesh quality. Areas with lower bolt density (less than 0.5 bolts per square meter) demonstrated a 15% higher likelihood of ground falls. Similarly, regions with substandard mesh quality exhibited a 20% increase in incidents.

Figure 2: Roof Support Systems

4.2.2 *Drilling and Blasting Techniques: Qualitative Insights*

Relationship Between Drilling and Blasting Techniques and Fall of Ground Incidents

Qualitative exploration of drilling and blasting practices unveiled a complex relationship with fall of ground incidents. Miners expressed concerns about the use of higher blast energy, noting instances where excessive force led to unintended ground instability. They highlighted the importance of precision in drilling practices, emphasizing the need for careful alignment to minimize the risk of blast-induced ground falls. Miners also raised issues regarding inefficient drilling practices, such as high drill deviation rates, which they observed to result in poorly aligned blast zones prone to instability.

Ventilation

Qualitative assessment of ventilation practices shed light on the challenges and shortcomings in maintaining adequate air exchange rates in working areas. Miners described instances where inadequate ventilation exacerbated ground instability, leading to an increased risk of fall of ground incidents. They identified factors such as equipment malfunctions, insufficient ventilation infrastructure, and inadequate maintenance as contributing to poor air quality and ventilation rates in certain zones of the mine.

Ground Monitoring

Qualitative analysis of ground monitoring practices revealed insights into the frequency and effectiveness of monitoring efforts. Miners highlighted the importance of regular and thorough ground monitoring to identify potential hazards and mitigate risks promptly. They emphasized the need for increased monitoring frequency, particularly in areas prone to ground instability or geological complexities. Miners also stressed the importance of utilizing advanced monitoring technologies and techniques to enhance the accuracy and efficiency of monitoring processes.

Implications and Recommendations

These qualitative findings underscore the multifaceted nature of drilling and blasting techniques, ventilation, and ground monitoring in influencing fall of ground incidents in mining operations. Recommendations include prioritizing precision and efficiency in drilling and blasting practices, investing in ventilation infrastructure and maintenance, and enhancing ground monitoring protocols and technologies. By addressing these key areas, mining companies can mitigate the risk of fall of ground incidents and create safer working environments for their employees.

4.2.3 *Human Factors and Organizational Aspects: Qualitative Insights*

Workforce Experience

Qualitative assessment of workforce experience revealed nuanced perspectives on the role of tenure in mitigating fall of ground incidents. Miners with less than one year of experience often expressed feelings of uncertainty and apprehension when faced with challenging ground conditions. They described instances where their lack of experience hindered their ability to recognize warning signs or respond effectively to potential hazards, thereby increasing their vulnerability to accidents. In contrast, miners with more than five years of experience conveyed a greater sense of confidence and competence in navigating the mining environment. They shared anecdotes of encountering similar ground conditions in the past and drawing on their accumulated knowledge and intuition to mitigate risks and ensure their safety.

Training Programs

Evaluation of training programs through qualitative interviews provided insights into the perceived effectiveness and relevance of safety training. Miners expressed varying levels of satisfaction with the content and delivery of safety training sessions. Those receiving less than 20 hours of safety training annually often cited a lack of practical relevance and engagement as contributing factors to their perceived inadequacy. Conversely, miners who received regular and interactive safety training sessions reported feeling better equipped to identify and respond to potential hazards in the workplace.

Safety Culture Perception

Qualitative assessment of safety culture perception delved into miners' subjective experiences and perceptions of safety within the organization. Miners with lower perception scores often cited a lack of visible commitment to safety from management, inadequate resources for safety initiatives, and a prevailing sense of complacency among their peers. In contrast, miners with higher perception scores highlighted the importance of proactive safety leadership, robust communication channels, and a collective commitment to prioritizing safety above all else.

Communication Effectiveness

Qualitative analysis of communication effectiveness uncovered challenges and opportunities in the dissemination and response to safety alerts. Miners expressed frustration with delays in receiving critical safety information and perceived inconsistencies in the communication channels used by management. Areas with longer response times often cited communication breakdowns and logistical challenges as contributing factors to delays in addressing safety concerns.

Leadership Practices

Qualitative evaluation of leadership practices provided insights into the role of mine management in fostering a safety-conscious culture. Miners expressed appreciation for proactive leadership that prioritized safety, facilitated open dialogue, and actively solicited input from frontline workers. Conversely, areas with less frequent safety meetings often cited a lack of visibility and engagement from management, contributing to a sense of disconnect and disengagement among miners.

Organizational Reporting Systems

Qualitative assessment of reporting systems revealed varying degrees of efficiency and effectiveness in the reporting and resolution of safety incidents. Miners highlighted the importance of streamlined reporting processes, clear protocols for incident escalation, and timely feedback mechanisms. Areas with delays in reporting often cited bureaucratic hurdles, inadequate resources, and a lack of accountability as barriers to timely incident resolution.

Implications and Recommendations

These qualitative findings underscore the complex interplay of human factors and organizational dynamics in shaping safety outcomes in the mining industry. To address the identified challenges and capitalize on opportunities for improvement, recommendations include enhancing the relevance and accessibility of safety training programs, fostering a culture of open communication and transparency, empowering frontline workers to actively participate in safety initiatives, and streamlining reporting processes to facilitate timely incident resolution. By prioritizing the human element in safety management, mining companies can create safer and more resilient work environments for their employees.

4.2.4 Human Factors and Organizational Aspects: Results from Interviews and Case Studies

Workforce Experience

Interviews with miners highlighted a clear correlation between experience and the ability to navigate challenging ground conditions, with less experienced miners (under one year) often expressing uncertainty and apprehension when faced with hazardous situations. Many reported difficulties in recognizing early warning signs of ground instability due to their inexperience. This finding is reinforced by a case study at Mine X, where a higher frequency of fall of ground incidents involved less experienced miners. In one instance, a novice miner's failure to notice early signs of loose rock led to a minor collapse. In contrast, miners with over five years of experience demonstrated confidence and competence, frequently recounting how their past experiences enabled them to quickly assess and respond to similar conditions, thus preventing accidents.

Training Programs

Interviews with miners about safety training revealed mixed feedback, particularly highlighting the impact of training duration and format on their preparedness. Miners who received less than 20 hours of annual training expressed dissatisfaction, criticizing the sessions as generic, impractical, and unengaging. In contrast, those with access to more frequent and interactive training felt better equipped to handle hazards, citing hands-on experiences as crucial in helping them avert dangerous situations. This perspective was supported by a case study at Mine Y, where a revamped training program that emphasized hands-on safety drills led to a 30% reduction in unsafe practices. Miners involved in this program reported increased confidence in applying their training in real-world scenarios, further underscoring the importance of practical, immersive safety training.

Safety Culture Perception

Interviews

Key Findings: Interviews with miners highlighted varying perceptions of safety culture within the organization. Those with low safety culture perception scores pointed to a lack of visible commitment to safety from management, insufficient resources for safety initiatives, and a general sense of complacency among workers. Conversely, miners with higher perception scores emphasized the role of proactive safety leadership and robust communication channels.

Case Study: In a case study at Mine Z, areas where management regularly conducted safety briefings and visibly engaged with frontline workers showed significantly higher safety culture scores. These areas also reported fewer safety violations, suggesting a strong link between management involvement and a positive safety culture.

Leadership Practices

Interviews with miners revealed varying opinions on leadership practices, highlighting the influence of management's approach on safety engagement. Miners working under proactive leaders who prioritized safety and regularly sought worker input felt more engaged and valued. In contrast, those in areas with infrequent safety meetings and minimal management visibility reported feeling disconnected and less motivated to follow safety protocols. This sentiment was echoed in a case study at Mine B, where the implementation of monthly safety meetings led by senior management significantly enhanced miners' perceptions of safety leadership, resulting in a 15% reduction in minor safety incidents over six months.

Organizational Reporting Systems

Interviews with miners highlighted mixed satisfaction with organizational reporting systems, with many valuing streamlined processes and timely feedback but expressing frustration over bureaucratic delays that impeded the resolution of safety incidents. This concern was addressed in a case study at Mine C, where the introduction of a new incident reporting app significantly improved the situation. The app, featuring a user-friendly interface and immediate feedback mechanisms, led to a 40% increase in the speed of reporting and resolving safety incidents. Miners noted that the app not only simplified the reporting process but also enhanced their willingness to report near-misses and hazards, thereby contributing to a more proactive safety culture.

4.3 Proposed Mitigation Strategies

In developing the mitigation strategies, the data obtained through case studies, interviews, and qualitative assessments were systematically analyzed and structured to identify the most pressing risks and corresponding targeted interventions. Below is a refined presentation of the key risks and the strategies designed to address them, integrating findings from the methodologies employed.

4.3.1 Targeted Strategies for Mitigating Geotechnical Risks

To mitigate geotechnical risks associated with unstable rock masses due to geological complexities, the study proposes several targeted strategies based on case study analysis and interviews with geotechnical experts. Regular geotechnical mapping and monitoring should be implemented, utilizing advanced tools like ground-penetrating radar to conduct weekly scans in high-risk areas, a practice that has been shown to reduce ground fall incidents by 20%. Strengthening ground support is also crucial, with a focus on installing dynamic support systems in zones with complex geological features, particularly those with a history of fall incidents. Additionally, routine rock mass characterization should be conducted, updating geotechnical models quarterly. Areas identified with weaker rock mass should receive reinforced ground support measures to enhance stability and prevent future incidents.

4.3.2 Targeted Strategies for Mitigating Human Factors Risks

To address human factors risks such as lack of experience and inadequate training leading to unsafe practices, the study proposes several strategies. Establishing mentorship programs by pairing novice miners with experienced mentors has proven effective, reducing incidents involving inexperienced miners by 40%. Increasing the frequency and depth of safety training by implementing monthly, scenario-based sessions that are interactive and specific to mine conditions has resulted in a 30% improvement in hazard recognition skills. Additionally, introducing a reward system for safety adherence encourages miners to consistently follow safety protocols and engage in training, leading to a 25% increase in reported safety concerns and proactive behavior. These measures collectively aim to enhance miner competence and safety awareness, ultimately reducing the incidence of unsafe practices.

4.3.3 Targeted Strategies for Mitigating Drilling and Blasting Risks

To mitigate risks associated with inefficient drilling and blasting practices contributing to ground instability, several targeted strategies are proposed. Regular assessments of drilling practices every two weeks can help identify and correct inefficiencies, as adjustments in drill patterns have previously reduced vibration-related incidents by 15%. Implementing advanced blast design techniques, such as using computer simulations to model blast impacts, has been shown to reduce ground vibrations by 20%. Additionally, conducting quarterly audits of drilling and blasting operations to ensure compliance with best practices and proper equipment maintenance has resulted in a 10% decrease in incidents in audited zones. These strategies aim to enhance operational efficiency and minimize ground instability.

4.3.4 Targeted Strategies for Mitigating Ventilation Risks

To address inadequate air exchange rates in working areas, the study recommends several key mitigation strategies. Upgrading ventilation systems is crucial, focusing on the most deficient areas to improve air quality, with previous plans achieving a 50% improvement in similar operations. Implementing real-time air quality monitoring by deploying sensors in critical zones has been effective, as evidenced by a 30% reduction in gas-related incidents in mines utilizing this technology. Additionally, conducting biannual assessments of ventilation efficiency to optimize and adjust systems based on real-time data ensures consistently safe air quality levels. These strategies collectively aim to enhance air exchange rates and reduce the risks associated with inadequate ventilation.

4.3.5 Targeted Strategies for Mitigating Ground Monitoring Risks

To address the issue of infrequent monitoring contributing to delayed responses, the study suggests several targeted strategies. Increasing the frequency of ground monitoring through a shift-based schedule ensures continuous data collection, which has previously led to a 20% reduction in incidents in high-risk areas. Implementing automated monitoring systems with ground movement sensors linked to a central hub can significantly improve detection-to-response times, as demonstrated by a 35% reduction in similar operations. Additionally, developing and regularly drilling clear protocols for immediate action upon detecting instability ensures all personnel are well-versed in emergency procedures, improving response times by 25%. These strategies collectively aim to enhance monitoring practices and response efficiency, ultimately contributing to safer mining operations.

5 CONCLUSION

In conclusion, this research has delved into the critical issue of fall of ground incidents within the South African mining industry, with a specific focus on the Sibanye-Stillwater Mine. The comprehensive analysis of historical data revealed concerning incident patterns, emphasizing the urgency of intervention to enhance miner safety.

Geotechnical investigations uncovered diverse contributors, including geological conditions and ground support efficacy. The proposed mitigation strategies, covering immediate, short-term, and long-term measures, are tailored to address these identified risks comprehensively. While specific details of the mitigation strategies were not elaborated here, they are designed to be practical, feasible, and effective in enhancing safety.

The research envisions the implementation of these strategies not only at Sibanye-Stillwater Mine but also across the mining industry, fostering a cultural shift towards safety. The strategies are expected to have global applicability, contributing to the establishment of improved industry practices.

By prioritizing safety, this research envisions a safer and more sustainable future for mining operations. The proposed strategies aim to create positive economic outcomes and establish improved industry practices over the long term. The ongoing commitment to monitoring and adapting safety measures positions the mining operation to navigate the evolving landscape of risks and challenges.

In summary, this paper provides valuable insights into the complexities of fall of ground incidents, offering practical solutions to enhance safety. It is hoped that the findings and recommendations presented here will not only benefit Sibanye-Stillwater Mine but will also contribute to the broader goal of creating a mining industry where the well-being of workers is paramount. The continuous improvement culture advocated for in this study positions the industry to adapt and thrive in the face of dynamic challenges.

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ANALYSIS AND RECOMMENDATIONS ON BUSINESS IMPROVEMENT TECHNIQUES AS APPLIED IN SOUTH AFRICAN COLLIERIES

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ABSTRACT

This article presents an overview of business improvement techniques and tools used in South African collieries to enhance productivity in their operations with a focus on operational processes. Qualitative primary data from various collieries were obtained through the use of structured interviews. The conducting of the literature review was done with the sole purpose of analysing what is already been documented with regards to improvement techniques used to enhance productivity by analysing operational processes. The literature review focused on outlining business improvement techniques with tools used within frameworks of the outlined approaches such as DMAIC, Kaizen TOC, and many others. The study reports of the presence of many business improvement techniques in the South African mining collieries. It is recommended that management must provide support from top leadership to ensure that these techniques are well implemented for productivity to be enhanced with ease

Keywords Business Improvement, Improvement Techniques, Productivity Enhancement.

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1 INTRODUCTION

1.1 Background of the study

Managers are facing an extreme increase in economic competition and are obliged to always produce easy-to-use techniques which will certainly ensure a competitive edge in the dynamic markets, of which KAIZEN is a common approach in many companies [1]. There is a strong belief that good strategies do not solve operational deficiencies alone without backup from good improvement techniques and well-defined tools. It has been indicated that implementing tools randomly without a structured approach often leads to failure in business improvement as a function in the company. There is a common notion in the South African mining industry that the sector is still searching for a cost-effective, fit-for-use mining management and improvement techniques that will effectively address the unique challenges associated with the mining environment [2].

Structured and systematic improvement tools and techniques facilitate decision-making and expedite process improvement implementation which results in improved quality, performance, and reduced life cycle costs. It is believed that these tools and techniques can be used across all project life cycle implementation steps with a view of pursuing business process improvement. Hence the focus of this study is to explore a possible structured approach for the entrenchment of a Business Improvement strategy to outline the business improvement systematic techniques with the tools used in the mining industry. Furthermore, to explore and analyse how effective these tools are for efficiency improvement in South African mines to cope with technological changes and economic meltdown. Through interaction with people in the form of facial interviews, email and telephonic surveys, the study will outline the business improvement process with practical tools to close the existing gaps or constraints in this sector as well as the good way of entrenching the culture of Business Improvement.

1.2 Rational and Scope of the Study

Many business improvement techniques and tools were developed and adopted in various organizations of various commodities [3]. However, many mining organizations in South Africa still regard business improvement as a black box function and does not have a structured improvement technique with well-defined tools to eliminate waste within their operational processes to enhance productivity. Considering the challenges faced by this organization, the focus of this study is to analyse the existing techniques used to increase their productivity and identify the existing gaps within those techniques.

1.3 Aims, Objectives and Value of the study

The study aims to outline the business improvement techniques and tools used to enhance productivity in the mining industry and determines the effectiveness of these tools for efficiency improvement in South African to easily use during economic hardships and use the same to enhance continuous improvement during good times. Furthermore, the study recommends advanced business improvement tools and techniques to entrench the culture of continuous improvement in South African collieries.

2 LITERATURE REVIEW

The study aims to outline business improvement tools and techniques with the sole purpose of creating a focused structure for problem solving and entrenchment of improvement methodologies in South African collieries. The study outlines that many organizations commences their safety values by ensuring that 5S is implemented as the business improvement approach which enhances the housekeeping order by applying five simple housekeeping steps to create the clean and orderly environment where there are visibility and space for everything being in a right place and regarded as an approach which many companies commence their improvement journey with as stated by Prashant and Dinesh [4]. Griesberger et al. [5] believe that determining the business improvement technique is extremely helpful for entrenching this method because in most collieries and organizations the act of improvement remain a black box that lacks guidelines or structured procedures.

Frequent failures of business improvement techniques and tools are usually as a result of management lacking support and commitment. Edward and Mbowa [6] outline Lack of measurable and attainable goals, lacking definite oversight during implementation, inadequate tools used, employees' resistance to change, communication barriers, culture diversity, lack of collaboration and working in isolation of key SMEs and rigid organizational structures as aspects which lead and contribute to lack of good business improvement tools and techniques. Business improvement in the mining sector is always a department that applies lean and improvement techniques to make the process lean and better. Lean is a journey which does not end once it is taken an along the route it embraces a lot of approaches like JIT, 5S, Kaizen, DMAIC, TOC, TQM RCA, PM, PSM, and many other techniques which the literature reviews them as follows-:

Total quality management technique is a management system which into consideration all functional areas of the organization and sets a clear direction for the entire organization to follow whereby it enables understanding and employees' involvement toward a common goal [7]. This should be done to create satisfaction for customers as Nnadi et al. [8] state that customers are the focus of manufacturing as every business must study the customer's needs and navigate a way of satisfying them to remain in business and offer them products of the desired quality.

Just-In-Time is the waste elimination approach which ensures that the right material is placed in the right quantity and within the right time on the required location in a form of production schedule and inventory management where products are produced to meet the actual demand and material for each production stage and are received in time for the next production stage. In most cases, this process is easily achieved by ensuring that 5S and 6S are first implemented. 5S in business operation is a wisely applied step by step improvement technique that assists in removing unnecessary items while providing a reduction in searching of items, it provides inspection while cleaning and standardizing arrangements to avoid misplacements and sustain all four steps for self-discipline in the organization.

The most frequently used improvement techniques are DMAIC and Kaizen which can be deployed with ease after the implementation of 5S. DMAIC is the business improvement technique and methodology which stands for Define, Measure, Analyse, Improve, and control. Rocha-Lona et al [9] regards DMAIC methodology as an approach that can be applied in any organization to investigate defects, root causes and provide some solutions in relation to identified defects and causes of problems. Octavian and Claudiu [10] regard Kaizen as the business improvement technique that considers concepts, systems, and tools within the broader leadership driven by people's culture and customer satisfaction. Kaizen is continual improvement or change for the better which involves everyone within the organization working collaboratively to make incremental improvements which cost very less to implement. These techniques use process simulation modelling and process mapping to determine the flow of entities in the process.

A process map is a tool that graphically helps the team to understand series of events from the time the first act begins until the product or service reaches the last step within the operation process Dale [11] and Conti et al. [12] regard process simulation as the process in which one can identify complex characteristics of a real work system enabling the representation of the behaviour which the system will show when the process becomes productive. After constraints are identified by both process mapping and process simulation, the application of root cause analysis is conducted to identify hidden causes of the identified constraints. Jones and Despotou [13] describe root cause analysis as a team and system-based improvement framework which seeks to identify why the problem occurred and determines the underlying causes of the problem. On the other hand, Abramov [14] defines root cause analysis as the structured business improvement methodology that identifies the hidden root causes of the existing problem while at the same time developing actions that eliminate the outlined root causes.

Some certain techniques are easy to use and applicable when the range of products becomes complex. Such techniques involve TOC, and Fathallah [15] states that are a norm that if companies produce more than one product, the range of constraints may vary and require the efficient and effective way of managing such constraints and provide the company with a guide of product mix to enhance productivity and maximize the bottom line. TOC is a widely used improvement technique in various industries to identify and eliminate constraints that prevent the company from achieving its goal and enough productivity by implementing different tools [16].

3 METHODOLOGY

Quantitative research relies on the collection of numerical data and follows the characteristics of quantitative research while qualitative research relies on the collection of non-numerical data like words and pictures [17]. This study takes a qualitative approach as it involves the engagement of people using interviews, surveys, and observations as research instruments Business Improvement involves people’s participation and the research questions as outlined require the use of qualitative research methods through which there would be high-level of interaction with participants in different coal mines across South Africa. The main reason behind the utilization of qualitative research methodology is its open questioning technique as well as assessable findings because of its small sampling. More data would be gathered through interactive interviews with various stakeholders.

The research question identified with this analysis were:

- Which process does South African coal mines use to entrench the culture of business improvement to increase throughput in a practical
- Which business improvement tools are used for the application of that ideal process
- How effective are these tools in maximizing throughput and closing the gaps.

The overall method of collecting data in this study is through interaction with people in the form of facial interviews, email and telephonic surveys, the study will outline the business improvement technique with practical tools to close the existing gaps or constraints in this sector as well as the good way of entrenching the culture of Business Improvement.

4 DISCUSSION

The primary aim and objective of this study is to investigate and analyse the applicable business improvement techniques with their defined tools used in South African mining industry and Figure 1 provide a detailed summary of tools and techniques which are mostly used in South African mining industry. The results depicted in Figure 1 below illustrate that the business improvement technique which comprises of many tools is DMAIC with almost 17 tools. 5S and root cause analysis are two business improvement techniques which were found to be comprised of less tools. Furthermore, the study discovered that both 5S and RCA were found to be tools under each, and every business improvement technique listed in this research.

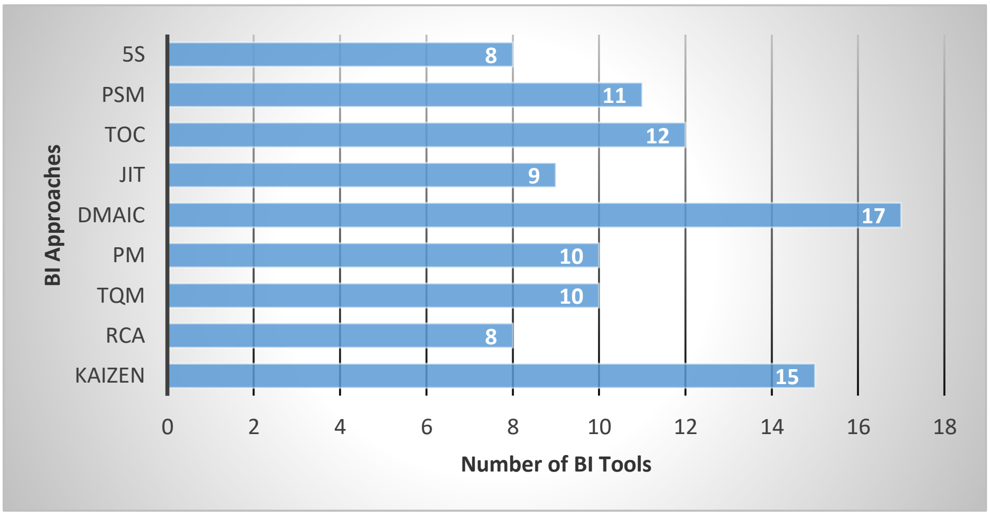

Figure 1. Business Improvement Technique and Number of Tools

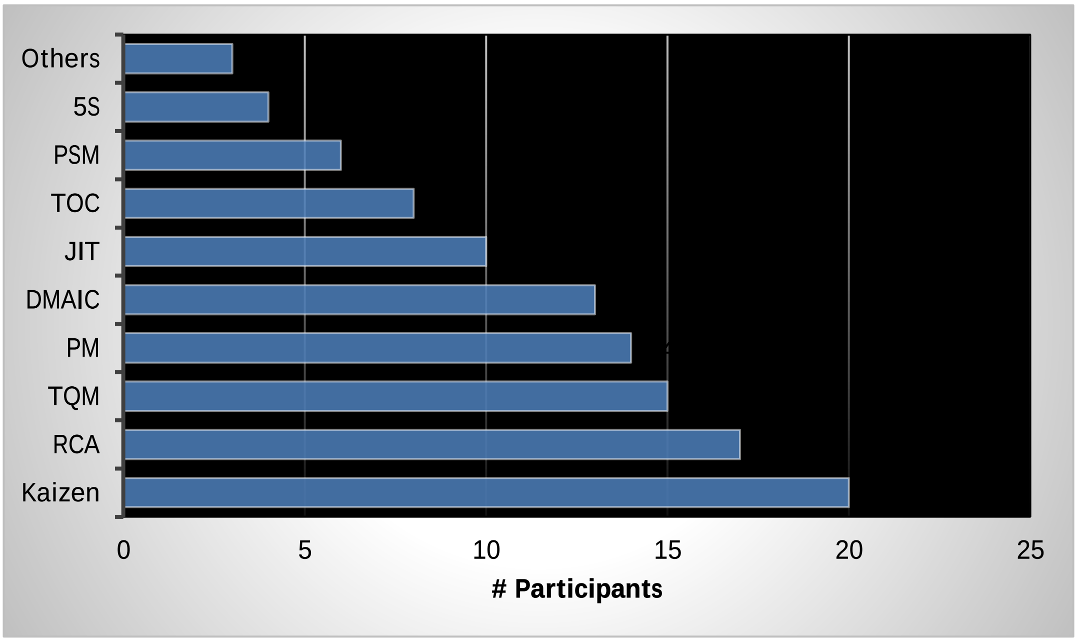

Figure 2. Business Improvement Techniques vs Number of Participants

The study found that there are almost nine business improvement techniques mostly used in the South African mining industry. Figure 2 illustrates the number of participants using a particular business improvement technique where 5S was the least used technique. Octavian and Claudiu [10] in their study discovered that Kaizen is the business improvement technique that considers concepts, systems, and tools within the broader leadership driven by people's culture and customer satisfaction. The study discovered that Kaizen was the most used business improvement technique whereby almost 20 participants were found to be applying it to root out operational bottlenecks found in their operational processes. This was further illustrated in Figure 3 whereby Kaizen did constitute 18% of the total techniques within the South African mining industry and 5S as the least used technique applied by less than 5 participants did constitute only 4%. The study discovered that, though 5S was not applied by many as a technique on its own, it was mostly applied as a tool within all these techniques. It was found that before the application of any improvement technique as an approach, 5S was always the first tool to be applied with the sole purpose of making the environment clean and everything placed where they are supposed to be and visible.

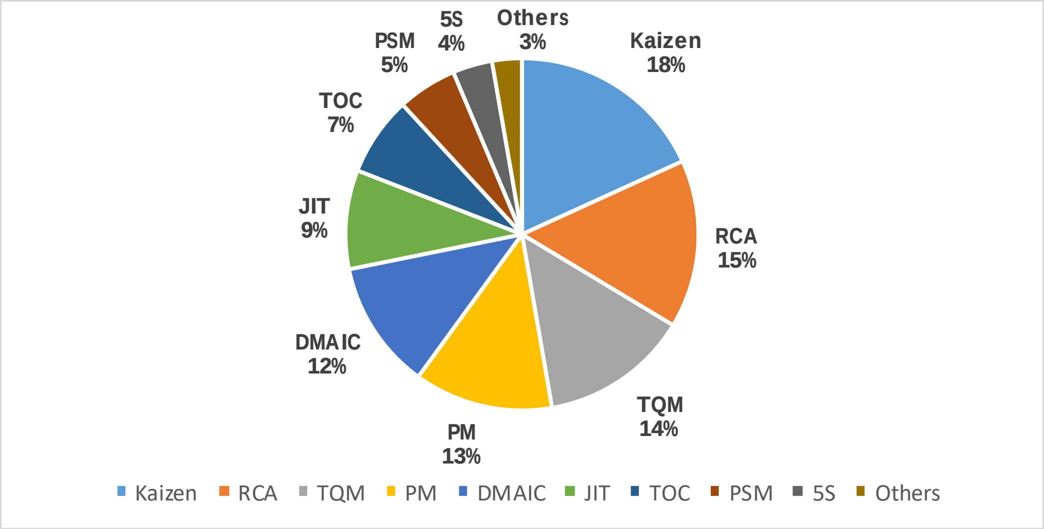

Figure 3. Percentages of Business Improvement Techniques

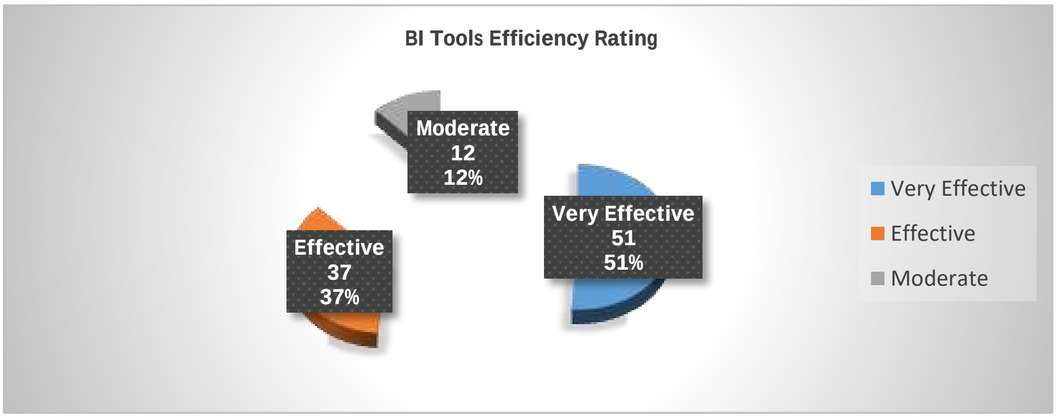

Figure 4. Efficiency of Business Improvement Tools

4.1 Summary of the findings

The study highlighted that there are many business improvement techniques deployed in various collieries in South Africa whereby Kaizen was found to be the most frequently used business improvement approach together with Root Cause Analysis as well as Total Quality Management. Other business improvement approaches that are used include Process Mapping, DMAIC, and Just-In-Time. As illustrated in Figure 2, other participants still believe in the traditional process of solving problems in their respective collieries. The standard traditional problem-solving steps include (1) Problem identification (2) Analyses of the identified problem (3) Exploration of potential solutions (4) Selection of the right solution and (5) Implementation of the selected solutions. Furthermore, in Figure 1, the study outlined business improvement techniques with their respective tools used. Of the outlined techniques in Figure 1 and 3 respectively, DMAIC was found to be an approach with more tools in a range of 17 followed by Kaizen with 15 tools, TQM and PM were found to be in a range of 10 tools each, JIT had 9 tools and RCA had 8 tools. Among all these business improvement tools, 51% were found to be very effective, with 37% being effective and 12% were moderate as suggested by the study.

5 CONCLUSION

Based on the information provided by the study, it was discovered that there are more advanced business improvement techniques within the South African mining sector equipped with well-defined business improvement tools. It is recommended that if these techniques are applied well with management support as well as clearly defined change management, the productivity of many collieries will indeed be enhanced as all operational deficiencies would be rooted out. It is further recommended that the company should take into consideration its culture diversity, available resources, and training capability when selecting which business improvement techniques and tools to entrench the culture of business improvement. Further studies should be done to determine the difference between tools and techniques and why other techniques become tools of other techniques.

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OPTIMIZING QUALITY IN THE AUTOMOTIVE SECTOR: IDENTIFYING IMPROVEMENT STRATEGIES FOR REDUCING DENTS

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ABSTRACT

The automotive industry is an exceedingly competitive sector where maintaining the quality of the products assembled is crucial. An automotive assembly plant in South Africa has been encountering a high number of dents on the front and rear doors of SUV cars, leading to costly and time-consuming rework and discarding. This study was conducted to analyse and identify improvement strategies that would reduce daily dent occurrences on the front and rear doors of SUV cars. A qualitative approach involving observations through Gemba walks and document analysis using a quality leadership system was used to collect data. Data indicates that major contributors of dents were in-house logistics (loading & unloading of doors) and stillage design of door panels. This study recommended lean manufacturing in the form of a continuous improvement strategy that offers a systematic approach to addressing root causes and promoting continuous improvement in terms of automation, and enhancing assembly processes to mitigate defects.

Keywords: Process Improvement, Quality Excellence, Defects

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1 INTRODUCTION

Automotive industries operate under the philosophy of "quality" [1]. According to Braun [2], quality significantly influences consumers, and decision-making processes and is regarded as a crucial determinant of both a product's and a company's success. Recent estimates indicate that the automotive sector consistently contributes over 7% to South Africa's annual gross domestic product (GDP), highlighting the industry's significant importance to the country's economy [3]. Therefore, it is crucial to maintain high quality in the automotive industry to continue contributing significantly to the country's GDP. However, the methods for improving quality products are complicated, and as the world evolves, some of these methods become more advanced and costly. The automotive assembly industry has implemented concurrent engineering, continuous improvement, and statistical process control, but the fundamental difficulty is determining which quality approaches are most likely to improve quality and overall corporate value [4].

The automotive assembly plant aims to maintain quality, focusing on achieving zero defects in production processes. However, despite this priority, an unexpected increase in dent defects on the body exterior doors of SUV cars has been detected. In this study, dent refers to an area of a door panel that becomes hollow or protrudes outward due to pressure. A significant number of dents can impede production efficiency by increasing costs and prolonging the time required for rework. A study done by Mushavhanamadi [5], showed that a decrease in the cost of waste will result in a marginally improved profit. In this case, rework refers to repairing the SUV doors into products that meet the quality standards of the automotive assembly plant. These challenges have served as a driving force for this study to investigate the underlying factors contributing to dents, as well as explore effective process improvement strategies aimed at minimizing the occurrence of dents on the front and rear door panels within the automotive assembly plant.

2 LITERATURE REVIEW

2.1 Enhancing Product Quality through Process Improvement.

Process improvement strategies can be implemented to improve the quality of products within automotive industries. The growing number of market rivals encourages businesses to constantly improve their processes and implement novel strategies for increasing their product variety and offering more and more tailored items [6]. The process of identifying, analysing, and enhancing current business processes to increase performance, achieve best practice standards, or simply improve quality and the user experience for customers and end users is known as process improvement [7]. According to Gunasekaran [8], enhancing quality not only leads to cost reduction but also enhances productivity by eliminating the need for rework and unnecessary inspections.

2.2 Quality Management Strategies in the Automotive Industry.

Six Sigma, a part of lean manufacturing, uses modern statistical methods and specific management strategies to identify and correct process flaws, aiming to improve process output quality and foster healthier corporate environments [9]. According to Rahmanasari [10], errors may be decreased, and waste can be removed by effectively combining the Lean Six Sigma framework with DMAIC tools and methods. This will lessen the amount of non-value-added jobs performed on the production line. To reduce the number of door panel dents occurring daily, lean manufacturing can be utilized to streamline the handling procedure, eliminate unnecessary processes, and lower the probability of errors occurring during the assembly of SUV car doors. An automotive company in Indonesia engaged in the exporting and manufacturing of vehicles and parts, experienced a high number of dents on the cylinder head components it produces [10]. The company highly prioritizes zero defects in its production processes. Wicaksono [10] further emphasizes that the automotive company applied Toyota Business Practices (TBP), a method used to implement kaizen in daily work developed by Toyota [10]. The utilization of Toyota Business Practices led to improvements such as enhancing the positioning of the shutter table, implementing a slipper stand, and refining the design of the slipper stopper within the manufacturing plant. These enhancements resulted in a reduction of 4.35% in the average occurrence of dent defects per unit.

A comprehensive management approach called total quality management (TQM) aims to improve process efficiency and customer satisfaction [11]. By promoting a motivated workforce, managerial dedication, open communication, and complete participation, Total Quality Management (TQM) enhances customer, employee, and operational effectiveness [13]. The research by Ngubane [12] emphasizes the significance of TQM as an essential tool in the automotive industry in Durban. This research also views TQM as one of the strategies that can also be employed to improve process efficiency of the SUV assembly process.

Implementation of process improvement strategies requires the automotive assembly plant to acknowledge that numerous factors can contribute to a specific outcome. The Canadian root cause analysis framework emphasizes that conducting a root cause analysis is a critical aspect of comprehending the causes behind defects [13]. Joshi [13] successfully used a Pareto chart and cause and effect diagram to identify and classify the reasons that were responsible for defective casting production. A Pareto chart is generated through Pareto analysis, which is commonly referred to as the 80/20 rule. Many companies now use both Pareto charts and cause-and-effect diagrams as tools to improve the quality of their products. However, aside from the impact of dents on the appearance of SUV products, a significant number of dents can impede production efficiency by increasing cost and prolonging the time required for rework. Lower waste expenditures will lead to a small increase in profitability [5]. Rework in this context refers to fixing the doors to satisfy the organization's quality requirements. The investigation into the underlying causes of dents and the brainstorming of efficient process optimization techniques to reduce the likelihood of dents on panels used for front and rear doors have been spurred by these difficulties of rework and waste.

2.3 Aim

The aim of this research is to investigate and identify the root causes of dents and propose process improvement strategies to reduce the dents defects encountered on front and rear door panels of SUV cars.

2.4 Research questions

- What are the working practices causing dent defects on front and rear SUV door panels?
- What process improvement strategies will best reduce the occurrences of dents on the SUV door panels?

3 METHODOLOGY

3.1 Research Approach and Population

The research employed a qualitative methodology, using document analysis and observations to identify practices causing more than 25 dents defects that are being detected daily in an automotive assembly plant in South Africa. Further, the research evaluated process improvement strategies to reduce the occurrence of dent defects on SUV doors. The study was conducted within the automotive assembly plant with five trained operators. Observations were conducted to observe trained operators working on assembling the SUV doors. Practices such as handling, packing, and transportation of door panels were observed to comprehend the causes of dent defects on SUV car doors. The quality leadership system's quality report was analysed to determine the number of dent defects encountered in different shop floor departments: the body shop, the paint shop final line, and shipping.

3.2 Sampling Techniques

A purposive sampling method was used. Purposive sampling is a type of non-probability sampling where the researcher deliberately selects individuals for inclusion in the sample based on specific criteria [14]. Purposive sampling was conducted to focus on the assembly department, which provided rapid answers to the research questions, given the time constraints. The study specifically focused on a department with numerous dent defects on the front and rear car doors within the automotive assembly plant. The assembly line consists of trainees (beginners who still need extra support and training to develop their skills and knowledge), and trained operators (team members who have earned their reputation through years of experience and can work independently). Trained operators were selected to reflect the actual results of the study.

3.3 Data collection

Working alongside the industrial engineering manager from the automotive assembly plant, the researcher spent 22 working days analysing the company's daily quality control reporting an order to identify daily detected dents defects. The research shows that the defect rates were consistent at all three production shifts which means that the problem was not confined to a specific time of day. For a duration of another 22 working days, the researcher, industrial engineering manager, and trained operators spent time observing the body shop department's working practices, which included handling, packing, and transportation processes of door panels. The observations provided this study with valuable insights into potential causes of dents on SUV door panels.

3.4 Data analysis

The quality leadership system was used to analyse the daily-detected number of dents from various assembly departments and was reviewed to understand from which departments dents are most concentrated. The root-cause analysis was also used to evaluate the data collected through observations and daily quality reports in the assembly plant.

3.5 Ethical Considerations

The operations manager granted permission to conduct the study within the automotive assembly plant. The industrial engineering manager further granted limited access to the assembly plant's quality report. When conducting observations, participants were made aware of the purpose of the study and the researcher ensured that they received required personal protective equipment.

4 FINDINGS DISCUSSIONS

The study aimed to investigate the causes and dents on SUV door panels and identify process improvement strategies to reduce dents within the automotive assembly plant, focusing on the exteriors of SUV car door panels. Through observations and document analysis departments including the body shop, paint shop, final line, and shipping were investigated.

4.1 Findings from document analysis using quality leadership system at the assembly section.

Figure 1 illustrates the daily detection of dent defects across all three production shifts and various assembly line departments: the body shop, paint shop, final line, and shipping departments. Doors are inspected for quality before being sent to the assembly line, with particular attention given to dent issues in the same area of the door panel to ensure they are dent-free. The analysis of daily records revealed varying contributions to dent defects across departments. The body shop reported the highest average of 41 dents defects per day, followed by the paint shop with three, while the final line and shipping departments had significantly fewer defects. Given the automotive assembly plant's acceptable limit of 25 or fewer defects per day, prioritizing improvement practices in the body shop is imperative.

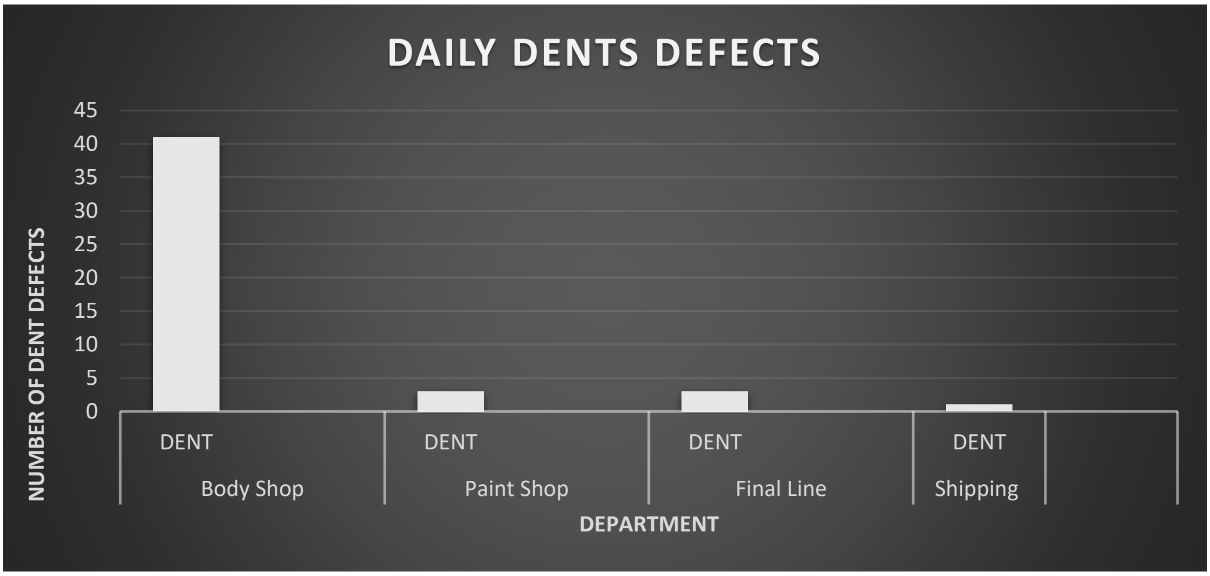

Figure 1: Daily number of dents from various departments.

4.2 Findings from observations conducted at the Body department.

Further investigation was conducted through observations in the body shop department to determine the root causes of dent defects in the SUV car doors. Findings revealed key factors that contribute to dent defects; the key factors include:

- Equipment issues with the door manipulator, which is designed to load and unload doors manually controlled by an operator. The manipulator collides with the doors packed on the stillage when unloading which results in the door being dented.
- Difficulties in material handling due to the door stillage design. The proximity of the doors within the stillage makes it challenging the door manipulator to access them effectively. This difficulty can lead to unintended impacts and dents on the doors.
- Method-related problems during the hooking process. The method of unloading involves positioning the back of the door manipulator's tip against the doors during the hooking process. The use of a steel tip on the manipulator can cause dents when it strikes the doors, as steel is a hard material.
- Transportation issue arises from the tight arrangement and movement of doors. When the door stillage is transported to the body shop, the doors being so close together results in shaking during the journey, which leads to collisions and dents.

4.3 Identified process improvement strategies to reduce the dent defects on SUV doors.

Aligned with the Kaizen philosophy of continuous improvement, the adoption of automation, specifically the Electrical Monorail System (EMS) Conveyor, emerged as a potential solution. The automotive industry is looking into new ways to make vehicles safer and more efficient. One idea is to use electric monorail systems (EMS) to stop door dents, which often happen when parking or opening doors. Hot stamping plays a key role in making door impact beams, but the tough materials used can break in crashes [15]. By using electric monorail systems hot stamping, laser heat treatment, and new materials, the car industry can make big steps to reduce door dents and boost vehicle safety [15]. The EMS conveyor offers several benefits to address the identified problem. Firstly, it streamlines material handling processes, reducing manual labour and potential damage to doors. Secondly, by automating transportation, the EMS conveyor minimized the risk of collisions and dents during transit, thereby improving product quality. Literature supports the effectiveness of automation in improving manufacturing processes. For instance, a study by Mares [11] demonstrated that automation systems, such as conveyors, significantly reduce production lead times and improve overall productivity in automotive assembly plants. Table 1 presents a discussion on the proposed recommendation to introduce automation within the automotive assembly plant to reduce dents in the automotive sector.

Table 1: Discussion of proposed recommendations.

	Potential Solutions	Discussion of proposed recommendations	Reference
1	Impact of Automation on Quality Improvement	Literature indicates that the use of automation improves manufacturing processes. For example, a study found that automation systems such as conveyors could dramatically reduce manufacturing lead times and enhance overall productivity in the automotive assembly plants.	[16]
2	Cost-Benefit Analysis	An improvement in dent defects helps to improve product quality while reducing production costs by making less waste and rework necessary. Reduction in waste cost is reported to slightly increase the profit	[5]
3	Lean Manufacturing and Continuous Improvement	The kaizen philosophy is far less reactive than Total Quality Management - the former is about getting people to think iteratively and incrementally about quality, the ‘management’ is in self-management, and they are encouraged to make small improvements frequently to processes and reduce defects.	[10]
4	Employee Training and Involvement	Employee involvement in noticing and addressing issues related to quality paves the way for the establishment of a culture of continuous improvement and accountability.	[17]
5	Monitoring and Evaluation	Continuous monitoring and evaluation of the implemented solutions are crucial to ensure their effectiveness. Regular audits, performance metrics, and feedback mechanisms should be established to track improvements and identify any new issues that may arise.	[18]

5 CONCLUSION

Addressing the challenges of dents on SUV cars' body exteriors in the automotive industry demands a multifaceted approach rooted in continuous improvement and innovation. Through a qualitative analysis of observations and document analysis, Six Sigma developed a systematic strategy for identifying and eliminating root causes of defects that were transportation, loading and unloading, and storage processes.

This study recommends that Implementing Lean Manufacturing such as automation technology and continuous improvement (kaizen) practices can substantially decrease dent defects and elevate overall product quality. By tackling the root causes of defects and promoting a culture of proactive issue resolution, automotive companies can minimize risks, cut down on expenses, and attain sustained excellence in quality and operational efficiency.

In conclusion, these approaches offer automotive companies a global market advantage whilst adding to the body of knowledge readily available in the automotive space, additionally assisting automotive companies that face similar challenges. Future Research could incorporate adopting AI and other 4IR Technologies to monitor and improve quality management. Comparison with other Solutions by evaluating the cost-benefit analysis of altering the door manipulator, improving the stillage, or applying other lean manufacturing strategies. This helps to determine how to reduce the incidence of dent problems where they have been identified to be frequent

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PARAMETRIC STUDY OF THE QUEUING MODEL IN TELEMEDICINE

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ABSTRACT

Telemedicine applications provide patients with convenient and accessible remote healthcare, but prolonged wait times and server congestion can detract from both patient satisfaction and system efficiency. This study utilizes the Revoledu online queuing system tool to systematically analyse the factors influencing telemedicine performance by varying individual parameters. This interactive calculator allows users to enter parameters such as arrival rate, service rate, to calculate various performance metrics for queuing models. The results indicate that increasing the number of servers or service rates significantly reduces patient wait times, although the benefits plateau after a certain threshold. Conversely, higher patient arrival rates lead to longer wait times and increased server congestion, reducing the likelihood of idle servers. These findings underscore the importance of effectively managing server capacity, service rates, and patient load. By highlighting the relevance of queuing theory to telemedicine, this study contributes to the expanding research focused on enhancing the efficiency and effectiveness of telemedicine services.

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1 INTRODUCTION

In recent years, the use of internet-based services like telemedicine has surged dramatically[1]. The COVID-19 pandemic has profoundly impacted global healthcare, accelerating the adoption of telemedicine and transforming the delivery of medical services [2]. Telemedicine encompasses technologies that enable real-time communication between patients and healthcare professionals, allowing for the provision of remote therapeutic services through tools like video conferencing and patient monitoring [3]. This technology is particularly beneficial for patients in remote areas, far from hospitals, offering them access to essential healthcare services from a distance.

Telemedicine apps offer patients a convenient and accessible way to receive medical care remotely [4]. However, long wait times and congested servers can negatively impact the patient experience and diminish the effectiveness of the telemedicine system. While telemedicine has become an essential component of modern healthcare, allowing patients to consult with healthcare providers from the comfort of their homes, it still faces challenges similar to those in physical consultations—such as long queues—which can affect patient satisfaction. Telemedicine applications have the potential to revolutionize patient convenience and remote consultations in healthcare [5]. However, excessive wait times and server overload can significantly diminish their effectiveness and frustrate patients.

The purpose of this study is to apply queuing theory to analyse the performance of a telemedicine app, identifying key variables that influence wait times, server utilization, and, ultimately, the patient experience. The study provides a comprehensive understanding of the interactions between queuing system characteristics and the telemedicine application. This knowledge will then be used to develop strategies for improving app performance and ensuring efficient patient care delivery. This paper has the following objectives:

1. Assess the impact of server capacity: Evaluate how increasing the number of servers in the telemedicine app influences patient wait times and queue lengths.
2. Analyse the effect of service rates: Investigate how changes in service rates—the speed at which patients are processed—affect wait times and server utilization across the system.
3. Examine the impact of arrival rates: Determine how variations in the number of patients entering the system within a given time frame influence wait times, server congestion, and queue lengths.
4. Explore the relationship between server utilization and patient load: Analyse how patient arrival rates affect the likelihood of finding an idle server and the subsequent impact on the patient experience.

2 LITERATURE REVIEW

Telehealth, or telemedicine, refers to the use of ICT for long-distance healthcare. While the terms are often used interchangeably, they have distinct meanings. Telehealth encompasses public health education and healthcare services across various professions. In contrast, telemedicine specifically pertains to medical services provided by clinicians, including the use of technology for clinical diagnosis and monitoring [6]. Telemedicine, utilizing information and communication technology, enables doctors to provide remote care and share patient data across different locations. Its primary benefits include facilitating diagnosis and treatment for patients in remote and rural areas [7]. Telemedicine services typically involve dynamic and unpredictable patient arrival rates, varying service times, and limited system capacity—factors that closely align with the parameters of queuing theory.

Nonetheless, the phrase "telemedicine" was first used in the 1970s, and the ensuing decades saw a number of important advancements. The development of modern telemedicine has been greatly influenced by the usage of video conferencing and information technology innovations [6]. Over the past few decades, telemedicine has grown remarkably, propelled by breakthroughs in technology, shifting healthcare demands, and growing acceptance of virtual care. The widespread use of cell phones and the development of the internet have expedited the uptake of telemedicine. Global telemedicine usage surged as a result of the COVID-19 pandemic and the necessity for distant healthcare solutions. Ten years ago, only 35% of hospitals in the United States used telehealth to connect doctors and patients remotely. Today, that number has risen to 76%. The COVID-19 pandemic has further highlighted the importance of telehealth, driving increased interest and usage of technology for both receiving and providing healthcare due to concerns about virus transmission during in-person visits [8].

A survey found that nearly 75% of Americans reported an increased interest in virtual treatment due to the pandemic. Additionally, within the first three months of the pandemic, 25% of Americans over 50 had a virtual health care visit, a significant increase from just 4% in the year prior [8]. The pandemic has significantly impacted physicians and specialists in South Africa, with consultation rates dropping from 60% to 90%, raising concerns about their financial stability. Telehealth has emerged as a solution, offering three primary modes of delivery [8]:

- Synchronous: Real-time communication between the physician and patient via phone or computer.
- Asynchronous: Sharing information such as pictures or messages with the doctor for review at a later time.
- Remote Patient Monitoring: Collecting and transmitting health measurements, such as blood pressure or weight, from a patient to a healthcare professional.

There are several benefits to using technology to administer healthcare, such as financial savings, ease of use, the capacity to treat patients with limited mobility or those living in remote locations without access to a local clinic or doctor, reduce patients no show, increased access to health care, and remote monitoring [9], [10], [11]. These factors have significantly increased telehealth usage over the past decade. Additionally, the pandemic has highlighted the advantages of telemedicine, which provides a more cost-effective virtual consultation option compared to in-person visits [9]. Telemedicine appointments are substantially cheaper than in-person visits. For example, an emergency room visit typically costs between R1200 and R2000 per day, while an in-person doctor's visit ranges from R350 to R400. In contrast, the average cost of a telemedicine appointment is approximately R200 per visit [9].

Queuing theory, also known as waiting line theory or queue theory, is the mathematical study of the structure, function, and congestion of waiting lines or queues [12]. This subfield of mathematics explores all aspects of line formation, including the operation and underlying causes. Queuing theory examines various elements, such as the number of customers, their arrival patterns, and the process of waiting. These "customers" can represent anything from cars and people to data packets or other entities [13]. A queuing scenario consists of two main components:

- A person or object making a service request—often referred to as the client, task, or request.
- The server—this person or object completes or delivers the services.

The complete system of standing in line is examined by queuing theory, which takes into account factors such as the average service completion time, number of servers, number of clients, capacity of the waiting space, and customer arrival rate. Discipline in queuing refers to the guidelines that the queue follows, such as first-in, first-out, prioritized, or serve-in-random-order policies theory [13].

Queuing theory was first introduced in the early 20th century by Danish mathematician and engineer Agner Krarup Erlang. He worked for the Copenhagen Telephone Exchange and wanted to analyse and optimize its operations. He sought to determine how many circuits were needed to provide an acceptable level of telephone service, for people not to be “on hold” (or in a telephone queue) for too long. He was also curious to find out how many telephone operators were needed to process a given volume of calls. The result of his mathematical research was published in 1920 as "Telephone Waiting Times," which included some of the earliest queuing models and laid the groundwork for later applications of queuing theory [14].

To categorize different types of queuing systems, or nodes, queuing theory employs Kendall's notation, represented as A/S/c/K/N/D [15]:

- A: The arrival process.
- S: The service time distribution.
- c: The number of servers.
- K: The queue's capacity (if infinite, it is denoted by ∞).
- N: The number of potential customers (if infinite, it is denoted by ∞).
- D: The queuing discipline (assumed to be first-in, first-out if omitted).

For example, consider an ATM, which can serve:

- One customer at a time,
- With a randomly distributed arrival process and service time,
- In a first-in, first-out order,
- With infinite queue capacity and potential customers.

This system is classified as an M/M/1 queuing model in queuing theory, where "M" stands for Markovian, indicating a stochastic process used to describe randomness. Queuing theory calculators often require selecting a queuing model using Kendall's notation before computing the necessary inputs.

Standing in line is a common experience, serving several essential functions as a process. Queues are both fair and necessary for managing consumer flow when resources are limited. However, if a queuing system isn't designed to handle overcapacity, it can lead to negative outcomes. For example, a website without a queuing system or mechanisms to manage incoming traffic may slow down or crash when overwhelmed by too many users.

Queuing theory is significant because it provides methods for optimizing queues and helps describe key characteristics, such as average wait time. From an economic standpoint, queuing theory in operations research is crucial for designing efficient and cost-effective workflow systems. Due to the plethora of circumstances involving queues, queuing theory is highly versatile and powerful. Among the many applications of queueing theory are the following: Transportation, Telecommunications, Finance, Logistics, Emergency services, Computing, industrial design, Project administration, Operational analysis, and Online queuing.

An online queue system effectively manages spikes in website and app traffic by redirecting users to a virtual queue. This approach ensures that the site or app remains operational around the clock, regardless of demand, thereby preventing failures across the entire user experience. For hospitals, a virtual queuing system allows for the maintenance of online systems and patient records while capturing critical online activity during peak times [16]. The application of queuing theory is instrumental in identifying and resolving process bottlenecks, whether they involve people, objects, or information awaiting service. Such delays can be inconvenient, inefficient, and detrimental to business, particularly when customers are involved. By leveraging queuing theory, organizations can analyse current processes and identify more efficient alternatives [13].

3 METHODOLOGY

This study employs a quantitative approach, selecting the M/M/s/N queuing methodology based on the specific features of the telemedicine application and infrastructure under study. The M/M/s/N queuing model is commonly used to analyse and optimize systems where customers arrive randomly and require service, such as telecommunications networks, computer systems, and customer service centres. This model allows for the quantification of key performance metrics, including the average number of customers in the system, the average time each customer spends in the system, and server utilization [17].

The Revoledu online queuing system computation tool was utilized to generate and collect data on queuing system behaviour. Revoledu provides interactive calculators that allow users to input parameters such as arrival rate, service rate, and server count to calculate various performance metrics for different queuing models (Figure 1). This hands-on approach enables users to explore how different variables impact system performance. Some tools also include simulations that visually depict how queues develop and operate over time, offering a dynamic view of queuing systems in real-world scenarios.

In this study, Revoledu was used to simulate a queuing system, adopting a scenario-based approach where all variables were held constant except for one, which was systematically varied. This method allowed us to evaluate the effect of each parameter on system performance. The initial data values were based on an existing telemedicine model. After running 20 different scenarios, the results were compiled into a comprehensive table and analysed graphically to identify trends. The resulting graphs illustrate the relationships between the adjusted parameter (independent variable) and the queuing system's performance metrics (dependent variables).

The proposed queuing system consists of the following parameters [17], [18]:

Inputs parameters

- **The arrival rate** is the number of customers arriving at the system per unit time. In our study the arrival rate will be equal to the number of patients arriving at the system.
- **The service rate** is the number of customers (patients) a server can serve per unit time.
- **The capacity** of the system is the total number of customers the system can hold.
- **The number of servers** is the number of servers available to process customer requests. In this study, the number of servers represents the number of doctors or physicians available on the platform.

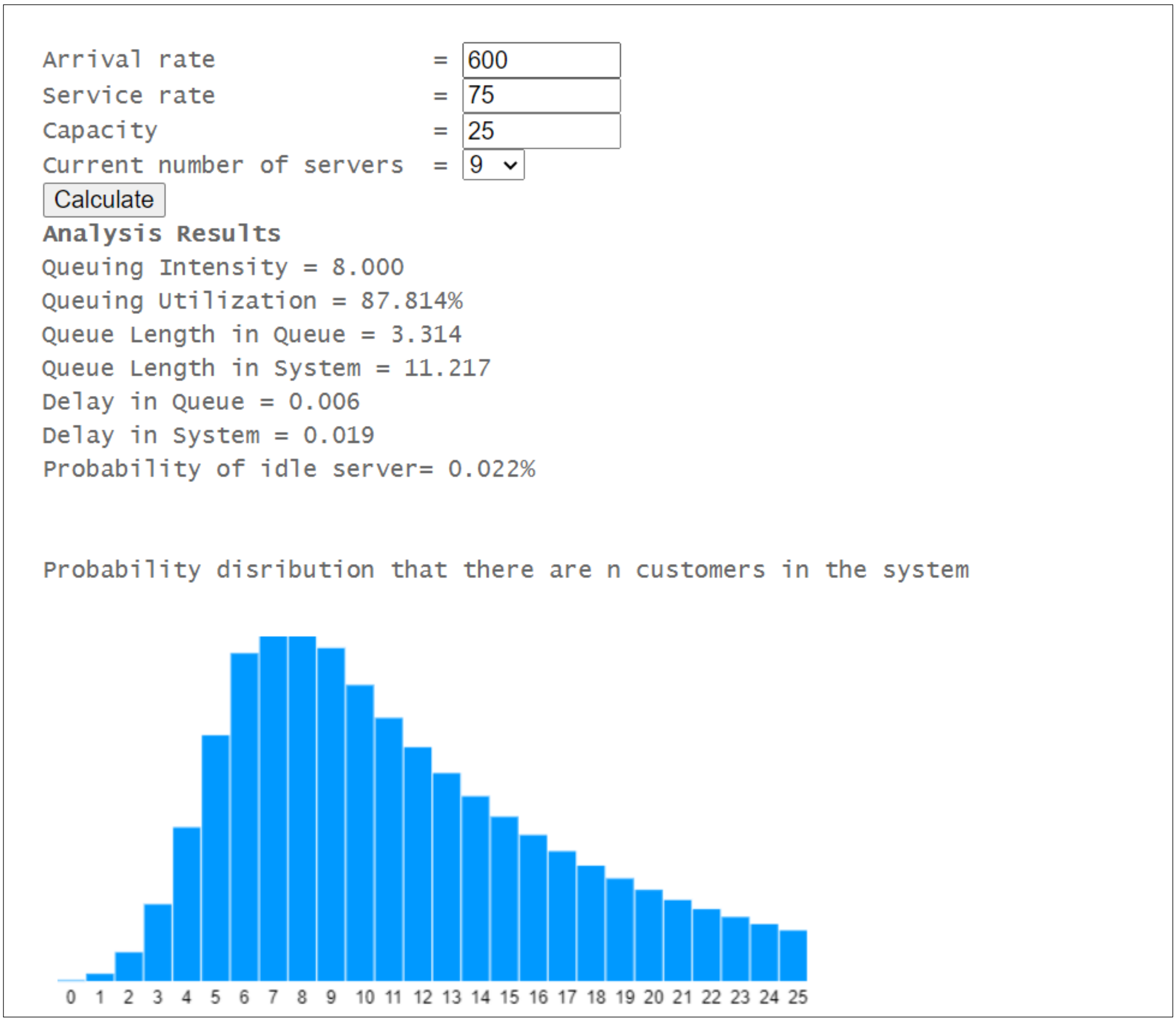
Outputs parameters

- **Queue intensity**: This metric reflects the average number of customers in the queue waiting to be served by a server. It essentially represents the workload on the queue. Higher queuing intensity signifies a longer queue and more customers waiting.
- **Queue utilization**: This metric indicates how busy the servers are on average. A value of 100% signifies all servers are occupied, while a value below 100% indicates some servers are idle.
- **Queue length in queue**: which is the number of customers waiting in the queue before being served by a server.
- ***Queue length in system:*** which is the total number of customers in the system, including those waiting in the queue and those being served by servers.
- **Delay in queue**: which signifies the average amount of time a customer spends waiting in the queue before being served by a server.
- **Delay in system**: which encompasses the delay in queue and the service time at the server.

- **Probability of idle server**: It represents the probability that no customers are in the system, meaning all servers are idle.

This study focuses on creating multiple scenarios where each parameter was adjusted within a predetermined range. The various range can be summarized as follows:

- Arrival rate: 600 to 1000.
- Service rate: 100 to 200.
- Capacity: 35 to 75
- Number of servers: 11 to 19.



Arrival rate = 600
Service rate = 75
Capacity = 25
Current number of servers = 9

Analysis Results
Queuing Intensity = 8.000
Queuing Utilization = 87.814%
Queue Length in Queue = 3.314
Queue Length in System = 11.217
Delay in Queue = 0.006
Delay in System = 0.019
Probability of idle server= 0.022%

Probability disribution that there are n customers in the system

Figure 1: Revoledu's screenshot

This paper considers a M/M/s/N queuing model because it offers a more realistic representation by limiting the system's capacity to N. However, it should be used with caution, as the capacity here refers to a strict cutoff in the number of customers, not the physical size of the waiting area. In this model, if a customer arrives when the queue has reached its maximum size, the system must reject the customer, resulting in a lost customer [18]. The arrival distribution of clients follows poison distribution, while the distribution of service time follows exponential distribution with the number of parallel servers and N queuing capacity.

The variables and the queuing equations considered in this study are given as follows [18]:

- Arrival rate (number of customers/unit time) λ
- Service rate (number of customers/unit time) μ.
- Number of servers s
- Capacity of the system, N
- Maximum queue size = N-s
- Utilization factor U (percentage of the time that all servers are busy)

$$U = \frac{L-L_q}{s} \tag{1}$$

- Probability that there are no customers in the system P_0

$$P_0=\left(1 + \sum_{i=1}^{s}\frac{\rho^i}{i!}\,\frac{\rho^s}{s!}\sum_{j=s+1}^{N}\left(\frac{\rho}{s}\right)^{j-s}\right)^{-1} \tag{2}$$

- Probability that there are n customers in the system P_n

$$P_n=\begin{cases}\frac{\rho^n}{n!}\,P_0 & if\ 1 \le n \le s\\ \frac{\rho^n}{s!s^{n-s}}\,P_0 & if\ s+1 \le n \le N\\ 0 & if\ n > N\end{cases} \tag{3}$$

- Average time a customer spends in waiting line waiting for service W_q

$$Wq = \frac{L_q}{\lambda(1-P_{n})} \tag{4}$$

- Average number of customers spends in the system W (in waiting line and being served),

$$W = W_q + \frac{1}{\mu} \tag{5}$$

- Average number of customers in waiting line for service L_q

$$Lq = \sum_{n}^{N}(n-s)P_n \tag{6}$$

- Average number of customers in the system L (in waiting line and being served)

$$L= \sum_{n=0}^{N} nP_n \tag{7}$$

4 RESULT AND FINDINGS

4.1 Analysis of outputs relationship with the increase of arrival rate

Figure 2 illustrates the queuing intensity and utilization for different arrival rates. The graph shows that both metrics increase as the arrival rate rises. This occurs because the system receives more patients than the doctors can manage, leading to longer waiting times and busier physicians. Figure 3 depicts the queue length and system length over time (arrival rate). Both queue length and system length increase significantly with higher arrival rates, indicating system overload at elevated arrival rates.

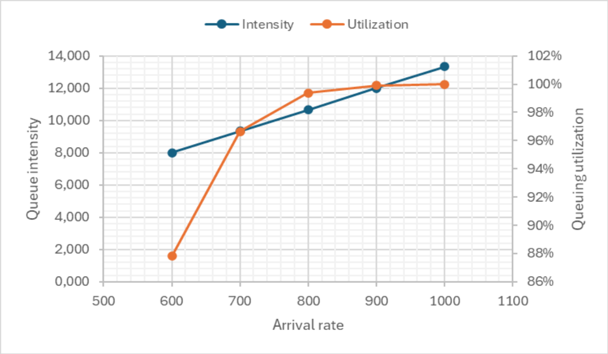


Figure 2: Queuing intensity and queuing utilization Vs Arrival rate

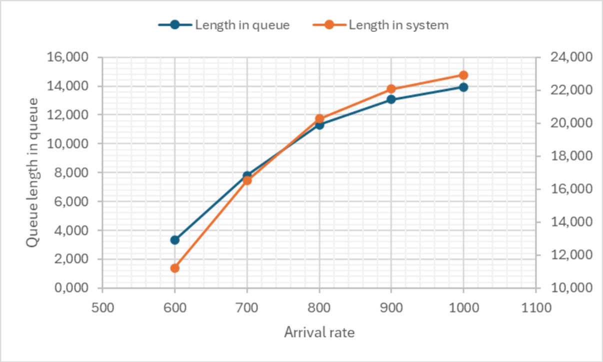


Figure 3: Queuing length and length in system Vs Arrival rate

Figure 4 shows the delay in queue and system experienced by patients as the arrival rate increases. Both delays lengthen as the arrival rate rises due to system overload, with more patients arriving than the physicians can manage, resulting in longer lines and wait times. This signifies a degradation in system performance due to congestion. Figure 5 illustrates the probability of an idle server, which gradually decreases as the arrival rate increases. This is because higher patient numbers mean physicians are constantly responding to arriving patients, reducing the likelihood of idle time.

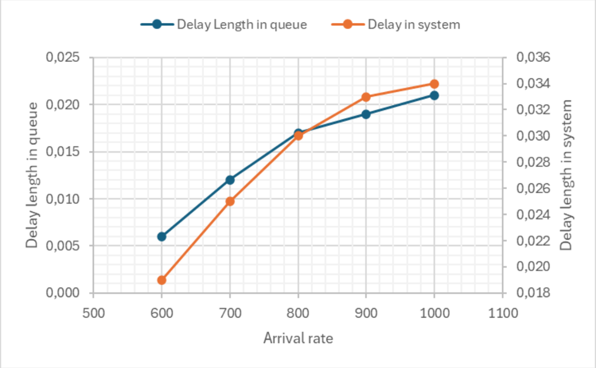


Figure 4: Delay length in queue and delay length in system Vs Arrival rate

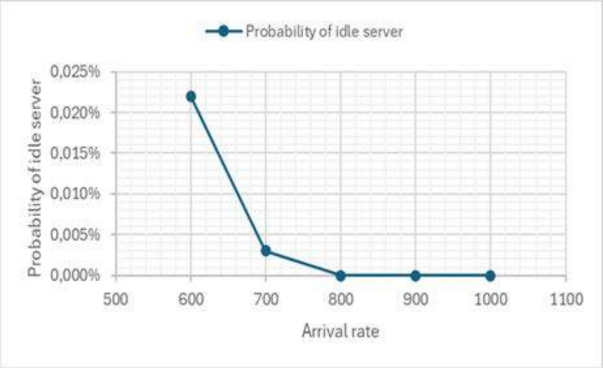


Figure 5: Probability of idle serve Vs Arrival rate

4.2 Analysis of outputs relationship with the increase of service rate

Figure 6 illustrates the impact of increasing the service rate on queuing intensity and utilization. As the service rate increases, both queuing intensity and utilization decrease. This is because higher service availability reduces the need for queuing in the system. Figure 7 shows the queue length and system length over time (service rate). Both lengths significantly decrease as the service rate rises. Physicians with a higher service rate can handle patients more quickly, reducing system congestion.

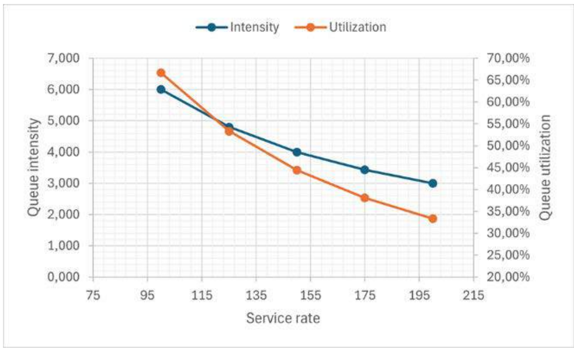


Figure 6: Queuing intensity and queuing utilization Vs service rate

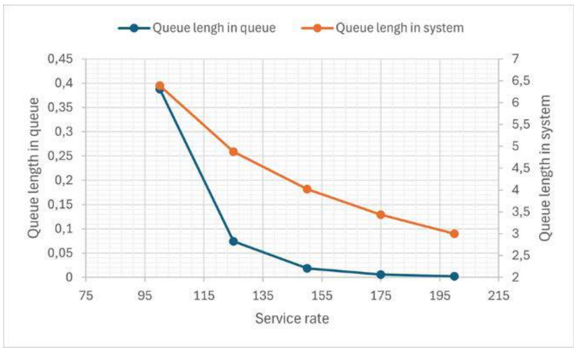


Figure 7: Queuing length and length in system Vs service rate

Figure 8 illustrates the delay in queue and system as the service rate increases. The graph shows that higher service rates result in reduced delays in both queue and system. Figure 9 shows the probability of idle physicians, which increases as the service rate rises.

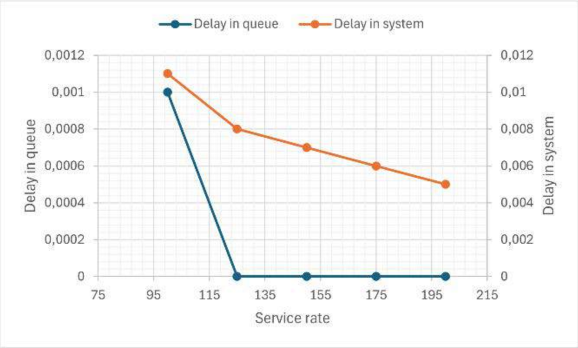


Figure 8: Delay length in queue and delay length in system Vs Arrival rate

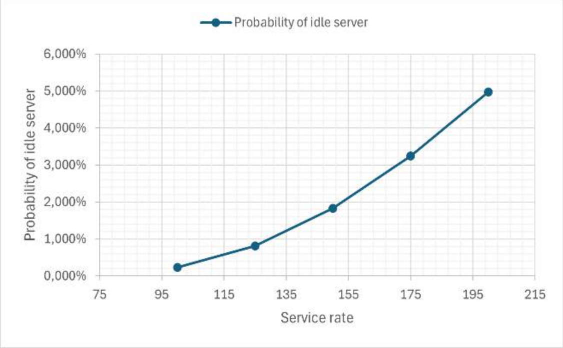


Figure 9: Probability of idle serve Vs service rate

4.3 Analysis of outputs relationship with the increase of capacity

Figure 10 demonstrates queuing intensity versus utilization. The graph shows that increasing capacity does not significantly impact queuing intensity, which remains constant. However, there is a slight increase in queuing utilization, stabilizing around a capacity of 50, indicating the system operates near optimal capacity. Figure 11 displays queue length in queue and system plotted against capacity. The graph reveals that as capacity increases, both queue lengths initially rise but stabilize beyond a capacity of 50. This indicates that expanding capacity improves queue management up to a certain threshold, beyond which additional capacity yields no further benefits. This insight is crucial for optimizing resource use and ensuring smooth system operation without unnecessary overcapacity.

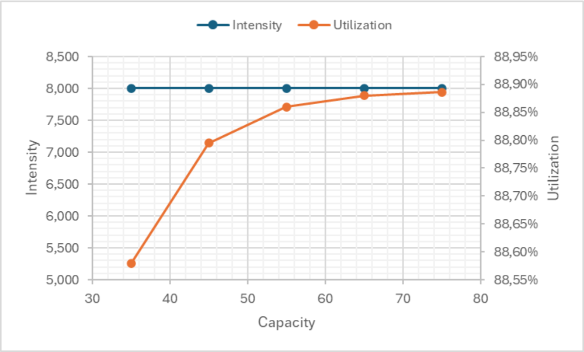


Figure 10: Queuing intensity and queuing utilization Vs capacity

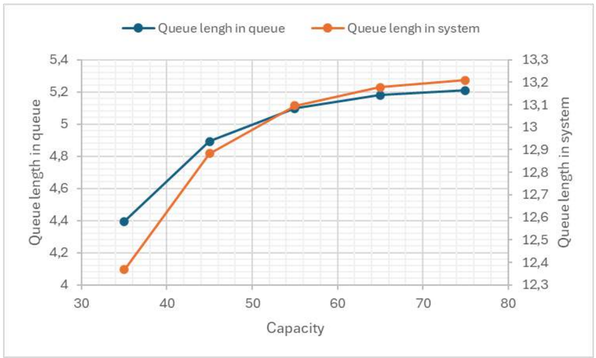


Figure 11: Queuing length and length in system Vs capacity

Figure 12 displays the delay in queue versus system delay, both plotted against capacity. The graph illustrates that increasing capacity beyond a certain threshold (around 50) results in higher queue and system delays, indicating an increased system load. However, beyond this limit, the delays level off, signifying that the system is operating at peak efficiency. Understanding these patterns is crucial for maximizing system efficiency and ensuring effective resource allocation without overburdening the system. Figure 13 illustrates the trend in the probability of idle physicians as capacity increases. The probability remains constant, indicating that increasing system capacity does not significantly impact physicians' idle time.

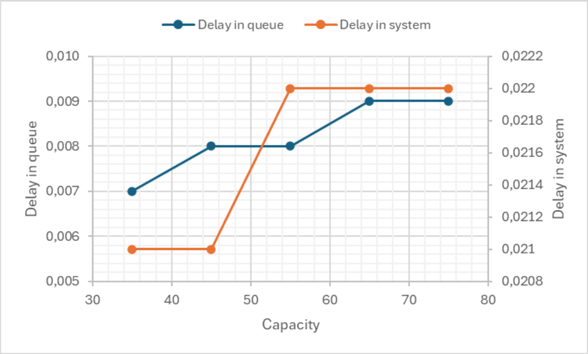


Figure 12: Delay length in queue and delay length in system Vs capacity

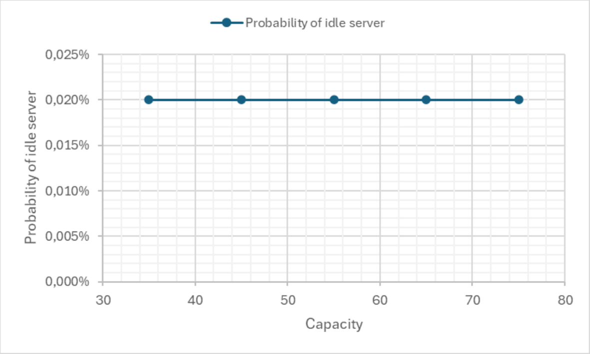


Figure 13: Probability of idle serve Vs capacity

4.4 Analysis of outputs relationship with the increase of number of servers or physicians

Figure 14 shows queue intensity versus utilization plotted against the number of servers. It is noticeable that queue intensity remains constant across different scenarios, while utilization decreases. This is because having more physicians available with a constant arrival rate reduces server utilization. Figure 15 illustrates queue length in queue versus system length plotted against the number of servers. The chart shows that increasing the number of servers significantly decreases patient queue length in the queue, as more physicians are available to serve them. However, there is only a slight decrease in system queue length since physicians cannot control the number of patients entering the system.

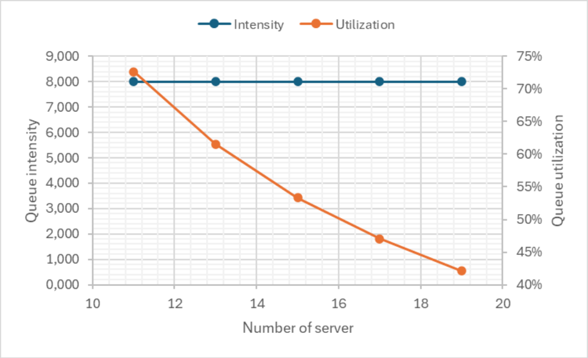


Figure 14: Queuing intensity and queuing utilization Vs number of server

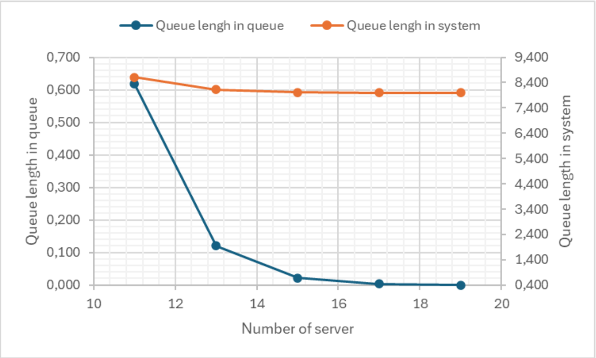


Figure 15: Queuing length and length in system Vs number of server

Figure 16, plotted against the number of servers, shows the difference between system and queue delays. It illustrates that increasing the server count reduces queue delay. More servers allow for a more optimal distribution of tasks, reducing bottlenecks and preventing any single server from being overloaded, thereby lowering queue latency. Figure 17 indicates a positive correlation between the number of servers and the likelihood of physicians being idle. As the number of servers increases, each physician's workload decreases at a constant arrival rate, increasing the likelihood of idle time.

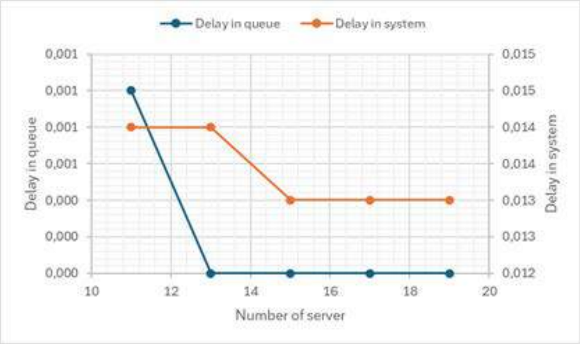


Figure 16: Delay length in queue and delay length in system Vs number of server

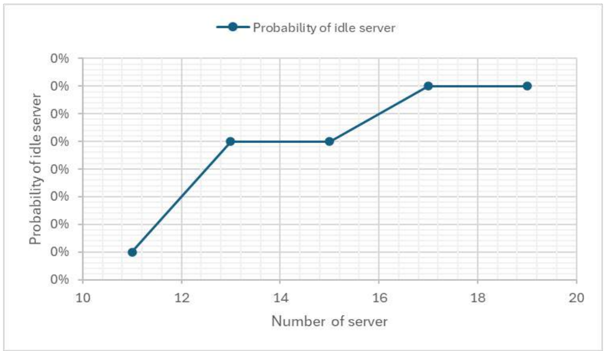


Figure 17: Probability of idle serve Vs capacity

5 CONCLUSION

This study investigated several queuing system factors to evaluate the functionality of a telemedicine application. The findings provide valuable insights into how these factors impact wait times, server utilization, and ultimately, the patient experience within the telemedicine system.

Impact of Server Capacity and Service Rates: The research shows that increasing the number of servers or the service rate (i.e., the speed at which servers process patients) can significantly reduce patient wait times and queue lengths [19]. This aligns with queuing theory, which suggests that increasing processing power or efficiency can alleviate congestion. However, the findings also indicate a point of diminishing returns. While initial increases in server capacity or service rate lead to notable reductions in wait times, subsequent increases yield progressively smaller benefits. This highlights the need to balance cost-effectiveness with resource allocation.

Arrival Rate and System Load: Conversely, an increase in the number of patients entering the system per unit of time has a negative impact. The study reveals that as the arrival rate rises, both queue lengths and wait times grow substantially. This leads to increased server congestion, potentially slowing down the system's ability to admit new patients. These findings highlight the importance of understanding patient demand trends and ensuring that the telemedicine app's capacity can accommodate anticipated patient loads. Research on telemedicine adoption suggests that these demands may fluctuate [20].

Patient Load and Server Utilization: The study also identified a significant relationship between arrival rate and server idleness. As the arrival rate increases, the likelihood of finding an idle server decreases sharply. This suggests that servers are constantly occupied under high patient load, which may delay the admission of new patients.

To sum up, this analysis highlights the significance of developing telemedicine apps holistically, taking into account the interactions between different queuing system factors. Developers can guarantee smooth operation and give patients a good user experience by closely monitoring and adjusting variables like the number of servers, service rates, and expected patient arrival rates. In order to optimize resource usage and wait times even further, future research could investigate the integration of machine learning or queue prediction algorithms to dynamically modify server allocation or service rates based on real-time patient demand. Furthermore, examining how patient demographics and appointment scheduling options affect arrival rates may yield insightful information for improving the functionality and design of telemedicine apps.

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A REVIEW OF POTENTIAL CHALLENGES AND OPPORTUNITIES OF BUSINESS PROCESS REENGINEERING IN THE ERA OF INDUSTRY 4.0

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ABSTRACT

Business Process Reengineering has become significant to organisations and businesses; this is because of its ability to relook at business processes to address technological advancements, especially in the era of Industry 4.0. This paper investigates the potential challenges and opportunities of Business Process Reengineering in the era of Industry 4.0. A systematic review approach is used to examine the technological, organisational and strategic challenges and opportunities presented by adopting BPR. The inclusion criteria for the literature include a timeframe of 2018-2024, ensuring a focus on current and relevant literature while identifying the existing gap. It is the researcher's view that future literature should expand on the strategic challenges and opportunities of BPR adoption in the era of Industry 4.0, as it was found that the adoption of BPR is impossible without IT.

Keywords: Business Process Reengineering, Industry 4.0, technological advancements, process improvements, IT framework.

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1 INTRODUCTION

Fourth Industrial Revolution, as some might say the 4IR, refers to the present era of highly advanced technology. [1] recently referred to 4IR as ‘’a new technological golden era’’. The South African government released a report of the presidential commission on the fourth Industrial Revolution in 2020, which mentioned that the 4IR era is where people are defining and reshaping the social, economic and political spheres using smart business models, connected and converged cyber, physical and biological systems [2].

Even though 4IR has always referred to technology, it is however more than just that. Over the recent years 4IR has developed as this massive force that is revamping industries, economies and societies. This era presents new ideas, possibilities, inventions and even new creations, and it is all about breaking all boundaries [3]. The fourth Industrial Revolution has the capability to elevate the global income levels and improve human life quality [4]. It is an opportunity to bring real-life changes to people; it can influence how leaders make decisions and can enforce those old policies to be amended. It is changing how everything is viewed and changing everyday life practices [5].

Industry 4.0 and 4IR both refer to technological advancements, and they are often used in the same way; there is, however, a bit of a difference between them. The term Industry 4.0 was first published in 2011 by the German government for their high-tech 2020 strategy, and the term has been used ever since [6]. Oztemel and Gursev wrote a paper on the ‘’Literature of Industry 4.0 and related technologies’’ where they stated that Industry 4.0 defines a method of taking information from ‘’machine dominant’’ production to digital production [7].[6] found and presented definitions of Industry 4.0 in the ‘’Challenges and benefits of Industry 4.0: an overview’’ paper according to 7 authors, in Table 1 below extracted from the paper.

Table 1 Definitions of Industry 4.0 [6]

Authors	Industry 4.0
Koch et al. (2014)	“The term Industry 4.0 stands for the fourth industrial revolution and is best understood as a new level of organization and control over the entire value chain of the life cycle of products, it is geared towards increasingly individualized customer requirements”
MacDougall (2014)	“Industry 4.0 or Smart industry refers to the technological evolution from embedded systems to cyber-physical systems. It connects embedded system production technologies and smart production processes to pave the way to a new technological age which will radically transform industry and production value chains and business models”
McKinsey Digital (2015)	“Industry 4.0 seen as a digitization of the manufacturing sector, with embedded sensors in virtually all product components and manufacturing equipment, ubiquitous cyber physical systems, and analysis of all relevant data”
Deloitte AG (2015)	“The term Industry 4.0 refers to a further development stage in the organization and management of the entire value chain process involved in manufacturing industry”
Geissbauer et al. (2016)	“Industry 4.0 - the fourth industrial revolution, focuses on the end-to-end digitization of all physical assets and integration into digital ecosystems with value chain partners”
Pfohl et al. (2015)	“Industry 4.0 is the sum of all disruptive innovations derived and implemented in a value chain to address the trends of digitalization, automization, transparency, mobility, modularization, network collaboration and socializing of products and processes”.

Authors	Industry 4.0
Hermann et al. (2015)	"Industry 4.0 is a collective term for technologies and concepts of value chain organization. Within the modular structured Smart Factories of Industry 4.0, CPS monitor physical processes, create a virtual copy of the physical world and make decentralized decisions. Over the IoT, CPS communicate and cooperate with each other and humans in real time. Via the IoS, both internal and cross organizational services are offered and utilized by participants of the value chain"

1.1 Background

Each evolution of Industry, from Industry 1.0 to the current Industry 4.0, has had a significant mark on technological improvements, the economy and society. The First Industrial Revolution, ''Industry 1.0,'' started in 1760 with the introduction of mechanical looms; stream engines were invested to automate the majority of the manual tasks, which led to new manufacturing processes which enhanced the economic structure [8,9]. The second Industrial Revolution, ''Industry 2.0'', started in the 19th century by introducing mass production, which was a major system at the time [8]. The cause of Industry 2.0 was due to improvements in electrical technology, which resulted in much more efficient methods of mass production and communication technologies [10].

1960 saw the introduction of Industry 3.0; this revolution was inspired by digital electronics, and digital computers changed how products were processed [11]. The invention of electronic and information technology in the 3IR automated production [12]; however, human help was still needed to complete the production process [9]; this emerged as the need for the Fourth Industrial Revolution. In the 2000s, Industry 4.0 began, and it has been building on the Third [9]. 4IR improved the production process and working efficiency of machines [13,11], which led to intelligent, self-sufficient production processes that use machines that can communicate with each other via digital connectivity [13]. This evolution uses concepts such as artificial intelligence, cloud computing, and the Internet of Things; this not only impacts industries and production but also impacts the economy as well [10]. The evolution of industries is summarised in Figure 1 below.

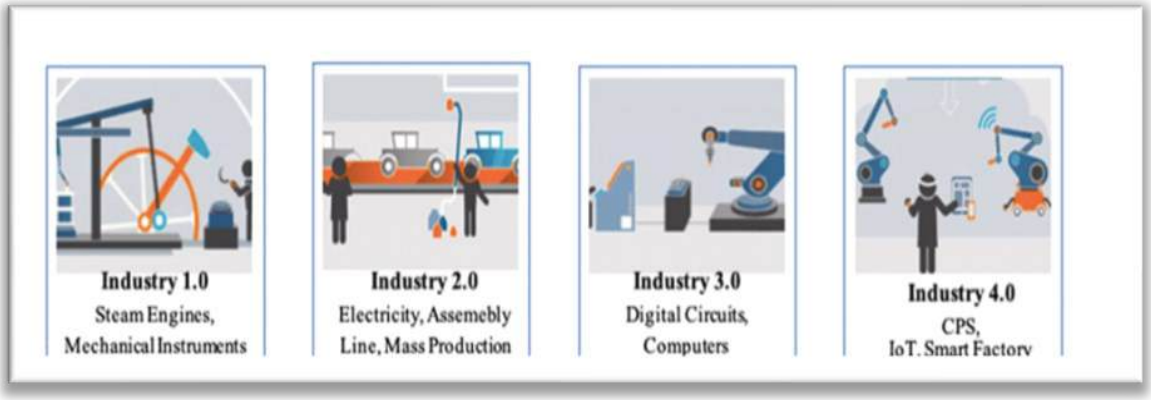

Figure 1: Summary of Industries [11]

The most significant component of Industry 4.0 is the Cyber-physical system (CPS), which means planting software in a manufacturing machine to understand itself and its capabilities; this will create smart machines that can manage themselves [11]. Napoleone, Macchi and Pozzetti [14] mentioned that CPSs have the ability to collect data about themselves and their surroundings, process it, connect to other systems and start off actions. The second significant component is the Internet of Things (IoT) and Internet of Services (IoS); this uses the internet that was already introduced in 3IR to connect to ''digital circuits'' in order to control different products [11]. IoS allows machines to link with products; the factory where this happens is called a smart factory [11]. [11] further mentioned that ''CPS, smart factory, and IoT and IoS are the foundations of Industry 4.0'' and that the improvement of these is why humans are no longer required to perform labour work. This is why the study of business processes in the era of Industry 4.0 become essential. These technologies change how things are done, and these changes have a lot of impact on business models.

Business Process Reengineering, short for BPR was first presented in 1990 by Hammer,

as he was referred to as the father of reengineering [15,16]. Business process reengineering, according to Hammer and Champy, is a radical restructuring and in-depth review of organisations' procedures to significantly increase critical updated indicators of success, such as service, speed, quality and cost [15].

[17] states that the term "BPR" entails completely rebuilding and reconsidering existing organisation procedures with the goal of effectively improving important performance measurements. According to [16] to produce fundamental and ongoing improvements in quality, service, price, development and lead time, BPR examines enhancing the Organisation's operations that can navigate evolving rivalry and expectations from customers by significantly restructuring the organisation's operations.

Business Process Reengineering is a vital aspect of the strategies, with the two most common fields being finance/banking and production [18]. BPR changes the angle at which businesses view their company's procedures while discovering how to reevaluate to optimise better operational efficiency [18]. For organisations to completely rebuild their operations, they need to significantly alter leadership dynamics, workflow designs, company regulations, and quality evaluation [17].

1.2 Aim of the study

This review looks into the potential challenges and opportunities presented by BPR in the era of Industry 4.0. The significance of this study lies in its relevance to organisations and businesses that aim to adopt Industry 4.0 and BPR; it will highlight the different categories of opportunities that come with the adoption and challenges that will need to be addressed to ensure effective adoption, such as technological, strategic and organizational categories. The study will contribute knowledge to the existing gap between Industry 4.0 and Business process reengineering literature.

Tariq and Khan [25] noted that prior to their work, Industry 4.0 had not been incorporated into any Business Process Reengineering framework. This points to a significant gap in the literature of Industry 4.0 and BPR that needs to be addressed. This study aims to fill this gap by providing a comprehensive literature review outlining the detailed categorisation of challenges and opportunities, offering a roadmap for organisations and businesses in the absence of Industry 4.0 in BPR framework. This review will answer the following questions:

- What are the technological, organisational and strategic challenges of BPR in the Industry 4.0 era?
- What are the technological, organisational and strategic opportunities of BPR in the Industry 4.0 era

By addressing these questions, the study will contribute to the existing body of knowledge by filling the identified gap and providing insights into the successful implementation of BPR in the era of Industry 4.0. Organisations and businesses can use these findings to effectively prepare and navigate the potential challenges of this implementation, leading to efficiency and innovation in the business processes.

2 LITERATURE REVIEW

2.1 Industry 4.0 and Business Process Reengineering

In this era of Industry 4.0, Business Process Reengineering becomes significant to organisations and businesses, this is because of its ability to relook at business processes to address the technological advancements in the era of 4IR. The concept of Business process reengineering was introduced and implemented in early 1990 [23] by Hammer, with a view to change business processes to better productivity [25]. Many authors such as [23,24,25] have cited Hammer and Champy's definition of BPR that states that BPR is the basic rethinking and redesign of business processes to fulfil ''dramatic improvements in critical measures of performances such as costs, quality, service and speed''.

[22] mentioned that Business process reengineering have four steps that requires to be taken step by step in order. Figure 2 below shows the 4 step BPR life cycle adopted by [22].

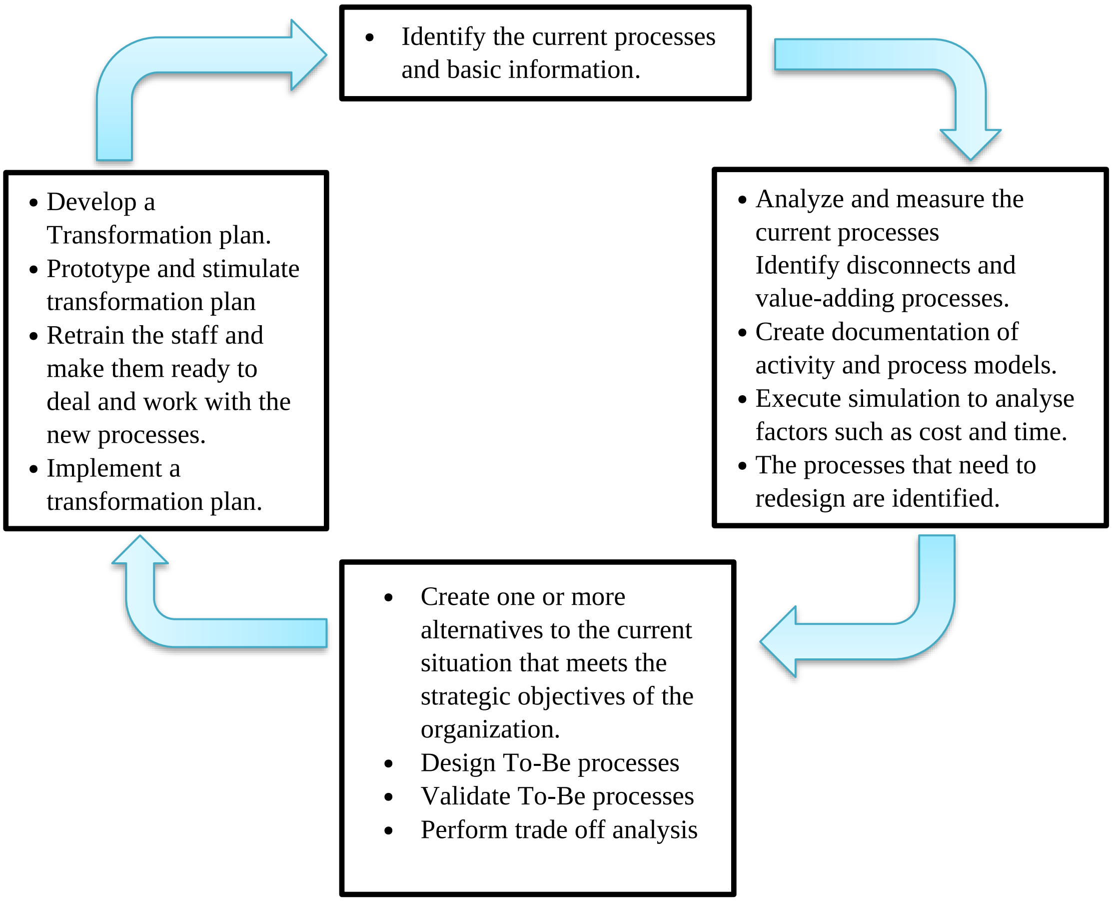

Figure 2: 4-step BPR life cycle adopted by Bayomy, Khedr, and Abd-Elmegid [22]

Another Business Process Reengineering life cycle with seven stages was adopted by author Nkomo and Marnewick [21], presented in figure 3 below. This life cycle does not differ much from the one adopted by [22], at the end they will offer the same results.

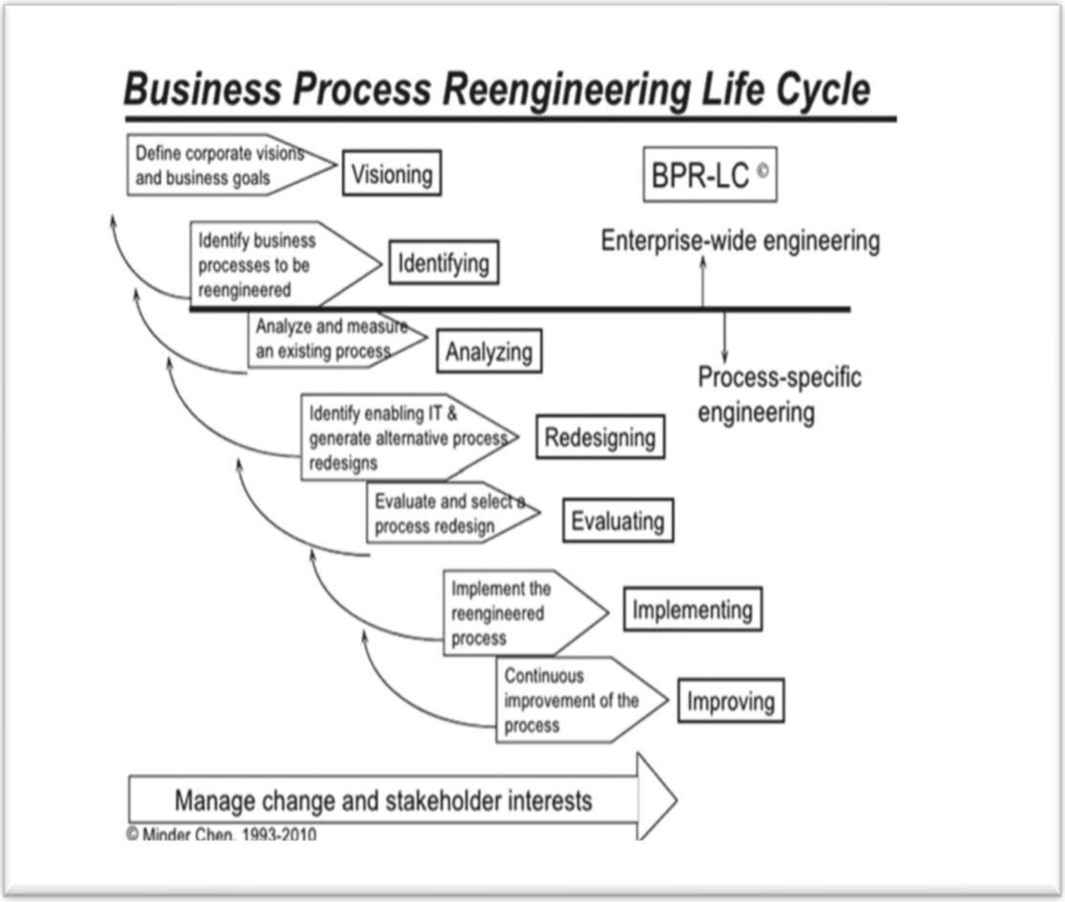

Figure 3: BPR life cycle

2.2 Real life implementation of BPR

Organisations and businesses adopting Industry 4.0 need to reengineer their current processes. BPR is a process improvement tool that can magnify the effects of Industry 4.0 [22]. Organisations require the help of BPR to effectively shift from machine-dominated production to digital manufacturing.

Some of the organisations that have adopted BPR in the era of Industry 4.0 include Ford and Amazon [23]. Amazon faced issues with the order fulfilment processes and the improvement of customer satisfaction [24]. As a solution, Amazon adopted BPR to address the fulfilment operations issues. Amazon introduced warehouse automation technologies and redesigned the warehouse layout. An intelligent inventory management system was adopted to minimize the time taken to move around the warehouse and ensure a more accurate order-picking system [24]. The implementation of BPR in Amazon reduced human error, increased speed and enhanced Amazon's inventory management system. This allowed the company to be certain that their most popular products were available while decreasing excess stock [23,24].

Ford is another company that adopted BPR in the mid-2000s. The production process was redesigned to eliminate bottlenecks, decrease waste and improve quality. Processes such as ''just-in-time production'' streamlined work processes and collaborative teams were introduced to help reduce costs and bring new models to the market faster. Ford also adjusted its processes to keep up with changing customer needs and make sure they provide quality products. They made things easier for customers by implementing one-click orders and providing personalized recommendations [23].

3 RESEARCH METHODOLOGY

This paper is a review of the past literature on the potential Business process reengineering challenges and opportunities presented by BPR in the era of Industry 4.0 in the form of a systematic review. A systematic review uses analytic methods to gather secondary data and analysis it [22], it is designed to provide current relevant literature to answer research questions at hand. The paper will report on the potential challenges and opportunities of Business process reengineering in the Industry 4.0 era.

The scope of the paper includes conference papers, academic papers, journal articles, company reports and only reliable websites. Google Scholar is used to search for secondary data using keywords such as ''Business process reengineering, Industry 4.0, 4IR, 4IR technologies disruptions, BPR + Industry 4.0 challenges, BPR + Industry 4.0 opportunities, industry 4.0 implications, technological disruptions, strategic IT frameworks in industry 4.0''. The time frame of the secondary date is 2018-2024. The table below highlights the search criteria for this paper.

Table 2: Search criteria

Literature search	Inclusion criteria	Exclusion criteria
• Conference papers • Academic papers • Journal articles • Company reports • Government reports • Reliable websites • Textbooks	• English written papers • Papers written between 2018 - 2024 • Papers focusing on 4IR and Industry 4.0 • Secondary and primary papers	• Any language that is not English • Papers published earlier than 2018 • Papers not highlighting challenges and opportunities that are not related to 4IR or Industry 4.0 • Papers lacking credibility • Not related to BPR or Industry 4.0

4 RESULTS AND DISCUSSION

This section presents and discusses the results from the past literature reviewed for this paper; the timeframe for the literature was between 2018-2024. The literature reviewed for this paper has found that the implementation of BPR in the era of Industry 4.0 can present some opportunities; however,, unfortunately,, there are also challenges. Authors Nkomo and Marnewick [21] suggested the use of Information Technology to guide the implementation of BPR; it is, however, that before BPR can be adopted, it is important to be aware of some of the different challenges and opportunities this will present the adoption. Nkomo Marnewick [21] further suggested that it is significant for processes to have an IT framework in order for the redesign or reengineer of businesses to be successful, this statement is supported by Kutama and Manzini [27] who mentioned that the adoption of Business Process Reengineering is impossible without IT.

This paper found and categorised the challenges and opportunities of BPR in the concept of Industry 4.0, the categories are technical, strategic and organisational. The technological category looks into the challenges and opportunities that are associated with incorporating technologies into the redesigning of processes. The organisational category discusses skills, training, and change management related to the adoption of business process reengineering in the organisation. Lastly, the strategic category highlights the incorporation of 4IR technologies and how they affect the organisation's strategic goals.

As mentioned in the paper, this study aims to answer the following questions:

- *What are the technological, organisational and strategic challenges of BPR in the Industry 4.0 era?*
- *What are the technological, organisational and strategic opportunities of BPR in the Industry 4.0 era?*

4.1 Number of studies by year of publication

As per the inclusion criteria, the study specifically examined papers published from 2018 to 2019. Figure 5 below presents the distribution of reviewed studies by year of publication. It is noted that majority of the papers reviewed are from 2020 and 2021, indicating a significant level of interest in the study of BPR and Industry 4.0 during these periods. However, there seems to be a noticeable decline in the studies from 2022 to 2024, suggesting a gap in recent in research activity.

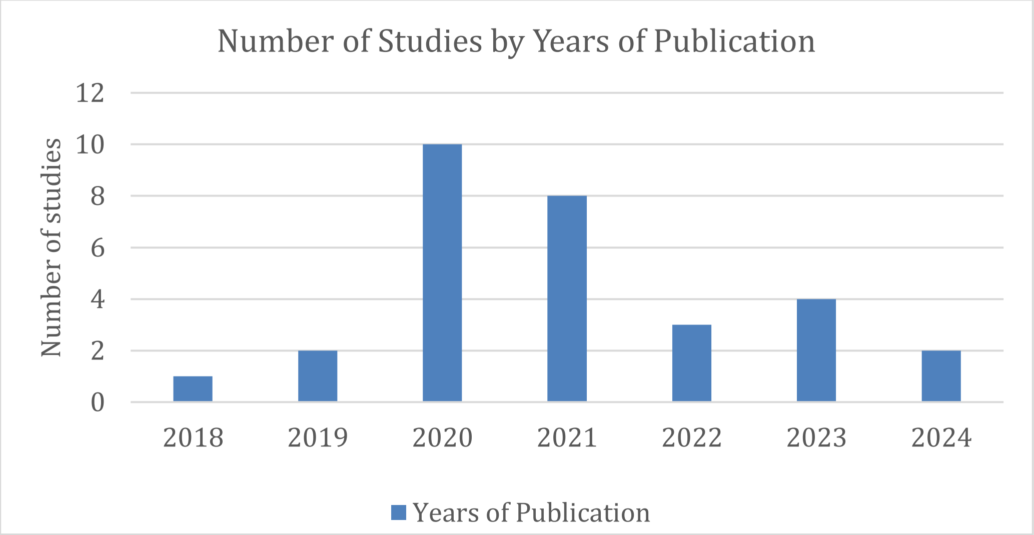

Figure 4 Number of Studies by years of publication

4.2 Type of publication

Among the studies reviewed as per figure 6 below, majority seems to be literature from journal articles, followed by conference papers and website articles. This breakdown highlights the primary dependence on peer-reviewed journal articles for literature on BPR and Industry 4.0, with lesser contribution from the other types of publications. The dependence on journal articles highlights the importance of trustworthiness in research.

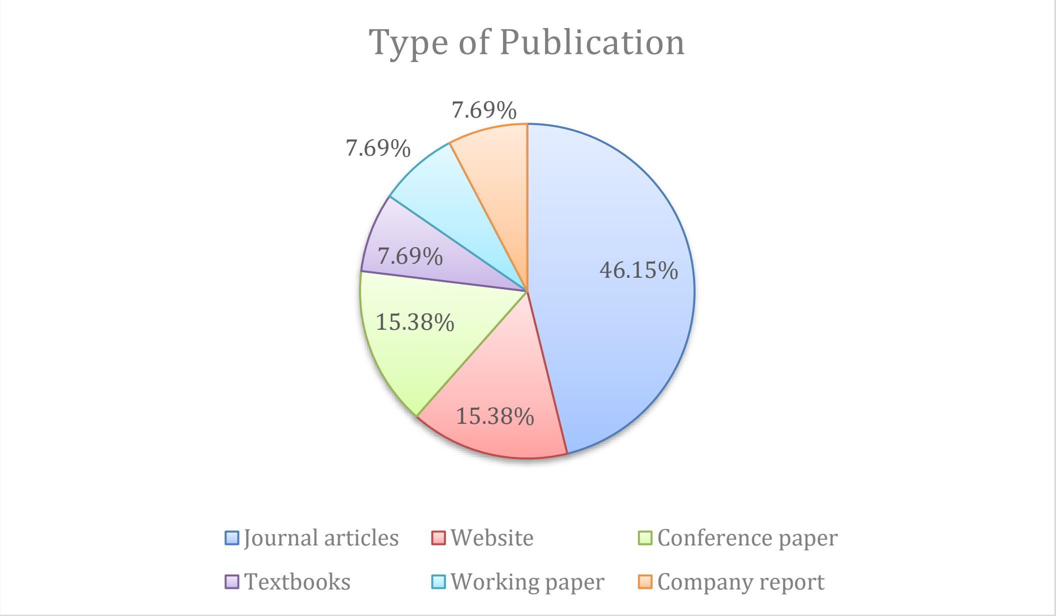

Figure 5 Type of Publication

4.3 The first question, ‘’What are the technological, organisational and strategic challenges of BPR in the Industry 4.0 era?’’ is answered in tables 3-5 below.

4.3.1 Table 3 provides a summary of the technological challenges of BPR in the Industry 4.0 era, and it highlights the authors who contributed to the literature and the year. Also, it includes the titles of the papers and articles, year and type of publications.

Table 3: Technological challenges of BPR in the Industry 4.0 era

Category 1: Technological challenges	Author/s	Title of paper/article	Year of publication	Type of publication
• Supply chain issues: with supply chains getting automated and digitalized, data privacy is now a challenge, this is a threat in how to redesign new supply chain process in Industry 4.0 • Data security: IoT allows organisations to be vulnerable to cyber-attacks and unwanted access	Khan, Haleem, and Mohd [28]	*Changes and improvements in Industry 5.0: A strategic approach to overcome the challenges of Industry 4.0*	2023	Journal article
	Horváth, Dóra, and Szabó [29]	*Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities?*	2019	Journal article

Category 1: Technological challenges	**Author/s**	**Title of paper/article**	**Year of publication**	**Type of publication**
	Siddiqui, Khan, Rashid, and Khan [35]	*Industry 4.0 Adoption in Transportation: Does Industry 4.0 Adoption Enhance Sustainability? A Systematic Literature Review*	2024	Journal article
• Lack of communication between Information technology department and other departments in the organisation	Fetais, Abdella, Al-Khalifa, and Hamouda. [20]	*Business Process Re-Engineering: A Literature Review-Based Analysis of Implementation Measures*	2022	Journal article
	Horváth, Dóra, and Roland Zs Szabó. [29]	*Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities?*	2019	Journal article

4.3.2 Table 4 provides a summary of the organisational challenges of BPR in the Industry 4.0 era, it highlights the authors that contributed to the literature and the year. Also, it includes the titles of the papers and articles, year and type of publications.

Table 4: Organisational Challenges of BPR in the Industry 4.0 era

Category 2: Organisational challenges	**Author/s**	**Title**	**Year of publication**	**Type of publication**
• Inadequate Knowledge • Reengineering the wrong processes • Unsuited implementors • Lack of resources • Lack of support • No analysis of the process beforehand	HiTechNectar [30]	*Business Process Reengineering Steps (BPR) & Challenges*		Website article
	Siddiqui, Khan, Rashid, and Khan [35]	*Industry 4.0 and Its Implications: Concept, Opportunities, and Future Directions*	2024	Journal article

Category 2: Organisational challenges	**Author/s**	**Title**	**Year of publication**	**Type of publication**
• Analysing the root cause • Inability to balance the present and future process • Integrating organizational change management • Investment of resources	Panorama consulting group [30]	*The Challenges of Implementing Business Process Reengineering*	2021	Website article
• Insufficient knowledge on how to reengineer processes • Incorrect placement of resources • Lack of support in redesigning processes	Harika, A., M. Sunil Kumar, V. Anantha Natarajan, and Suresh Kallam [19]	*Business process reengineering: issues and challenges*	2021	Conference paper
• Human resource: employees require training to work in smart factories and perform redesigned processes due to the Industry 4.0	Khan, Moin, Abid Haleem, and Mohd Javaid. [28]	*Changes and improvements in Industry 5.0: A strategic approach to overcome the challenges of Industry 4.0*	2023	Journal article
	Horváth, Dóra, and Roland Zs Szabó [29]	*Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities?*	2019	Journal article
• Change management	Siregar, Wicaksana [15]	*Literature Review on Business Process Reengineering*	2021	Journal article

4.3.3 Table 5 provides a summary of the strategic challenges of BPR in the Industry 4.0 era, it highlights the authors that contributed to the literature and the year. Also, it includes the titles of the papers and articles, year and type of publications.

Table 5: Strategic challenges of BPR in the Industry 4.0 era

Category 3: Strategic challenges	Author/s	Title of paper/article	Year of publication	Type of publication
• Vulnerability to volatility of economy • Lack of Information Technology framework when reengineering business processes • Higher investment costs	Harika, A., M. Sunil Kumar, V. Anantha Natarajan, and Suresh Kallam. [19]	*Business process reengineering: issues and challenges*	2021	Conference paper

4.4 The last question ''What are the technological, organisational and strategic opportunities of BPR in the Industry 4.0 era?'' is answered in tables 6-8 below.

4.4.1 Table 6 provides a summary of the technological opportunities of BPR in the Industry 4.0 era, it highlights the authors that contributed to the literature and the year. Also, it includes the titles of the papers and articles, year and type of publications.

Table 6: Technological opportunities of BPR in the Industry 4.0 era

Category 1: Technological opportunities	Author/g	Title of paper/article	Year of publication	Type of publication
• Digital manufacturing can support multiple technologies can at the same time. Technologies such as robotics, sensors, automation machines can be used to automate processes and increase efficiency and productivity • Advanced analytics can use data from sensors to record insights to improve planning and decision making that can enhance operations • Technologies like 3D printing can design and print out products on site, reducing lead time	PC4IR [2]	Report of the presidential commission on the fourth industrial revolution	2020	Government report
	Alexander [32]	Key Opportunities and Challenges for 4IR in South Africa'	2022	Working paper

Category 1: Technological opportunities	Author/g	Title of paper/article	Year of publication	Type of publication
• Digital manufacturing can optimize mass production • Artificial intelligence, machine learning can be used by digital sales to interact with customers • Automation can decrease manufacturing time and eliminate waste.				
• BPR teams get support from new technology during the BPR implementation. • IT Framework and transparency increases the chances of excelling in redesigning business processes.	Harika, A., M. Sunil Kumar, V. Anantha Natarajan, and Suresh Kallam. [19]	Business process reengineering: issues and challenges.	2021	Conference paper
• Advanced technologies will provide greater operational flexibility on production process	Abdelmajied [33]	Industry 4.0 and Its Implications: Concept, Opportunities, and Future Directions	2022	Textbook
	Harika, A., M. Sunil Kumar, V. Anantha Natarajan, and Suresh Kallam. [19]	Business process reengineering: issues and challenges.	2021	Conference paper
• Information system and communication technology (ICT) ensures the necessary information for BPR implementation is	AbdEllatif, Farhan, and Shehata [34]	Overcoming business process reengineering obstacles using ontology-based knowledge	2018	Journal article

Category 1: Technological opportunities	**Author/g**	**Title of paper/article**	**Year of publication**	**Type of publication**
available at any time		map methodology		

4.4.2 Table 7 provides a summary of the organisational opportunities of BPR in the Industry 4.0 era, it highlights the authors that contributed to the literature and the year. Also, it includes the titles of the papers and articles, year and type of publications.

Table 7: Organisational opportunities of BPR in the industry 4.0 era

Category 2: Organisational opportunities	**Author/s**	**Title of paper/article**	**Year of publication**	**Type of publication**
• Workforce upskilling: digital advancement such as machine learning and remote assistance presents an opportunity to reduce time taken to train the workforce and improve productivity.	PC4IR [2]	Report of the presidential commission on the fourth industrial revolution”,	2020	Government report
	Alexander [32]	Key Opportunities and Challenges for 4IR in South Africa'	2022	Working paper
• More efficient utilization of resources • Productivity growth • Integrate production to a lager supply chain • Growing demand for new knowledge and skills	Abdelmajied [34]	Industry 4.0 and Its Implications: Concept, Opportunities and Future Direction	2022	Textbook

4.4.3 Table 8 provides a summary of the strategic opportunities of BPR in the Industry 4.0 era, it highlights the authors that contributed to the literature and the year. Also, it includes the titles of the papers and articles, year and type of publications.

Table 8: Strategic opportunities of BPR in the Industry 4.0 era

Category 3: Strategic opportunities	**Author/s**	**Title of paper/article**	**Year of publication**	**Type of publication**
• Effective IT infrastructure allows successful BPR adoption • Linking strategic goals and IT during process redesign can increase	Siregar, Wicaksana [15]	A Literature Review on Business Process Reengineering	2021	Journal article

Category 3: Strategic opportunities	Author/s	Title of paper/article	Year of publication	Type of publication
customer satisfaction				
• Introduction of new business process and models • Responsive value chains • Integration of producers and customers, increasing market demands and customer connection • Foundation of increasing digital market models • Elimination of barriers between information and physical structures.	Abdelmajied [34]	Industry 4.0 and Its Implications: Concept, Opportunities, and Future Directions	2022	textbook

4.5 Number of challenges and opportunities

4.5.1 A summary of the number of challenges is presented in figure 6 below. The majority of the challenges are organizational at 71.43%; these include insufficient knowledge on how to reengineer processes, incorrect placement of resources and lack of support in redesigning processes, among others. This high number of organisational challenges indicates a skill gap in the workforce for implementing BPR in the era of Industry 4.0. The workforce needs to have relevant skills to be able to integrate advanced technologies with existing processes.

Figure 6 Number of challenges

4.5.2 A summary of the number of opportunities is presented in figure 7 below. Majority of the challenges are technological at 47.62%, these includes more efficient utilization of resources, productivity growth, integration of production to a lager supply chain and growing demand for new knowledge and skills. This high number highlights numerous benefits and possibilities offered by integrating advanced technologies. It also indicates that adopting BPR in the era of Industry 4.0 can lead to magnificent improvements in efficiency, innovation and competitive advantage.

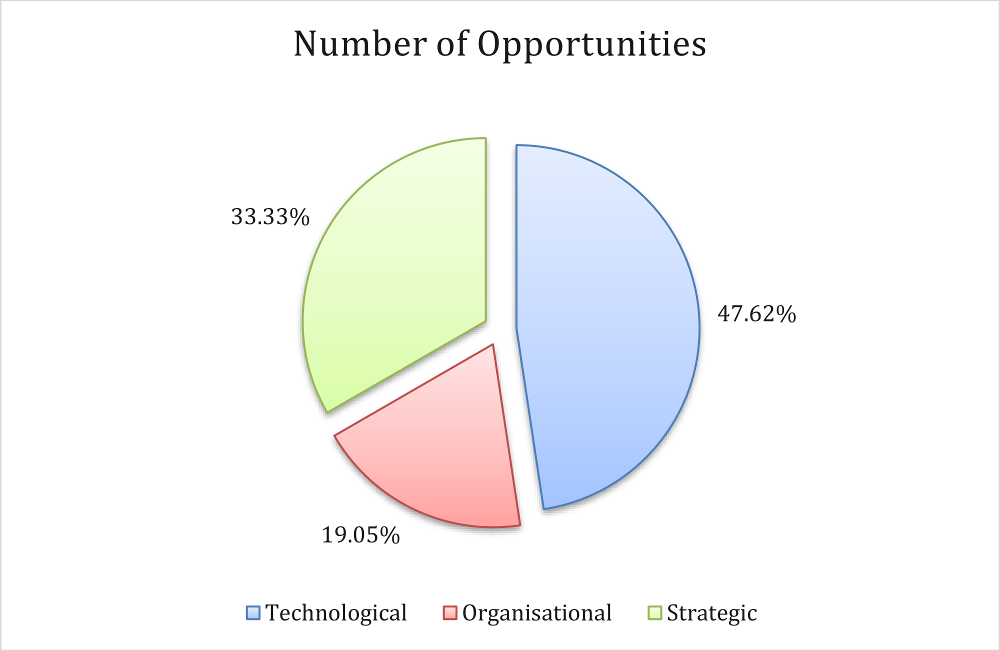

Figure 7 Number of Opportunities

5 CONCLUSIONS

Business Process Reengineering keeps gaining more momentum as time goes, it has been implemented as a solution to the technological advancements of the 4IR. The adoption of BPR represents various opportunities and challenges; this paper categorised these into three:

technology, organisation and strategy. The technological category looks into the challenges and opportunities that are associated with incorporating technologies into the redesigning of processes. The technological challenges found includes supply chain issues, this refers to the redesign of supply chain process to be automated and digitalized. The issue that this presents is the challenge of data privacy, this is a threat to an automated supply chain because it presents a chance for data to be hacked and leaked and fall into the wrong hands. However, there are technological opportunities such as automation and digitalization increasing efficiency and productivity.

Organisational category discusses skills, training and change management related to the adoption of Business process reengineering in the organization. The organizational challenges found includes having BPR being implemented by unskilled and unsuited implementers, lack of support by the organization to implement BPR and no resources to implement the redesign of processes. The organisational opportunities however workforce upskilling, the adoption of BPR and digital advancements present an opportunity for organisations to upskills their employees to get new knowledge and skills. The study further revealed that 71.43% of the challenges are organizational challenges, such as insufficient knowledge on how to reengineer processes, incorrect placement of resource and lack of support in redesigning processes among others. This emphasizes a skill gap in the workshop, hindering the effectiveness of BPR implementation in the Industry 4.0 era.

Lastly the strategic category highlights the incorporation of 4IR technologies and how it affects the organisation’s strategic goals. The paper found that one of the challenges includes the lack of IT framework when adopting BPR, this affects the success of the implementation. It was found that linking strategic goals and IT during process redesign can increase customer satisfaction. However, a high number of opportunities was found to be technological opportunities, which presented the benefits and possibilities offered by integrating advanced technologies. It also indicates that adopting BPR in the era of Industry 4.0 can lead to magnificent improvements in efficiency, innovation and competitive advantage. This is followed by strategic opportunities (33.33%), which indicates that linking strategic goals and IT during process redesign can increase customer satisfaction, among other opportunities.

Despites these finding, the study had a few limitations, the analysis only considered the existing literature and secondary data. The study was limited to investigating a broad number of challenges and opportunities in BPR and Industry 4.0, without looking into industry-specific factors, different industries may have different challenges and opportunities when adopting BPR with Industry 4.0 technologies. The study also did not consider how these challenges and opportunities apply to different organisation sizes, smaller organisations might face different challenges/opportunities compared to large organisations. Since the study only considered the existing literature and secondary data, it did not take into consideration the input from industry experts who might bring a different perspective into BPR and Industry 4.0.

5.1 Recommendations

It is recommended that future literature looks further into the following:

- To address the limitation of this study, future studies should consider gathering primary data from industry experts and implementors of BPR.
- Expand the strategic challenges and opportunities of BPR adoption in the era of Industry 4.0 as it was found that the adoption of BPR is impossible without IT.
- Investigate the ethical considerations when redesigning processes in the Industry 4.0 era
- Risk management in automation of processes.

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A SYSTEMATIC LITERATURE REVIEW FOR EXPLORING THE SUSTAINABILITY IMPACT OF ANIMAL-SOURCE FOOD SUPPLY CHAINS

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ABSTRACT

As sustainability has become increasingly important in industrial engineering, a critical area of focus has emerged: Optimising animal-source food supply chains for sustainability. Although these supply chains are crucial for economic growth, they significantly contribute to sustainability challenges. Optimising animal-source food supply chains for sustainability will aim to balance economic competitiveness with environmental and social responsibility. While economic efficiency has traditionally been a primary focus, industrial engineers are now recognising the urgency of aligning these goals with environmental and social responsibility. This shift will foster innovation and resilience in changing market dynamics.

By embracing sustainable practices within these supply chain operations, organisations can mitigate risks, enhance brand reputation, comply with regulations, and achieve long-term success in a rapidly evolving global marketplace. This systematic review illustrates the key themes, trends, challenges and knowledge gaps that require further research within the current literature related to the sustainability of animal-source food supply chains.

Keywords: Sustainability, animal-source food, supply chain

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1 INTRODUCTION

In recent years, the sustainability of animal-source food supply chains has emerged as a critical issue in the field of food production and consumption [1]. As the global population continues to grow, the demand for animal-source food such as meat, dairy, and eggs has increased significantly, placing pressure on existing supply chains and raising concerns about their long-term sustainability. For instance, the livestock sector is responsible for around 14.5% of global greenhouse gas emissions, and the production of animal-source food is linked to deforestation, water pollution, and biodiversity loss [2]. It is essential to organise and align all segments of the animal-source food supply chain to achieve unified objectives and ensure long-term sustainability [3].

Sustainability, in the context of animal-source food supply chains, extends beyond focusing solely on environmental aspects. It takes a holistic approach that integrates economic, social, and environmental dimensions [4]. It involves the responsible management of resources to fulfil current requirements without compromising the ability of future generations to meet their own needs. This multifaceted concept emphasises the significance of balancing economic, social, and environmental sustainability to ensure the longevity and adaptability of food supply chains [5].

Previous studies were restricted to one aspect of the supply chain and did not consider the entire chain. A chain perspective is important, as sustainability issues emerge at various stages along the chain [6]. A sustainable supply chain performance includes both traditional metrics for profit and loss and a broader definition of performance that takes the environmental and social aspects into account. Evaluation of a multifaceted strategy combining economic, environmental, and social components is necessary for sustainable supply chain management. Within the literature on supply chain sustainability, this is referred to as the triple bottom line [7],[8].

There is growing global consensus on the need to transform food systems to achieve critical global goals. The Sustainable Development Goals (SDG) highlight the need to minimise adverse environmental effects, use land more sustainably, and seek ways to restore areas that have lost biodiversity or nutrients in order to fulfil future demands. The livestock sector is an important part of these challenges [9]. This review addresses two of the 17 sustainability development goals, SDG12: Responsible consumption and production, and SDG15: Life on land [10].

The research question for this systematic literature review is to establish the current landscape of literature related to the sustainability of animal-source food supply chains, including key themes, trends, challenges and knowledge gaps that require further research. This systematic literature review considers the literature on animal-source food supply chains as a vehicle to introduce more sustainable methods and improve the responsible consumption and production of animal-source food, which is linked to SDG12. The purpose of this review is therefore to identify important topics and developments, and address challenges in this area. Furthermore, the review will assess the extent of knowledge available on the topic and pinpoint any gaps that may exist and require further research.

Following the introductory section, Section 2 will explain the approach and methodology used throughout this systematic literature review. Section 3 will present the results and analysis, incorporating content analysis. Section 4 will discuss the literature, and finally, Section 5 will address the conclusion.

2 APPROACH AND METHODS

This paper reports on a systematic literature review conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) 2020 statement as defined by Page *et al*. [11].

Systematic literature reviews use explicit, systematic methods to collate and synthesise findings of studies that address a clearly formulated question [11]. The PRISMA methodology is used to ensure the transparent and complete reporting of this systematic review [12].

The approach for this systematic literature review is illustrated in Figure 1. The figure shows the phases of this review as well as the associated processes in the PRISMA flow diagram for the identification of new studies via databases. The three phases of a systematic literature review include Phase 1: Identification, Phase 2: Screening and Phase 3: Included. Each phase is discussed below.

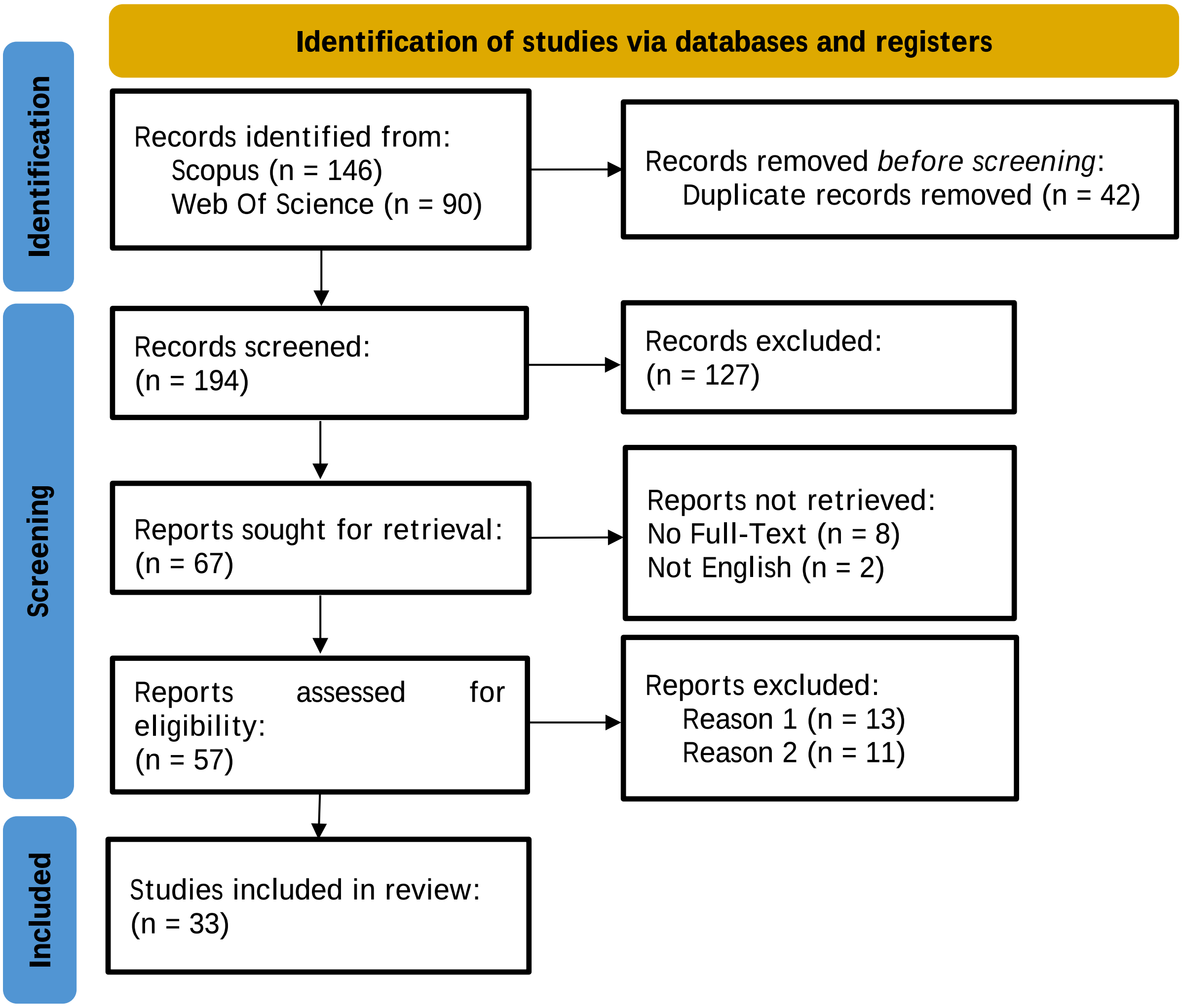

Figure 1: Flow of information through the phases of a systematic literature review [11].

2.1 Phase 1: Identification

In Phase 1 of the review, the information sources and keywords were identified, and search strategies were developed and applied. In the first step of Phase 1 information sources with a large amount of available literature were identified.

The first and main information source was chosen to be Scopus. Scopus is one of the largest curated abstract and citation databases and it covers most scientific fields. Scopus includes papers published since 1966, with over 76 million records [13]. Web of Science was chosen as the second information source, since it provides a common search language, navigation environment, and data structure allowing a broad search across different resources [14].

For Scopus, the search was conducted within article titles, abstracts and keywords. There was no limitation placed on the language and dates. For Web of Science there was also no limitation placed on the dates.

During the second step of Phase 1, the keywords were identified. This was initiated by examining recent works on the sustainability of the supply chains of animal-source foods. This preliminary examination resulted in keywords and combinations of keywords that relate to sustainability, animal-source foods, and supply chains.

In steps three and four of Phase 1, the search strategies were developed from the keywords and applied to the relevant information sources. The last search date for the information sources was 29 April 2024. The information sources, their search strategies, and the number of documents found are summarised in Table 1.

Table 1: Information sources and their search strategies.

Information Source	Search Strategy	Number of documents
Scopus	TITLE-ABS-KEY ("Animal* Source* Food*" OR "Animal* Food* Product*" OR "Livestock* Product*") AND TITLE-ABS-KEY ("Supply* Chain*" OR "Food* System*") AND TITLE-ABS-KEY ("Sustainability*" OR "Sustainable*" OR "Sustain*") AND NOT TITLE-ABS-KEY ("Diet*")	146
Web of Science	"Animal* Source* Food*" OR "Animal* Food* Product" OR "Livestock* Product*" (All Fields) and "Supply* Chain*" (All Fields) and "Sustainability*" OR "Sustainable*" OR "Sustain*" (All Fields)	90

Scopus returned a total of 146 items and Web of Science returned a total of 90 items that matched the search strategy. The last step in this phase was to remove duplicate records before screening can take place. To eliminate duplicates, data refinement was conducted on the titles. After removing the 42 duplicate records, 194 records remained to be screened.

2.2 Phase 2: Screening

According to the PRISMA methodology Phase 2 is the screening process. This involves screening the titles and abstracts of the identified reports to help identify irrelevant reports that should be excluded from the review [11]. The full texts of the remaining reports are then retrieved. If there are reports whose full text cannot be retrieved it is excluded. The last step of this phase involves assessing the reports for eligibility using an eligibility criteria.

The titles and abstracts of the 194 identified records in Phase 1 were screened for relevance. Based on this step, 127 reports were excluded. The full text of the remaining 67 reports were then retrieved. Due to the lack of access, 8 reports could not be retrieved, and 2 reports were in a different language than English. These 10 reports were therefore excluded. The eligibility assessment of the remaining 57 full-text documents were conducted using the eligibility criteria in Figure 2 below.

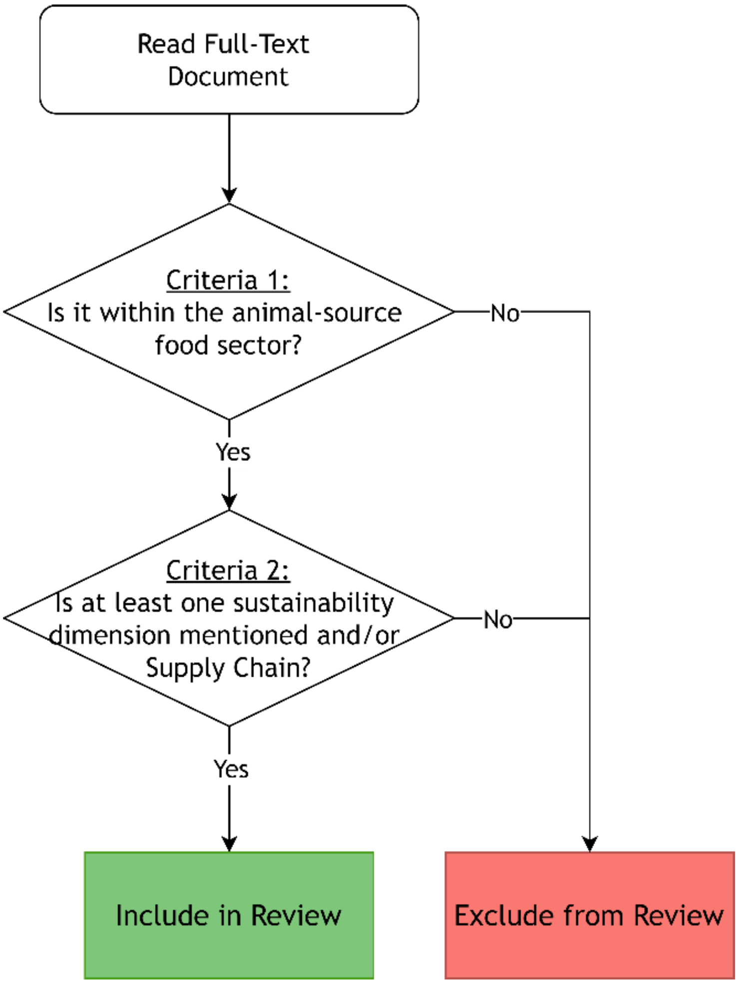

Figure 2: Eligibility criteria.

The eligibility criteria started with reading each full-text document and then deciding whether it obliged criteria 1 and criteria 2. Criteria 1 was whether it was related to the animal-source food sector. Criteria 2 considered the following 3 different outcomes: The first being whether at least one sustainability dimension was mentioned and the other being whether the supply chain was addressed. The last outcome is if the document fulfilled both above mentioned outcomes. Criteria 1 was failed by 13 documents and 11 documents passed criteria 1 but failed criteria 2. After excluding the reports that failed the eligibility criteria, 33 reports remained.

2.3 Phase 3: Included

During this phase the remaining documents are listed. The references of these documents are listed in Table 2, and they are grouped according to the year they were published. The table also indicates the number of documents per year. Grouping the documents per year shows the fluctuations of publications from year to year.

Table 2: Documents included.

Year	List of references	Number of documents
2004 - 2014	[3], [6], [15], [16], [17], [18], [19]	7
2016	[20]	1
2017	[21]	1
2018	[22]	1
2019	[7], [23], [24]	3
2020	[25]	1
2021	[26], [27], [28], [29], [30]	5
2022	[31], [32]	2
2023	[8], [9], [33], [34], [35], [36], [37]	7
2024	[2], [38], [39], [40], [41]	5
	Total	**33**

3 RESULTS AND ANALYSIS

In this section of the article, the findings generated from Section 2 were further analysed using bibliometric analysis and content analysis techniques. The purpose of this additional analysis was to gain deeper insights into the impact and significance of the findings obtained from Section 2.

3.1 Bibliometric analysis

A bibliometric analysis is conducted to identify emerging trends in academic publications, including the performance of articles and journals, collaboration patterns among researchers, and key concepts within a specific field. This analysis offers insight into the structure and evolution of a research domain [42]. The tool used to facilitate this bibliometric analysis was Biblioshiny from Bibliometrix. This tool is designed to provide advanced bibliometric analysis capabilities, allowing researchers to explore and visualise various aspects of scholarly literature [43].

3.1.1 Annual Scientific Production

The annual scientific production graph, as shown in Figure 3, provides the number of documents that were produced during each year with the x-axis representing the year the articles were published and the y-axis representing the number of articles published each year. The purpose of this graph is to gain insights into the evolution and trends of research in this field of research over time. This graph can provide researchers with a better understanding of the growth of a field and provide insights into the direction of future research.

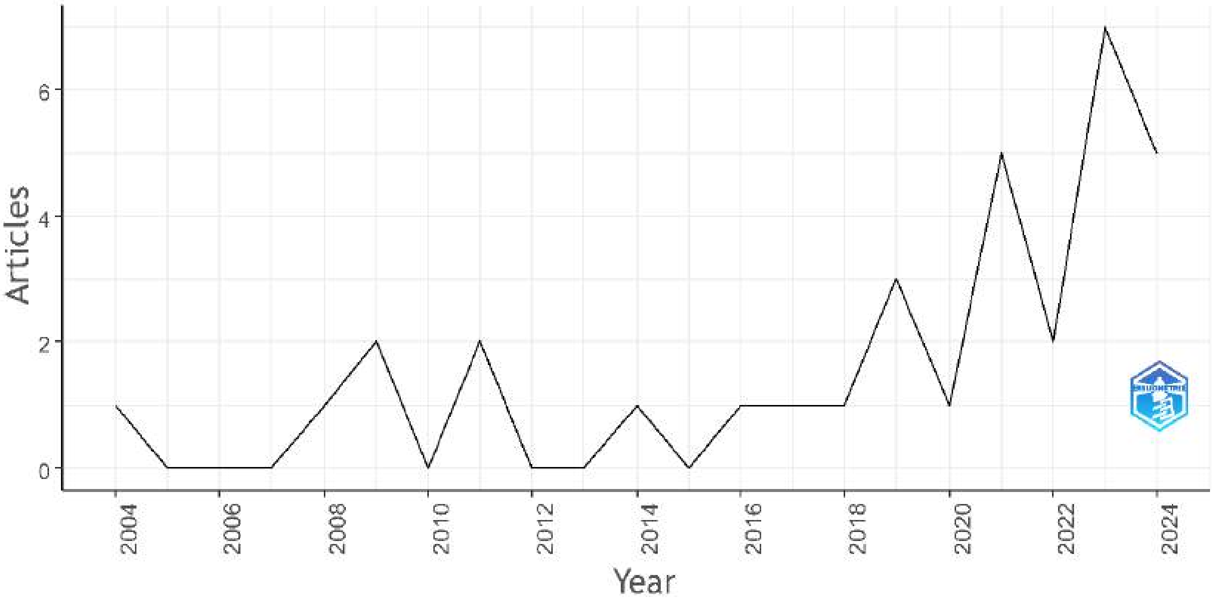

Figure 3: Annual scientific production.

Based on the data provided in the graph the number of publications fluctuates significantly from year to year. This uneven publication history is evident, with some years showing no publications, while others have multiple publications. The graph suggests that research output in this field has been inconsistent.

Despite the fluctuations, the graph reveals a recent increase in publication output. The highest number of publications in a single year was 7 in 2023, followed by 5 in 2021 and 2024. This trend suggests that research in this field has gained momentum in the last few years, with more researchers contributing to the body of knowledge.

3.1.2 Country Scientific Production

The country scientific production is visually represented in Figure 4. This map illustrates the number of authors contributing to each document from different countries. The map shows the countries shaded based on the number of articles produced in each country. The darker the shade of blue, the more articles the country has contributed. The purpose of this illustration is to gain insights into the global distribution of research output and the contribution of different nations to the literature. This information can help to understand the gap that exists for this research in specific countries.

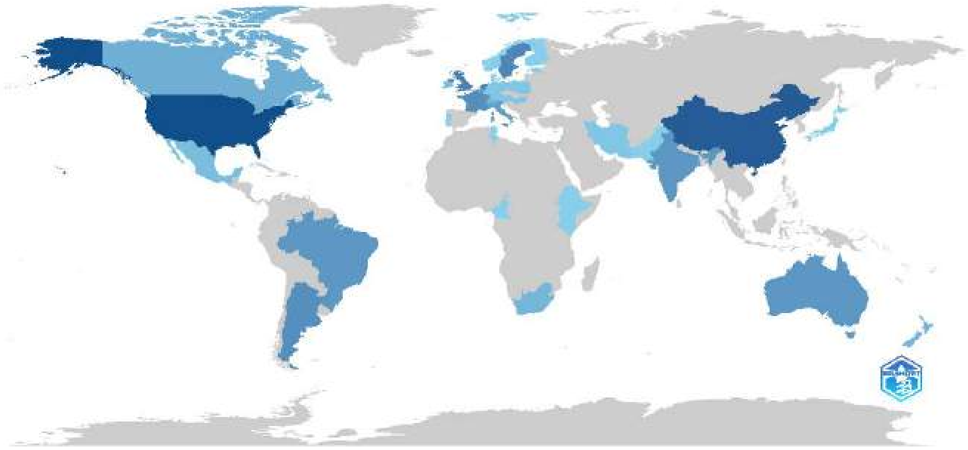

Figure 4: Country scientific production.

Based on the data provided the United States has the most publications followed closely by China, indicating that they have the most active contribution to the field. This map highlights that a wide variety of countries contributed to this research field. Out of the 33 documents analysed, 37 different countries contributed. This indicates a strong research output globally. The results emphasise the global nature of scientific research in this field. This suggests that researchers from diverse locations are contributing to the advancement of knowledge in this field.

3.1.3 Most Relevant Authors

Figure 5 provides an overview of the most relevant authors in this research field, where the x-axis represents the number of documents produced by each author and the y-axis represents the authors. The purpose of this information is to identify key contributors who have made significant contributions to the research in this field. The data provides insights into the distribution of authors.

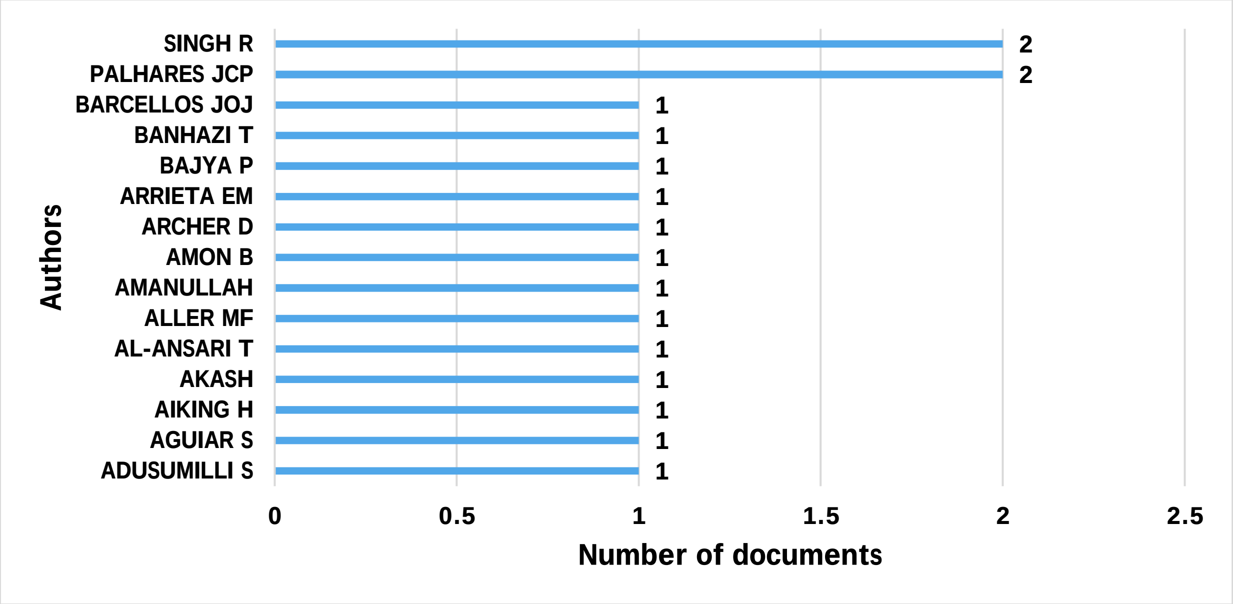

Figure 5: Most relevant author.

The data shows that only two authors, Singh R and Palhares JCP, contributed to more than one document. This suggests that there is no single prominent author who has made a significant contribution to the research field. The literature includes a diverse range of authors, indicating that the field is a collaborative effort with contributions from multiple researchers.

3.1.4 Prominence of documents

To determine the prominence of documents in this field, it is essential to examine the most globally cited documents. This will identify which documents have had the most significant impact globally and have been referenced extensively by other researchers. Figure 6 illustrates this information, where the x-axis represents the number of citations globally for each article and the y-axis represents the titles and publication year of each article.

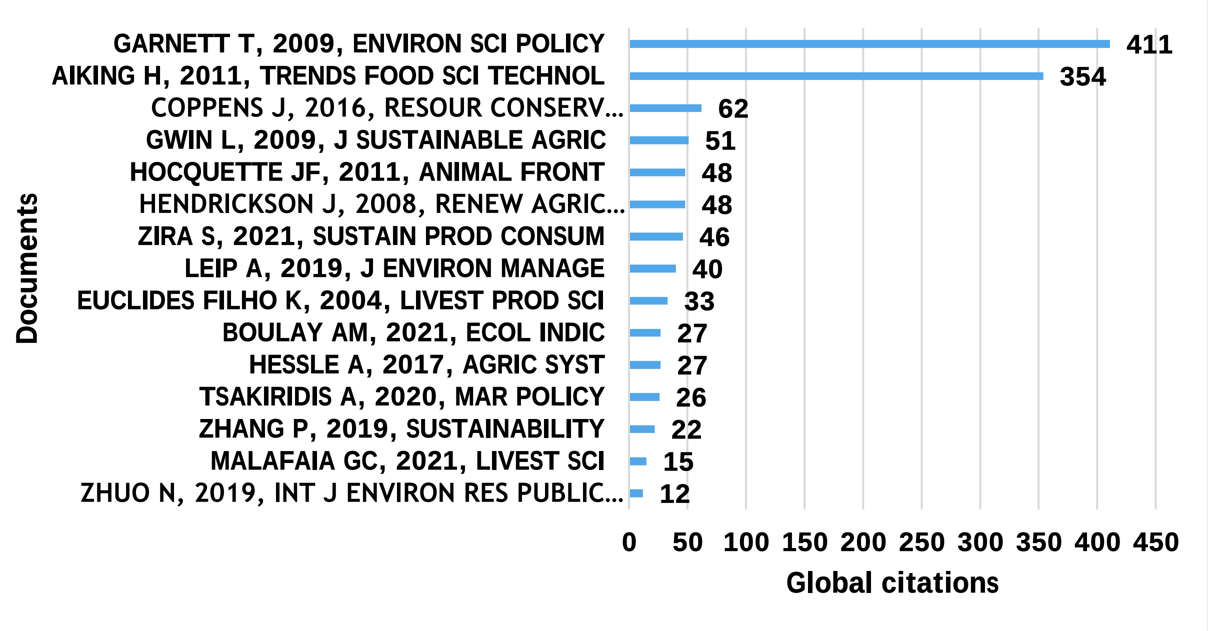

Figure 6: Most global cited document.

The data indicates that two documents stand out with significantly more citations compared to the rest of the publications [17], [19]. These two documents have received a substantially higher number of citations, indicating their extensive global contributions to the research field.

3.2 Content-Analysis

Content analysis is important when conducting a systematic literature review because it allows researchers to systematically and objectively analyse the depth of existing literature on a particular topic. This method helps in identifying key themes, patterns, and gaps in the research, ensuring a comprehensive understanding of the subject area. The content analysis for this systematic literature review was conducted by looking at the strategic diagram (thematic map) and word cloud of the keywords involved in each report. The analysis looked at the type of sustainability issue and the type of animal-source food each report was conducted on. The tool used to facilitate this analysis was Biblioshiny from Bibliometrix [43].

3.2.1 Thematic analysis

A thematic analysis was conducted to identify the primary themes emerging from the literature. This involved applying co-word analysis, which involves grouping keywords into clusters and treating these clusters as themes. Each theme obtained through this process is characterised by two key parameters: Density and centrality. These parameters are mapped onto a two-dimensional space, creating a strategic diagram [44].

In this diagram, the themes are plotted according to their centrality (x-axis) and density (y-axis). The density parameter represents the development degree of each theme, indicating the extent to which the theme has been explored and developed in the field. The centrality parameter represents the relevance degree of each theme, indicating its importance and significance within the field.

The strategic diagram for the relevant literature is presented in Figure 7 as a thematic map, providing a visual representation of the themes and their relationship within the research field.

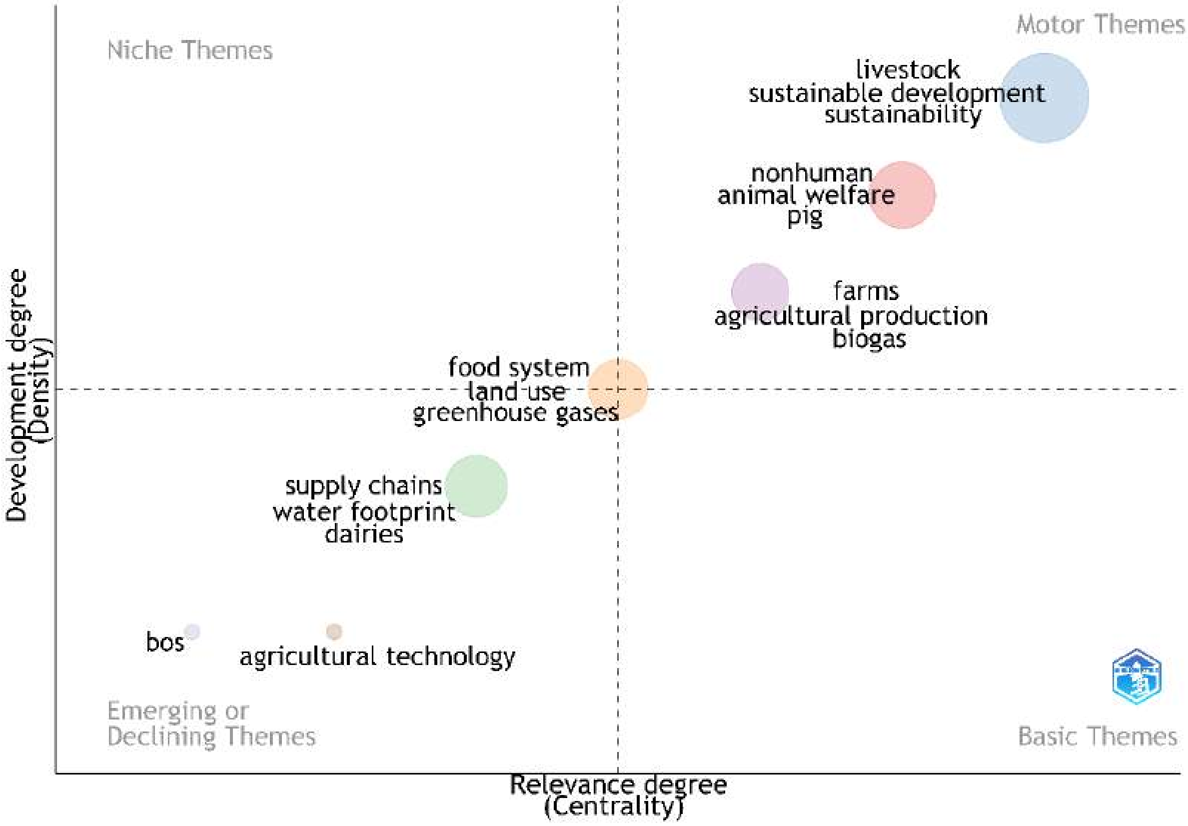

Figure 7: Thematic map.

A thematic map is a very intuitive plot, and we can analyse themes according to the quadrant in which they are placed. Looking at the thematic map in Figure 7 we can see that there is one theme that does not belong to any of the quadrants. This theme has medium density and centrality, meaning that it is neither well-developed nor highly relevant within the research field. The cluster of keywords for this theme is food system, land use and greenhouse gasses.

The themes in the upper-left quadrant have high density and low centrality, indicating that they are well-developed but not particularly important for the field. These themes are known as “niche themes”. In the relevant literature, no themes were identified in this quadrant.

Themes in the lower-right quadrant have low density and high centrality meaning that they are important for the research field but not yet well-developed. These themes are known as “basic themes”. In the relevant literature, no themes were identified.

Themes in the upper-right quadrant have both high centrality and density, meaning that they are both well-developed and important for the structuring of the research field. They are known as “motor themes”. In the relevant literature, three themes were identified in this quadrant: “farms, agricultural production and biogas”, “nonhuman, animal welfare and pig”, and “livestock, sustainable development and sustainability”.

The lower-left quadrant contains themes that are both weakly developed and unrelated. These themes have low density and low centrality, mainly representing either emerging or declining themes. Three themes were identified in this quadrant within the relevant literature: “Supply chains, water footprint and dairies”, “agricultural technology”, and “bos”.

The strategic diagram highlights the relative importance and development of each theme within the research field. This information is valuable for guiding future research directions, identifying gaps in the literature, and understanding the overall structure and evolution of the research field.

3.2.2 Keywords

The word cloud of the keywords, illustrated in Figure 8, was used to identify the key themes across the literature. As seen from this figure food security, livestock, and livestock production were the most used keywords throughout the relevant literature.

Figure 8: Word cloud.

The above keywords were organised into two sections: Sustainability factors and type of animal-source food. By using the keywords, it will show us the type of factor each article focuses on as well as the type of animal-source food that was focused on. This will identify how much literature there is on certain topics which can then be used to identify the gaps in the literature.

Table 3 provides a comprehensive overview of the sustainability factors identified from the keywords in the literature, and it also illustrates the number of documents per factor. This overview allows an understanding of the thematic focus of the literature and how different sustainability concepts are being discussed. The table categorises each sustainability factor according to its dimension (environmental, social or economic). This gives a sense of the distribution of the research field. By examining the distribution of the research field across these dimensions, areas that may be underrepresented in the current literature can be identified. This can guide future research efforts to address gaps in the existing knowledge base.

Table 3: Sustainability factors and corresponding references.

Sustainability dimension	Sustainability factor	List of reference	Number of documents
Environmental sustainability	Greenhouse gas emissions	[2], [6], [8], [9], [15], [17], [18], [21], [22], [24], [25], [28], [29], [30], [31], [32], [33], [35], [37], [41]	20
	Fertiliser	[8], [15], [17], [19], [20], [21], [22], [24], [25], [28], [32], [33]	12
	Water footprint	[2], [6], [8], [20], [21], [22], [23], [27], [32], [35], [38], [39]	12
	Land use	[6], [9], [15], [16], [17], [18], [19], [21], [25], [26], [27], [28], [32], [39], [41]	15
	Feed	[2], [6], [8], [16], [17], [18], [19], [21], [27], [28], [29], [32], [34], [35], [36], [37], [39], [41]	18
	Manure	[2], [3], [6], [7], [15], [17], [20], [21], [22], [24], [25], [26], [28], [31], [32], [33], [35]	17
Social sustainability	Food security	[6], [8], [9], [17], [19], [20], [21], [22], [25], [30], [31], [35], [37], [40]	14
	Animal welfare	[3], [6], [7], [16], [18], [26], [28], [29], [30], [31], [34], [36], [40]	13
All the sustainability dimensions	Food waste	[6], [28], [33], [34], [35], [37], [41]	7
	Precision livestock farming	[6], [18], [22], [30], [31], [34], [36], [40]	8

The environmental sustainability dimension includes the following factors: Greenhouse gas emissions, fertiliser, water footprint, feed, and manure. Greenhouse gas emissions refer to the release of gases such as carbon dioxide, methane, and nitrous oxide into the atmosphere, which contribute to climate change [17]. Fertilisers are chemicals used to enhance crop growth [33]. The water footprint refers to the total amount of water used and reducing water usage is vital for sustainability [23]. Land use refers to how land is managed and utilised for agriculture. Sustainable land use practices ensure that natural ecosystems are preserved, and resources are used efficiently [17]. The feed used for livestock can have significant environmental impacts, such as water pollution and greenhouse gas emissions. Sustainable feed options are essential for maintaining ecological balance [41]. Manure from livestock can be a significant source of pollution if not managed properly. Sustainable manure management practices can help reduce environmental impacts [24].

The social sustainability dimension includes food security and animal welfare. Food security refers to the availability and access to sufficient, safe, and nutritious food [17]. Animal welfare refers to the treatment and living conditions of animals raised for food [30].

There are two factors namely food waste and precision livestock farming that has an impact on all three sustainability dimensions. Food waste refers to the loss or disposal of edible food [37]. Precision livestock farming involves using technology and data analysis to optimise livestock production, reduce waste, and improve animal welfare [34].

From this analysis it is clear that the environmental sustainability dimension is the most talked about in literature. It is also clear that there are no articles that talk about factors that solely belong to the economic sustainability dimension. The economic sustainability dimension is only mentioned with factors that contribute to all three dimensions.

The factor that is referred to in most documents is greenhouse gas emissions with 20 documents, followed by feed and manure with 18 and 17 documents respectively. The factors that are referred to in the least number of documents is food waste and precision livestock farming with 7 and 8 documents respectively.

Four documents focus on innovative solutions that integrate multiple sustainability dimensions, such as turning food waste into feed for animals or turning manure into fertiliser for the land [24], [33], [37], [41]. These solutions demonstrate the potential for interdisciplinary approaches to address sustainability challenges. Three documents focus on calculating factors like emissions and water usage to make conclusions about sustainability [20], [23], [25]. This highlights the importance of data-driven decision-making in sustainability research.

Overall, this analysis shows the widespread knowledge across the research field, but it also indicates the need for more comprehensive studies that consider all three sustainability dimensions and address the interconnected factors.

Table 4 provides an overview of the type of animal-source food, identified from the keywords, that the literature was conducted on. This table categorises the documents by animal-source food and includes the number of documents associated with each. The purpose of examining this table is to gain insight into the specific animal-source foods that were studied in the literature, which can help identify trends and patterns in the research.

Table 4: Type of animal-source food and corresponding references.

Animal-source food	List of reference	Number of documents
Cattle/beef	[2], [3], [6], [8], [9], [16], [17], [18], [19], [20], [21], [23], [24], [25], [26], [27], [30], [31], [32], [33], [34], [35]	22
Diary Milk	[2], [9], [17], [19], [20], [21], [23], [24], [25], [27], [30], [31], [32], [33], [35], [38]	16
Poultry	[2], [9], [17], [19], [20], [23], [24], [25], [27], [29], [30], [31], [32], [36], [40]	15
Pig/pork	[2], [7], [9], [17], [19], [20], [23], [24], [25], [27], [28], [30], [31], [32], [36], [40]	16
Sheep	[8], [17], [19], [20], [23], [25], [30], [31]	8
Seafood	[19], [25], [30]	3
Agriculture	[15], [22], [37], [39], [41]	5

This table indicates that cattle/beef is the most researched animal-source food category with 22 documents, indicating significant interest and attention in this area. Dairy milk and pig/pork is the second most researched category with 16 documents, followed by poultry with 15 documents, suggesting that these are also prominent areas of research. The least represented categories are sheep and seafood with 8 and 3 documents respectively, highlighting underexplored areas. It is important to note that the agriculture category includes 5 documents, which focusses on broader aspects of agriculture involving both crops and livestock. The table further suggests that only 7 out of the 33 documents cover all animal-source food categories, excluding seafood. This indicates that this field is not extensively researched.

4 DISCUSSION

When dealing with complex systems, it is important to recognise the interplay between associated keywords and their influence on each other. The three main keywords in this study are animal-source foods, sustainability, and supply chains. To understand the current state of research in these areas, it is crucial to analyse the number of documents at each intersection of these keywords.

The middle intersection, which overlaps all three keywords, was determined in Section 2 using the entire primary search strategy. By using this primary search strategy and excluding each keyword at a time, the number of documents for each intersection was established. The Venn diagram in Figure 9 shows the number of documents associated with each intersection.

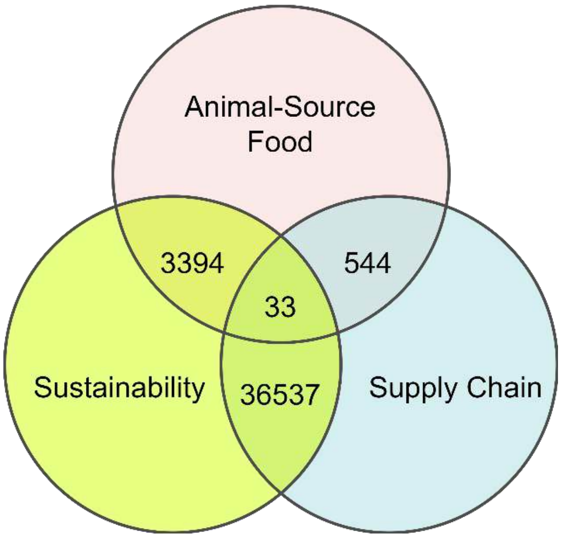

Figure 9: Venn diagram.

The largest number of documents (36,537) is found at the intersection of supply chains and sustainability, indicating that the sustainability of supply chains is a well-researched topic. This is likely due to the growing awareness of the environmental and social impacts of supply chains and the need for more sustainable practices.

The second-largest number of documents (3,394) is found at the intersection of animal-source foods and sustainability, suggesting that the sustainability of animal-source food production is also a significant area of research. This could be related to concerns about the environmental impact of livestock farming and the search for more sustainable methods of animal-source food production.

The smallest number of documents (544) is found at the intersection of animal-source foods and supply chains, indicating that the specific aspects of supply chains related to animal-source foods have received less attention. This could be due to the complexity of the topic, which involves considering both the nutritional and environmental aspects of animal-source foods.

The lowest number of documents (33) at the intersection of all three themes suggests that there is a gap in the literature regarding the specific combination of animal-source foods, sustainability, and supply chains. This gap presents an opportunity for further research to explore the interplay between these topics and provide insights into the development of sustainable and equitable supply chains for animal-source foods.

The highest number of documents at each individual intersection suggests that these topics are being studied extensively, but the relatively low number of documents at the intersection of all three (33) indicates that the specific combination of these themes has not been thoroughly explored yet.

The research field of animal-source food sustainability has garnered significant global interest, as evident by the wide geographic distribution of research output and the contributions of various nations to the literature. This widespread interest, combined with the prominent keywords identified, suggests a substantial gap in the literature that merits further exploration.

A key gap identified through content analysis is the lack of literature that simultaneously focuses on all three dimensions of sustainability (environmental, social, and economic) in the context of animal-source food supply chains. The literature also predominantly focuses on specific types of animal-source foods, which suggests a need for more comprehensive research that addresses animal-source foods in general, rather than focusing on specific types.

To address these gaps, future research should adopt a more holistic approach that integrates all three dimensions of sustainability while considering the entire animal-source food supply chain. This would provide a more comprehensive understanding of the challenges and opportunities for achieving sustainable practices in the production and consumption of animal-source foods.

5 CONCLUSION

This article presented a systematic literature review to study the existing literature on the sustainability impact of animal-source food supply chains. This review aimed to explore the intersection of animal-source food, sustainability, and supply chains, to identify the latest developments and knowledge gaps in the research field. Through the analysis of 33 documents, the review highlighted a substantial gap in the literature, indicating that there is a critical need for more comprehensive research that integrates all three dimensions of sustainability in the context of animal-source food supply chains.

The review highlighted that while there is a significant body of literature on individual aspects of sustainability, animal-source foods, and supply chains, there is a notable lack of research that simultaneously addresses all three themes. This gap suggests significant potential for future research to delve deeper into the themes and develop a more holistic approach to integrate multiple sustainability dimensions.

The knowledge gathered from this review serves as a theoretical basis for future research, which could support the development of more effective sustainability practices in animal-source food supply chains. By addressing the identified gaps, future research can advance our understanding of the complex interplay between animal-source foods, sustainability, and supply chains, ultimately informing more sustainable and equitable animal-source food supply chains.

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SHINING LIGHT ON 20 KEYS IMPLEMENTATION AT A SOUTH AFRICAN AGRICULTURAL COMPANY USING FOCUS GROUPS

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ABSTRACT

This research employs focus groups as a crucial methodological tool to gather qualitative insights into the implementation of the 20 Keys methodology within a South African Agricultural Company by examining the drivers and barriers influencing its success. The diverse set of stakeholders participate in focus groups, which facilitate an in-depth exploration of perspectives, experiences and perceptions related to the 20 Keys implementation process. These discussions focus on identifying key drivers contributing to successful implementation and barriers hindering progress within agricultural production. Through this structured approach, the focus groups aim to unveil aspects of organisational culture, change readiness, and industry-specific challenges that influence the effectiveness of the 20 Keys methodology. This study contributes insights for organisations seeking to create consistent and effective Continuous Improvement practices across operational sites, ultimately enhancing operational performance and fostering a culture of continuous improvement.

Keywords: drivers, barriers, continuous improvement, 20 keys, agriculture, production, south africa

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1 INTRODUCTION

In today's fast-paced world, marked by relentless competitiveness and an unyielding chase for higher profitability, organisations must continuously innovate and adapt to thrive in an ever-evolving landscape. New advanced technologies, like artificial intelligence, are reshaping all market sectors. Manufacturing companies, therefore, need new approaches to help them get ready for a faster, more sustainable future[1-3].

Organisations have turned to quality and Operational Excellence (OE) frameworks to adapt in order to obtain competitiveness in an increasingly dynamic business environment where change is the only constant [4, 5]. The general term "continuous improvement" (CI) has become the focus of arguments ever since the industrial sector started encountering intense global rivalry [6]. The Industrial Engineering profession has emerged as a field that emphasises productivity enhancements in both service and manufacturing environments as the design, enhancement, and installation of integrated systems of people, material, information, equipment, and energy are the focus of industrial engineering [7].

Some of the main principles of continuous improvement are identifying and eliminating inefficiencies, reducing waste, and improving processes throughout an organisation connected to the pursuit of better service, processes and products in organisations [8, 9]. This philosophy aligns with the evolving business landscape, which demands adaptability and responsiveness to remain competitive. Implementing continuous improvement involves a structured approach to problem-solving, data-driven decision-making, employee involvement, and a culture of learning and improvement. The operational advantages of participative management are emphasised in the literature on contemporary management ideas like Lean Management/Manufacturing, Total Quality Management (TQM), and Six Sigma [8, 10].

The 20 Keys Continuous Improvement Methodology, developed by Iwao Kobayashi, is an approach to enhancing organisational performance. It draws inspiration from Lean Manufacturing and Total Quality Management (TQM) principles, especially regarding waste elimination to streamline a process. This methodology embraces 20 "keys", each addressing specific aspects of an organisation, such as leadership, process optimisation, and employee engagement[11]. By optimising these areas, organisations can achieve significant improvements that collectively drive efficiency, productivity, and product quality. Perhaps most importantly, the methodology promotes a culture of continuous improvement and encourages employees at all levels to actively participate in identifying problems and suggesting solutions before its implementation. It has gained global recognition for its ability to cultivate sustainable excellence and adaptability across various industries and sectors [11].

The agricultural organisation investigated in this study has various operational sites specialising in agricultural production. These operational sites include a wheat and maise mill, a soya oil press, a chicken abattoir and two animal feed plants. With help from a 20 Keys licensed third-party consulting company, the 20 Keys methodology was introduced first to the chicken abattoir in 2016. From there, seeing the results and benefits of the system, implementation slowly but surely began at the other operational sites.

The progress of 20 Keys implementation on these sites is measured monthly/bimonthly by scoring a particular key using pre-drafted, key-specific 20 Keys check sheets [12].

The problem is that these different scores indicate that some operational sites have a slower 20 Key adoption rate than others, even though they have implemented 20 Keys over the same or longer periods.

The study aimed to investigate the barriers and drivers at the lagging site by identifying the employees' experiences.

2 LITERATURE REVIEW

The culture of Continuous Improvement and its tools and methods are critical to maintaining a manufacturing company's competitive position. However, research has shown that as many as two out of three continuous improvement programs fail when they do not meet goals and expectations[2].

2.1. Involvement and commitment of managers

The literature stresses how important it is that management shows commitment towards continuous improvement [13], both emotionally and physically [14]. Management supporting improvement activities has been shown to aid in the successful implementation of continuous improvement activities[2].

On the other hand, it is very important for managers to coach and empower their employees to encourage proactive thinking by workers, encouraging improved employee engagement and satisfaction[14].

2.2. Training, development, culture, and employee engagement

Employee performance impacts the bottom line of an sorganisation. Providing the correct training and resources will aid them in achieving their short-and long-term goals. This contributes to the company achieving its overall goals [15].

The literature also shows how employee engagement goes hand-in-hand with higher employee performance outcomes, which include productivity, employee retention, profitability, and customer and employee satisfaction[16].

2.3. Effective communication

Conveying the vision of change, improvement and goal alignment to the employees without effective communication structures is a guaranteed method for these continuous improvement initiatives to fail [14]. While effective communication is fundamental to the successful implementation of continuous improvement systems[13], poor communication can be equally detrimental to the same[17]. sThus, good communication is crucial for information flow within an organisational hierarchy, ensuring employees are aware of the goals and aims of the continuous improvement initiatives and encouraging higher employee engagement[18].

3 CURRENT STATE ANALYSIS

Measures of 20 Keys progress include the number of improvement suggestions given by the employees on site, as well as information obtained from two different anonymous Key surveys. The first survey collects information about Key 2 - Goal Alignment.

These questions focus mainly on the employee's function in the company, the quality of communication within their team and whether their team is working towards the same goals as the company. The second survey collects information about Key 10 - Workplace Discipline. These questions are oriented around five factors - Respect, Communication, Consultation, Reporting and Overall Discipline. The Key 10 surveys provide more information on how communication is done throughout individual departments, whether employees feel respected, whether employees are aware of specific rules and the importance of abiding by them, and how problems are addressed in their teams and the overall work environment.

According to the 20 Key measurements mentioned above, one operational site shows slower 20 Keys adoption than others, and the elements influencing successful 20 Keys practices (drivers) and the barriers impeding development thus need to be identified.

The slower progress of Site D can be seen in Figure 1 for Key 1 - Cleaning and Organising. This Key's check sheet covers basic and effective housekeeping, safety conformances, disposal of unnecessary items, basic ergonomics, and effective use of the 5S process, which includes Sort (Seiri), Set in Order (Seiton), Shine (Seiso), Standardize (Seiketsu), and Sustain (Shitsuke).

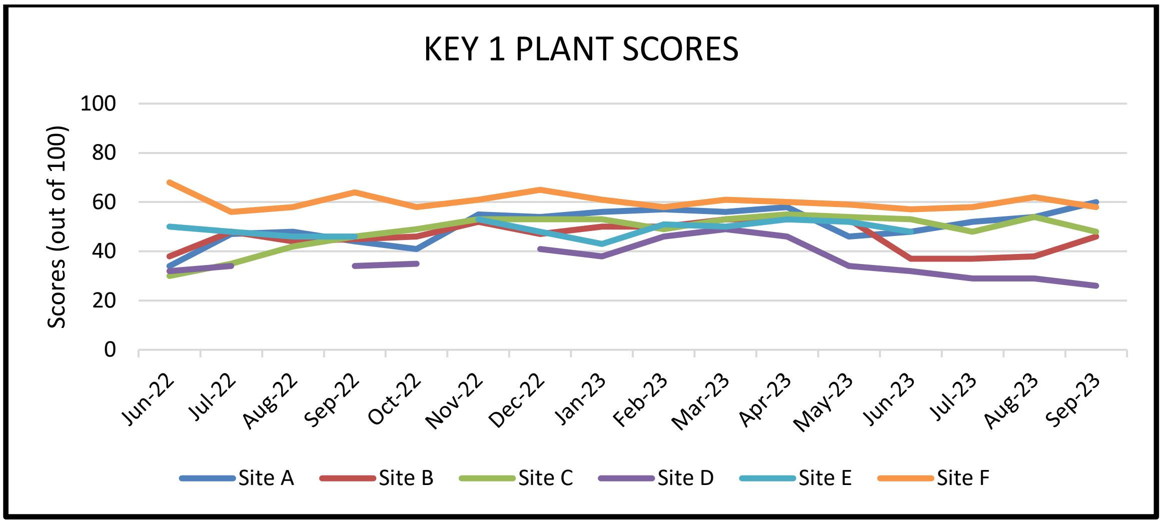

Figure 1: Plant Key 1 Progress over 12 months

The discontinuity indicated by the disconnected line of Site D is a result of geographical location and travelling distances, making it difficult to maintain a monthly inspection, as well as a worker's strike that caused the cancellation of an inspection as a matter of safety. Site F is the benchmark as this site was the first to implement 20 Keys successfully up to international standards. Sites A, B, and C scored steadily over the 12 months, while Site D has not. Comparing sites C and D, where both sites have been implementing the 20 Keys methodology for the same period, Site C clearly shows a steady improvement, whereas Site D does not.

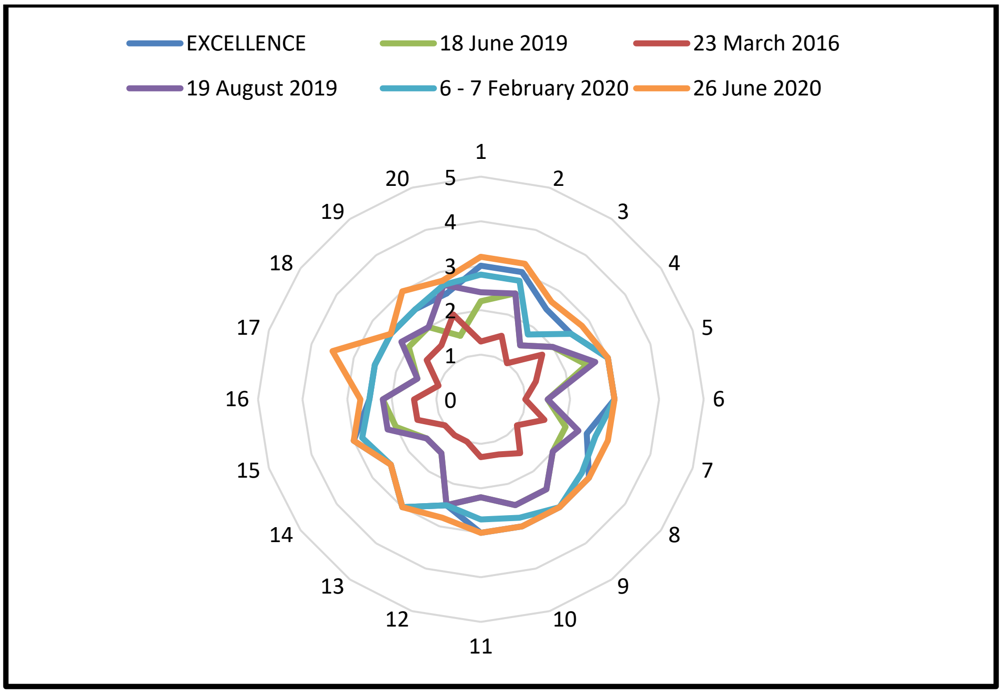

Figure 2: Radar Chart Representing the 20 Keys Progress of Site F

Another example of data obtained from the organisation can be seen in Figure 2. This radar chart is updated with each formal benchmarking done by a third-party Productivity and Management Consulting Company representative specialising in implementing the 20 Keys methodology. Professional 20 Keys implementation includes a benchmarking process done by an accredited third-party consulting company. This benchmarking process entails a two-to-three-day site inspection, resulting in a score for each of the 20 Keys. These scores are then summarised in a Radar chart.

Figure 2 shows how the Site has progressed over four years regarding its 20 Keys benchmarking results. It is evident that there was an improvement in each Key following each new benchmarking exercise.

The Radar charts of Site F, Figure 2 and Site D, Figure 3, will be compared. Sites A, B and C have only undergone one formal benchmarking exercise and will not be compared in this report.

Site F has successfully implemented 20 Keys and has received the Excellence Award for this successful implementation. This means that Site F is categorised as a World Class Facility according to the original standards set out by Kobayashi. Site F has had six benchmarking inspections within four years. Between 2016 and 2019, there was a pause in 20 Keys implementation as many capital projects took place during this time. The details of the Radar Chart in Figure 2 have been expanded on in Table 1.

Table 1: Site F Benchmarking Results 2016 -2022

Site F **BENCHMARK RESULTS**		**23 March 2016**	**18 June 2019**	**19 August 2019**	**21 October 2019**	**7 February 2020**	**26 June 2020**	**EXCELLENCE**
1	Cleaning & organising	1.30	2.20	2.40	2.20	2.80	3.20	**3.00**
2	Rationalising the system / Goal Alignment	1.50	2.50	2.50	2.20	2.80	3.20	**3.00**
3	Small Group Activities	1.00	1.50	1.50	1.50	1.80	2.70	**2.50**
4	Reducing Work-in-process	1.70	2.00	2.00	2.00	2.50	2.80	**2.50**
5	Quick Changeover Technology	1.30	2.50	2.70	2.80	3.00	3.00	**3.00**
6	Kaizen of Operations	1.00	1.50	1.50	1.50	3.00	3.00	**3.00**
7	Zero Monitor Manufacturing/Production	1.50	2.00	2.30	2.30	2.70	3.00	**2.50**
8	Coupled Manufacturing/Production	1.00	2.00	2.00	2.00	2.80	3.00	**3.00**
9	Maintaining Machines & Equipment	1.50	2.50	2.50	2.80	3.00	3.00	**3.00**
10	Workplace Discipline	1.30	2.50	2.50	2.50	2.80	3.00	**3.00**
11	Quality Assurance	1.30	2.20	2.20	2.00	2.70	3.00	**3.00**
12	Developing Your Suppliers	1.00	2.50	2.50	2.50	2.50	2.80	**2.50**
13	Eliminating Waste	1.00	1.50	1.50	1.50	3.00	3.00	**3.00**
14	Empowering Employees to Make Improvements	1.00	1.50	1.50	1.50	2.50	2.50	**2.50**
15	Skill Versatility & Cross Training	1.50	2.00	2.20	2.20	2.80	3.00	**3.00**
16	Production Scheduling	1.50	2.20	2.20	2.20	2.50	2.70	**2.50**
17	Efficiency Control	1.00	1.50	1.50	2.00	2.50	3.50	**2.50**

Site F **BENCHMARK RESULTS**		**23 March 2016**	**18 June 2019**	**19 August 2019**	**21 October 2019**	**7 February 2020**	**26 June 2020**	**EXCELLENCE**
18	Using Information Systems	1.50	2.00	2.20	2.30	2.50	2.50	**2.50**
19	Conserving Energy & Materials	1.50	2.00	2.00	2.00	2.50	3.00	**2.50**
20	Leading Technology / Site Technology	2.00	1.50	2.70	2.70	2.70	2.80	**2.50**
	Average - 20 Keys	1.32	2.01	2.12	2.14	2.67	2.94	**2.75**
	Standard deviation	0.51384902094538						

Table 1 shows how Site F improved by 122.72% over four years and received the Excellence Award in 2020. This was calculated using the first (2016) and last(2020) benchmarking results when the site received the Excellence Award.

Site D has had four benchmarking inspections to date, as displayed in the Radar Chart in Figure 3.

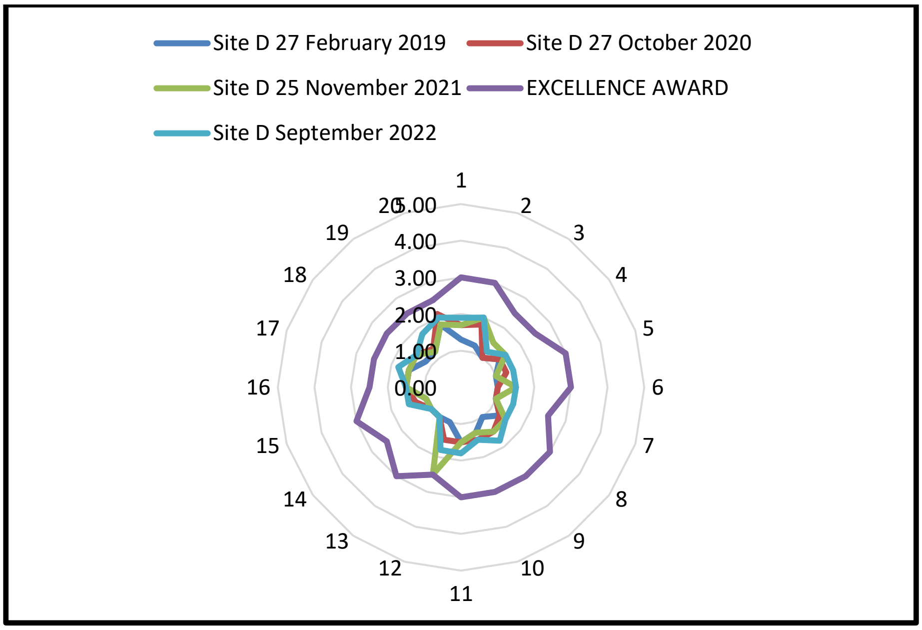

Figure 3: Radar Chart Representing 20 Keys Progress of Site D

The Radar Chart shows that Site D has made little and inconsistent progress since the first benchmarking of 2019. Table 2 contains a more detailed breakdown of the benchmarking done at Site D since 2019.

Table 2: Site D Benchmark Results 2019-2022

	Site D **BENCHMARK RESULTS**	**27 February 2019**	**27 October 2020**	**25 November 2021**	**22 September 2022**	**EXCELLENCE**
1	Cleaning & organising	1.30	1.70	1.70	1.90	**3.00**
2	Rationalising the system / Goal Alignment	1.20	1.80	2.00	2.00	**3.00**
3	Small Group Activities	1.00	1.00	1.50	1.20	**2.50**
4	Reducing Work-in-process	1.30	1.30	1.50	1.50	**2.50**
5	Quick Changeover Technology	1.00	1.30	1.00	1.50	**3.00**
6	Kaizen of Operations	1.00	1.00	1.50	1.50	**3.00**
7	Zero Monitor Manufacturing/Production	1.00	1.00	1.00	1.50	**2.50**
8	Coupled Manufacturing/Production	1.30	1.30	1.50	1.50	**3.00**
9	Maintaining Machines & Equipment	1.00	1.50	1.50	1.80	**3.00**
10	Workplace Discipline	1.30	1.50	1.30	1.50	**3.00**
11	Quality Assurance	1.50	1.50	1.50	1.80	**3.00**
12	Developing Your Suppliers	1.00	1.50	2.50	1.80	**2.50**
13	Eliminating Waste	1.00	1.00	1.00	1.00	**3.00**
14	Empowering Employees to Make Improvements	1.00	1.00	1.00	1.00	**2.50**
15	Skill Versatility & Cross Training	1.00	1.30	1.00	1.50	**3.00**
16	Production Scheduling	1.50	1.50	1.50	1.50	**2.50**
17	Efficiency Control	1.50	1.50	1.50	1.80	**2.50**
18	Using Information Systems	1.20	1.50	1.50	1.50	**2.50**
19	Conserving Energy & Materials	1.20	1.30	1.20	1.80	**2.50**
20	Leading Technology / Site Technology	1.80	2.10	1.80	2.00	**2.50**
	Average - 20 Keys	**1.2**	**1.4**	**1.5**	**1.6**	**2.75**
	Standard Deviation	0.14790199457749				

The results in Table 2 show a constant 0.1-point improvement with every benchmarking inspection or an overall improvement of 33,33% over the four years. Table 2 shows that only a few keys had incremental improvements but failed to show sustainable progress.

The evidence, presented visually, clearly shows a lack of progress at Site D within this organisation. This difference in implementation progress raises questions regarding the causes of the slower development and potential barriers to successful continuous improvement method deployment at Site D.

Sites D and F have similarities and differences, as summarised in Table 3.

Table 3: Similarities and Differences of Sites D and F

Similarities	
Site D	Site F
Agri-Processing sites.	
Need to be food safety accredited.	
Located in rural areas.	
Same implementation period being investigated (4 years).	
Differences	
Site D	Site F
Maize Mill	Chicken abattoir
+- 190	+- 1600 employees
Differences	
Had an industrial engineer do on-site visits frequently to drive continuous improvement progress.	Had an on-site industrial engineer driving continuous improvement progress.
Located in the Free State province	Located in the Limpopo Province

4 RESEARCH METHOD

4.1. Focus group

For this study, qualitative data was collected using a focus group of selected employees of site D. The researcher's role is that of an industrial engineer within the organisation and is part of the continuous improvement team responsible for implementing 20 Keys on site. Bias was addressed by reporting the results of this focus group verbatim. The researcher facilitated this focus group after receiving training on conducting a focus group. The focus group was to determine the drivers and barriers to 20 Keys implementation and adoption using the employees' onsite experiences. The focus group focused on the following questions:

1. What, in your opinion, are the barriers to successful 20 Keys implementation/adoption?
2. What do you think can be done to mitigate these barriers?
3. What, in your opinion, are the key drivers to successful 20 Keys implementation/adoption?
4. What do you think can be done to enhance these drivers?

The rest of the questions were probing questions used to get more information and opinions from the participants.

The focus group met for approximately two hours, and social breaks, refreshments, and snacks were provided to all participants.

4.2. Participants

The focus group consisted of 12 employees of Site D. For employees to be eligible and form part of the focus group, the requirements were that the employee must:

- Have had 20 Keys training specifically for Key 1, 2, or 3.
- Have been with the company for more than three Key 1 and Key 2 inspections.
- Be full-time employees of the company.
- Willing to participate in the study.

The age of these participants varied from 28 to 57, with some employees employed at the company since the first 20 Keys implementation in 2019. The focus group was held to get employees at different departments and management levels involved in identifying department-specific experiences, challenges and successes in their roles at different hierarchical levels. They perceive the drivers and barriers to continuous improvement differently. Production and maintenance supervisors, finance and admin supervisors/employees known to be honest and outspoken during similar discussions were chosen to be a part of the focus group. The Managing Director, Continuous Improvement Manager and Operations Manager were explicitly excluded from the focus group as these individuals might have influenced the answers given by the other employees. The participants were also diverse in terms of gender and ethnicity.

Ethical principles were adhered to for the duration of this study. The researchers completed ethics training and registered the study with the academic research ethics committee.

Ethical principles were adhered to for the duration of this study. The researchers completed ethics training and registered the study with the academic research ethics committee.

5 RESULTS AND DISCUSSION

After conducting the focus group, the transcript was correctly formatted to be used and analysed using Atlas.ti, a qualitative data analysis programme. This software identified barriers, drivers, and improvement ideas using codes to identify comments with the highest frequency.

The barriers identified during the focus group were:

1. A lack of understanding;
2. Resistance to change;
3. The time-consuming nature of the system;
4. The lack of management support and understanding;
5. The system feels like a burden and not something that makes work easier;
6. A lack of ownership from employees and department manager;
7. Scepticism regarding the system being implemented;
8. Being forced to adopt the system;
9. Frustration with the company;
10. Lack of communication;
11. The financial implication;
12. Lack of inclusion in decision-making regarding the implementation of the system;
13. The negative culture on-site;
14. The low literacy levels of the employees on-site;
15. The lack of discipline of the employees on-site;
16. The lack of buy-in from employees and management;
17. The lack of effective training;
18. The lack of customisation of the system;
19. The inconvenience of implementing the system (time-consuming, feels like a burden, bigger workload); and

20. Little to no recognition was received for good work.

During the analysis, it became evident that there was a lack of understanding of the 20 Keys system implementation and purpose. During the focus group, participants highlighted the fact that not everyone on site understands the 20 Keys system and the question surrounding the purpose of the implementation, especially Key 1. For example, they believe that if an employee has a specific production role, they should not be responsible for keeping their area clean since there is a team responsible for the cleaning onsite.

There also exists a resistance to change, which participants felt is related to many of the other barriers mentioned, such as scepticism about the system, the lack of ownership and management support, feeling insulted resulting from 20 Keys inspections as it feels as though someone is telling you, after many years, that you are doing your job incorrectly. Also, some employees do not understand why changing an already successful way of operating is necessary. As mentioned in the focus group, "They know how to do their job. Now someone comes in, gives them more work, changes the way the employee must do it but still expects it to be done in the same amount of time". This causes the employees to see the implementation in a negative light leading to a lot of resistance.

The participants also mentioned how the system feels like a burden and is too time-consuming. This refers to the meetings and graph updating necessary for Key 2 - Goal alignment and the time it takes to organise a space for Key 1. Key 2 focuses on the organisational structure, continuous communication within the team to ensure everyone is on the same page and the discussion of important Key Performance Indicators within the team. The Key uses graphs that need to be updated frequently and is seen as a burden and just an extra job taking up precious time. They feel like the system is just adding to their workload and it is not necessarily benefitting them the way they were told it would.

The analysis also identified a lack of management support and understanding, referring to the employees feeling like the system was forced "down their throats", they are not given the recognition they deserve after successful seasons, and the buy-in from management is low as they feel management is too busy and does not try to understand the implementation needs and differences within the different departments.

The lack of ownership by shop floor employees, heads of departments, and management was also identified through the analysis. This meant no one was leading by example and showing a positive attitude towards 20 Keys implementation, making the adoption of the system by the rest of the employees less likely.

Overall, scepticism about the 20 Keys system was also evident. Some participants mentioned that 20 Keys is a Japanese system, that it will not work in South Africa, where the culture is entirely different. Participants also mentioned a lack of understanding regarding how the strategy would work for different industries as they are different, which can be due to misunderstanding the concept and purpose of the system and a research gap regarding these cultural differences.

After the barriers were identified, the drivers were also identified by asking the participants what, in their experiences onsite, the key drivers of positive implementation progress were. The drivers identified by the focus group were:

1. Proper communication throughout departments and from the implementation team;
2. Physical results;
3. Visible results;
4. Proper understanding;
5. Proper recognition;
6. Accessible training and communication;
7. Motivation;

8. Less stressful work environment;
9. Making adoption of the system easier; and
10. Management seeing the results.

Participants stated that when proper communication was present, employees understood exactly what was expected of them and why. Tasks were then completed quicker and without frustration because of missing information. Physical results could be felt when the work environment improves, work is easier and quicker, and the employees could finally start to understand why 20 Keys could be beneficial and the purpose of the system.

The analysis showed that visible results were a key driver for the on-site employees. The environment looks better and has less clutter, and one can see the results of the improvements made with hard work. It was also evident that understanding the purpose of 20 Keys implementation through providing training and seeing results from other South African Industries implementing 20 Keys was a driver for the implementation on site as employees now understood the bigger picture.

Another key driver, according to the employees, is recognition. When it was given after success, they felt they were seen by management, and employee morale improved.

With both the barriers and drivers identified by the on-site employees, it was important to include them in the possible solutions for minimising the barriers and maximising the drivers of 20 Keys implementation/adoption on site. Questions 2 and 4 from the focus group questions assisted with this. The discussion took place, and employees offered their ideas on how to combat the barriers they experienced and what they thought were missing in the current implementation strategy that caused the slow progress on site.

Improvement ideas identified during the focus group were:

1. Effective training;
2. System customisation;
3. Improved communication from the implementation team;
4. Emphasising physical and visible results;
5. Incentives;
6. Creating health competition;
7. Increased involvement from management;
8. Being able to compare their results to other sites and collaborating with them continuously;
9. Making employees feel more included in decision-making and the implementation of the system;
10. Creating a designated team for implementation;
11. Feeling included in the implementation process and strategy;
12. Including 20 Keys in the induction onsite;
13. Developing standard operating procedures; and
14. Employees (especially HODs) taking ownership of their areas and teams.

From the list above, the most frequent improvement idea identified in the focus group was how employees need more effective training. This includes making the training easily accessible and understandable in all spoken languages, not just generic and theoretical training material but using more visual material and, importantly, providing adequate support afterwards.

There was also a focus on how 20 Keys is a system built for implementation in Japan and that it will not work in South Africa as the cultures are different. This initiated a discussion on the possibility of the system being customised to fit the different departments, as they have different processes and needs for continuous improvement.

Another important aspect the participants felt is crucial regarding management involvement is giving the necessary recognition and communication regarding results from implementation, whether in the form of incentives, team get-togethers, or celebrations, to mention only a few of the ideas mentioned in the focus group.

Overall, improved communication between employees, management, and the implementation team is a common theme identified during the focus group session. Differences in interpretations of 20 Keys results and comments, language barriers, and basic feedback necessary for employees to know what is expected from them regarding 20 Keys were also identified.

The participants also mentioned the company's culture being an issue and how implementing these improvement ideas will increase employee morale, buy-in, and organisational culture.

After conducting the focus group and analysing the results, the need for a customised and improved implementation strategy is evident.

6 CONCLUSIONS AND RECOMMENDATIONS

This research focused on Site D, the site with the slowest implementation progress. After identifying the drivers and barriers through the experiences of the employees of Site D, it was found that there is a need for the implementation strategy to be revised and customised to suit the culture and environment of the site in question.

This study emphasises the importance of continuously involving the company's employees in implementing a new system, particularly if they are the ones most impacted and responsible for the overall success of the implementation[15]. Ensuring that the employees are included in the decision and the method while simultaneously ensuring they have the necessary support from management and the specialised implementation team cannot be overlooked. This support includes but is not limited to, training, recognition, effective and accessible communication channels, continuous support regarding uncertainty/enquiries about the system implemented, and strategy, to name a few. Making sure that employees have access to these resources[19]. This will assist the organisation and employees attain diverse goals, such as improving the morale, sense of security, employee engagement, and overall fundamentals necessary to perform a particular job, especially regarding continuous improvement[14, 15].

Employees from the shop floor to the management level should be in continuous communication regarding the necessary resources, challenges faced, results and feedback on implementing 20 Keys. This will ensure that the employees feel included and valued in their company. This links to how important it is to provide the correct resources when employees need assistance with implementation[20].

Management involvement is a crucial factor in implementing any continuous improvement initiative. This includes support, trust, communication, and overall commitment to the initiative[13, 21] This aligns with the need of the employees for more involvement from management onsite

After an investigation of the problem by the focus group and the analysis of the focus group data, it is evident that there is a need to design an improved implementation strategy on site.

This study could benefit other agri-processing industries as a guideline for implementing a continuous improvement system. Knowing which obstacles to expect and which key drivers to emphasise will aid in making the process of implementation easier.

The future objectives of this study are to develop an improved strategy for 20 Keys implementation in an agricultural company in South Africa. Making the culture and diversity of the employees a focus in this strategy is strongly recommended. This new strategy should focus on overcoming the barriers and maximising the drivers of 20 Keys implementation and adoption.

Following the same approach, applying the 20 Keys methodology or Continuous Improvement systems in different agricultural and non-agricultural industries can be investigated, thus making the new strategy applicable to different industries and not just agricultural production sites.

It is also recommended that the other sites mentioned in this paper be researched.

Shining a light can often lead to some less-than-ideal discoveries, but without the light, the path forward is dark and uncertain, which no company can afford in today's world.

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IMPACT OF TOTAL PRODUCTIVE MAINTENANCE ON CONVEYOR BELT RELIABILITY

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ABSTRACT

Modern day mining operations are highly mechanized. Productivity in such settings is critically reliant upon reliability of mechanical equipment. In processing industries, machinery typically operate as part of a process and the overall plant reliability is a function of sub-system and component reliability. A range of possible approaches can be applied to improve machine availability. This research follows a maturity model-based approach towards the maturity and effectiveness of Autonomous Maintenance and Focused Improvement pillars of Total Productive Maintenance applied to a case mine. Observation studies were conducted to evaluate maturity levels of Autonomous Maintenance and Focused Improvement pillars, followed by an intervention on the maintenance practices. The results from the short-term intervention reflected an improvement in the conveyor belt meantime between failure, meantime to repair, number of failures and overall equipment effectiveness.

Keywords: Maintenance, Conveyor belts, Availability

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1 INTRODUCTION

An underground coal mine in Mpumalanga services a coal power station. The mine consists of three shafts that are designed to produce 14Mtpa of thermal coal. The continuous miner sections and conveyor belts which transport coal to surface, are designed to operate 20 hours, 5 working days of the week.

Coal mines typically do not have storage facilities underground. Rock/coal aggregates are hauled up to surface simultaneously with mining. Conveyor belts are the main mode of materials handling in coal mining. Conveyor belts breakdown renders further mining impossible and significantly impact mine productivity. To improve availability and reliability, conveyor belts undergo planned maintenance twice. Major maintenance work is planned for non-production shifts.

Continuous miner sections are sensitive to conveyor belt breakdowns. High conveyor belt availability is critically important in these sections. An urgent need arises to improve availability and reliability of conveyor belts to ensure optimized production in the continuous miner sections.

In the current experimental study, we consider an auxiliary conveyor belt in the case mine. The research demonstrated positive impact of TPM on the availability of conveyor belt. The full roll out of Autonomous Maintenance and Focused Improvement pillars across all the conveyor belts is expected to contribute significantly to improved overall productivity.

The aim of this study was to implement selected Total productive maintenance pillars on conveyor belts to improve availability and productivity of continuous miner sections in underground coal mines. The following research questions were put forward:

1.1 What is the maturity level of autonomous maintenance principles and practices on the underground coal conveyor belt?

1.2 What is the maturity level of Focused improvement principles and practices on the underground coal conveyor belt?

1.3 What is the impact of autonomous maintenance principles and practices on the availability of the underground coal conveyor belt?

1.4 What is the impact of focused improvement maintenance principles and practices on the availability of the underground coal conveyor belt?

2 LITERATURE REVIEW

2.1 Coal transportation

The commonly used transportation system in underground coal mines is conveyor belts. A conveyor belt is a simple piece of equipment and the most common means of transportation of bulk materials [1]. The belt conveyor is designed to carry a greater diversity of products at the rates of thousands of tons per hour in a continuous and uniform stream over long distances than any other continuously operating mechanical conveyors. The purpose of systematic maintenance of conveyor belts is to keep the system running at maximum and consistent efficiency, quality, and reliability [1]. Providing proper access for easy to see, easy to reach, easy to inspect and easy to replace is a fundamental consideration for effective operation and maintenance of the belt conveyor system.

2.2 Maintenance

Maintenance is defined as the actions intended for preserving a component or returning it to the physical state deemed appropriate to fulfil production objectives [2]. Maintenance is essential to manage equipment failures and to ensure maximum availability of components for continuous production [3]. The objective of maintenance activities is to plan all required inspections, repairs, and replacements [2].

Maintenance management is defined as all the activities of management that determine maintenance objectives, strategies, and responsibilities. Maintenance management activities are implemented through maintenance planning, control, and supervision which in turn improve the economic aspects of the organization [7].

Maintenance management consists of wide range of tasks such as preventative maintenance, inventory and procurement, work order system, computerized maintenance management systems, technical and interpersonal training, operational involvement, proactive maintenance, and continuous improvement [8].

2.3 Total Productive Maintenance

Total Productive Maintenance is a continuous implementation and improvement program which particularly looks at maintenance of a production system focusing on equipment, process, and operator components [9]. TPM aims to optimize equipment availability and efficient management of plant assets [10]. TPM minimizes the probability of equipment failures, manufacturing of non-conforming products and the occurrence of safety accidents. The pillars of TPM are implemented according to the existing culture and internal structures within each organization [11].

There are five pillars of TPM as acknowledged by [12], and contrary to this, Ahuja [13] mentions ten concepts, where six are classified as pillars while the four remaining are considered as base steps. There are nine important TPM pillars as acknowledged by [14] . The common pillars discussed in literature are described below [15]:

2.3.1 Autonomous Maintenance -Autonomous maintenance is a maintenance system that aims to create the operators' sense of belonging within the organization and promote ownership on the equipment assigned to them [16]. Autonomous maintenance promotes a culture in which operators are encouraged to learn and obtain skills required for equipment problem diagnosis and improvement projects [17].

2.3.2 Focused Improvement Focused improvement is also referred to as the Kaizen pillar, which focused on activities that maximize equipment effectiveness through waste elimination [18]. Overall Equipment Effectiveness is a key measure of a successfully implemented Focused Improvement pillar. OEE is defined as the ratio between the time spent on producing goods of approved quality to the scheduled production time [19]. The main objective of OEE is to identify the losses categorized in availability, performance, and quality [20].

2.3.3 Education and Training -The elementary purpose is to increase the operators and the people involved morale and experience by providing skills and technical training [16]. This promotes eagerness to work and perform required functions effectively and independently [24].The training offered to operators and maintenance crew diminishes failures due to lack of skills.

2.3.4 Office TPM-The Office TPM pillar is applied to increase the administrative functions productivity and efficiency through the identification and elimination of losses [21]. Office TPM objectives include the development of highly efficient offices, provision of support to production departments focusing on the workplace and standardized work procedures effective organization [25]. Losses in costs including accounting, purchasing, market technology and loss of communication are some of the losses that can be addressed and avoided through effective implementation of Office TPM [23].

2.3.5 Safety, hygiene, and environment (SHE)-The purpose of SHE is to ensure a workplace where there are zero accidents, zero occupational diseases and zero environmental accidents [14]. [13] emphasized that organizations should treat people respectfully as well as the environment.

2.4 Evaluation scales for end-user satisfaction

There are three types of scales that can be used for preliminary client evaluation. A Likert scale may be used in the service industry and consists of a series of statements, where the participant is asked to agree or disagree with each statement. Numerical scales have equal intervals that separate their numeric scale points. Numerical scales are often 5-point scales but may have 7 or 10 points [26]. Numerical scales utilize numbers to determine the level of satisfaction brought by use of a product, service, or process. The Hybrid expectation scale outlines levels to which a solution or intervention impacts a product, service, or process outcome to meet customer needs and expectations [26]

3 METHODOLOGY

The application of experimental research principles allowed the researcher to conduct a before-and-after-intervention-analysis of production throughput in line with the availability of the conveyor belts. Observation research techniques were applied to measure the adoption level of TPM pillars. Table 1 illustrates the 4-phased framework of methodology.

Table 1: 4-phased methodology approach

Phase 1	**1.Determining the study area**	**1.1Selection of pilot conveyor belt**	**1.2.Determination of study period**	**1.3.Selection of optimal TPM pillars**	
Phase 2	**2.Evaluation of the maturity levels of optimal TPM pillars on pilot conveyor belt maintenance practices**	**2.1.Development of maturity evaluation instruments**	**2.2.Scoring of autonomous maintenance elements**	**2.3.Scoring of focused improvement elements based on observations of work practices and standard operating procedures**	**2.4.Application of a hybrid expectation scale to interpret scores obtained from maturity evaluation instruments**
Phase 3	**3.Optimization of the adoption of optimal TPM pillars on pilot conveyor belt maintenance practices**	**3.1.TPM coaching and establishment of team**	**3.2.Standardization of root cause investigation**	**3.3.Adoption of visual performance management**	
Phase 4	**4.Re-evaluation of optimal TPM pillars maturity levels on pilot conveyor belt maintenance practices post adoption optimization**	**4.1.Scoring of autonomous maintenance elements**	**4.2.Scoring of focused improvement elements**	**4.3.Application of a hybrid expectation scale to interpret scores obtained from the maturity evaluation instruments**	

3.1 Phase 1: Determination of the study area

The study selected one pilot conveyor belt for adoption of the selected TPM pillars over a 10-week period. This was done to minimize the potential impact on production for the rest of the shaft.

The researcher proceeded to assess the principles and practices on the maintenance of the conveyor belts through observation research methods, which revealed partial implementation of Total Productive Maintenance. The historical downtime records impacting the availability of the pilot conveyor belt were analysed. Subsequent to a prioritisation matrix, two pillars of TPM were selected for full implementation, namely autonomous maintenance, and focused improvement.

3.2 Phase 2: Evaluation of autonomous maintenance and focused improvement maturity levels

The maturity model approach was applied to guide progressive implementation of Autonomous maintenance and Focused Improvement concepts. The maturity evaluation instrument employs a scale of 1 - 4 for scoring purposes. Table 2 and Table 3 illustrate the instruments and respective scores per TPM pillar.

Table 2: Autonomous Maintenance maturity gap analysis - evaluation instrument

Evaluation Criteria					**Score**
Autonomous maintenance					
Verification item	**4**	**3**	**2**	**1**	
Has the team received thorough training on TPM fundamentals?	Full training received	Partial training received	Little training received	No training received	1
Has the team been trained on how to perform self-maintenance on the conveyor belt?	Team knowledgeable on conveyor belts standard conditions and abnormalities to monitor	Team partially knowledgeable on conveyor belts standard conditions and abnormalities to monitor	Team demonstrating little knowledge on conveyor belts standard conditions and abnormalities to monitor	Team demonstrating no knowledge on conveyor belts standard conditions and abnormalities to monitor	
Items requiring cleaning, oil and greasing, dusting, fixing, and basic maintenance identified and tagged as the responsibility of the operators?	All Items requiring basic maintenance identified and tagged as the responsibility of the operator	Some Items requiring basic maintenance identified and tagged as the responsibility of the operator	Few Items requiring basic maintenance identified and tagged as the responsibility of the operator	No Items requiring basic maintenance identified and tagged as the responsibility of the operator	1
is the team trained on how to identify and tag abnormalities on the conveyor belt?	Team has received full training on identifying and tagging abnormalities on the conveyor belt	Team has received partial training on identifying and tagging abnormalities on the conveyor belt	Team has received little training on identifying and tagging abnormalities on the conveyor belt	Team has received no training on identifying and tagging abnormalities on the conveyor belt	1
Cleaning and Inspection training performed on all the operators?	Operators demonstrating full capability to clean and inspect conveyor belts	Operators demonstrating capability to clean and inspect conveyor belts with the assistance of maintenance crew	Operators not capable of cleaning and performing inspection on the conveyor belts.	Maintenance crew fully responsible for cleaning and inspection	1
Cleaning and inspection schedule developed and visualized for easy adherence?	Comprehensive schedule developed and visualized for the team	Partially comprehensive schedule developed but not visualized for the team	schedule in place not inclusive of all required activities	No schedule in place	1
Pillar total	24	18	12	6	6

Table 3: Focused Improvement maturity gap analysis - evaluation instrument

Evaluation Criteria					**Score**
Focused improvement					
Verification item	**4**	**3**	**2**	**1**	
Is there a standardized root cause analysis technique in place for investigation of all deviations from conveyor belts standard condition?	Standardized root cause analysis technique in place and applied	Standardized root cause partially in place and applied	Standard root cause technique in place but not applied	No standard root cause in place	1
Are the root causes of sporadic conveyor belts deviations known?	Root causes fully known and understood	Root causes partially understood	Little understanding of root causes of deviations	No understanding of root causes of deviations	1
is there a process in place to address sporadic conveyor belts deviations?	Process fully developed and followed to address sporadic conveyor belt deviations	Process partially developed and followed to address sporadic conveyor belt deviations	Process partially developed and rarely followed to address sporadic conveyor belt deviations	No Process developed to address sporadic conveyor belt deviations	1
Are chronic breakdowns flagged to plan for elimination/ improvement initiatives	Chronic deviations flagged to plan for improvement initiatives on maintenance processes	Chronic deviations partially flagged to plan for improvement initiatives on maintenance processes	Chronic deviations flagged with no follow up plans for improvement on maintenance processes	Chronic deviations not flagged for improvement on maintenance processes	1
Is there flexibility/agility in the current maintenance practices to allow for continuous improvement	Exceptional agility to allow and embrace continuous improvement initiatives	sufficient agility to allow and embrace continuous improvement initiatives	Little agility to allow and embrace continuous improvement initiatives	No agility to allow and embrace continuous improvement initiatives	1
Are the findings of deviations and solutions shared across the team to note as lessons learnt	extensive sharing and implementation of lessons learnt across the team	sufficient sharing and implementation of lessons learnt across the team	low sharing and implementation of lessons learnt across the team	no sharing and implementation of lessons learn across the team	1
Pillar total	24	18	12	6	6

The aggregate outcome of the maturity evaluation instrument was subjected to a hybrid expectation scale as illustrated in table 4 below. The highlighted column reflects subsequent scores.

Table 4: Autonomous maintenance and focused improvement - Hybrid expectation scale

Hybrid expectations category	**Met few expectations**	**Met some expectations**	**Met Most expectations**
	1-6	7-14	15-24
		Autonomous Maintenance	
Description of adoption control **expectation**	**Established basic conditions of the equipment and maintain those conditions**	Assessment of the wear on the conveyor belts and development of activities to address it	Autonomous management and standardization
Adoption enablers	**-Initial clean-up by maintenance crew and with established cleaning schedule at critical points**	-Developed measures to address root causes of deviations/dirt requiring frequent clean up at critical points. -Established standards of cleaning and inspection process	-Standardized and established maintenance activities with autonomous control
		Focused improvement	
Description of adoption control **expectation**	**Areas of improvement identified to address waste on the conveyor belts maintenance process**	Continuous improvement techniques in place to address waste.	Conveyor belts management techniques visualized supported with data enabling the team to make decisions to optimize processes
Adoption enablers	**View of the conveyor belt structure and clear visibility of critical areas with persistent deviations from belt standard**	Visual boards to improve stakeholder engagement point of reference.	FMEA analysis Why-why structure

3.3 Phase 3: Autonomous Maintenance and Focused improvement adoption

3.3.1 Autonomous Maintenance intervention

Subsequent to the gap analysis as illustrated in table 2 and table 3, remedial intervention strategies were formulated to improve compliance levels. The strategies ranged from training, goal setting and setting maintenance standards amongst others.

Operator training plan was developed to equip the operators with knowledge on becoming effective first responders to conveyor belts breakdowns. The training content was informed by the conveyor belts design standards.

A template of the operator check sheet which accommodates safety and operations related inspection, focusing on deviations and information which informs maintenance schedule was implemented.

3.3.2 Focused Improvement intervention

Root cause investigation

Standardization of root cause investigations through the adoption of the 5-whys methodology to eradicate reoccurrence of breakdowns

Adoption of visual performance management:

Installation of a visual board in management offices and at the conveyor belt teams meeting area. The visual board would serve to record breakdown frequency, downtime, plant, and equipment availability.

Implementation of a Gemba walk checklist was done to record findings observed.

Post intervention compliance and performance review was subsequently carried out for both pillars. The results are reflected in table 5 and table 6.

3.4 Phase 4: Post intervention review

Table 5: Autonomous Maintenance

Evaluation Criteria						**Score**
Autonomous maintenance						
	Verification item	**4**	**3**	**2**	**1**	
	Has the team received thorough training on TPM fundamentals?	Full training received	Partial training received	Little training received	No training received	4
	Has the team been trained on how to perform self-maintenance on the conveyor belt?	Team knowledgeable on conveyor belts standard conditions and abnormalities to monitor	Team partially knowledgeable on conveyor belts standard conditions and abnormalities to monitor	Team demonstrating little knowledge on conveyor belts standard conditions and abnormalities to monitor	Team demonstrating no knowledge on conveyor belts standard conditions and abnormalities to monitor	4
	Items requiring cleaning, oil and greasing, dusting, fixing, and basic maintenance identified and tagged as the responsibility of the operators?	All Items requiring basic maintenance identified and tagged as the responsibility of the operator	Some Items requiring basic maintenance identified and tagged as the responsibility of the operator	Few Items requiring basic maintenance identified and tagged as the responsibility of the operator	No Items requiring basic maintenance identified and tagged as the responsibility of the operator	4
	is the team trained on how to identify and tag abnormalities on the conveyor belt?	Team has received full training on identifying and tagging abnormalities on the conveyor belt	Team has received partial training on identifying and tagging abnormalities on the conveyor belt	Team has received little training on identifying and tagging abnormalities on the conveyor belt	Team has received no training on identifying and tagging abnormalities on the conveyor belt	4
	Cleaning and Inspection training performed on all the operators?	Operators demonstrating full capability to clean and inspect conveyor belts	Operators demonstrating capability to clean and inspect conveyor belts with the assistance of maintenance crew	Operators not capable of cleaning and performing inspection on the conveyor belts.	Maintenance crew fully responsible for cleaning and inspection	4
	Cleaning and inspection schedule developed and visualized for easy adherence?	Comprehensive schedule developed and visualized for the team	Partially comprehensive schedule developed but not visualized for the team	schedule in place not inclusive of all required activities	No schedule in place	4
Pillar total		24	18	12	6	24

Table 6: Focused Improvement

Evaluation Criteria					**Score**
Focused Improvement					
Verification item	**4**	**3**	**2**	**1**	
Is there a standardized root cause analysis technique in place for investigation of all deviations from conveyor belts standard condition?	Standardized root cause analysis technique in place and applied	Standardized root cause partially in place and applied	Standard root cause technique in place but not applied	No standard root cause in place	4
Are the root causes of sporadic conveyor belts deviations known?	Root causes fully known and understood	Root causes partially understood	Little understanding of root causes of deviations	No understanding of root causes of deviations	4
is there a process in place to address sporadic conveyor belts deviations?	Process fully developed and followed to address sporadic conveyor belt deviations	Process partially developed and followed to address sporadic conveyor belt deviations	Process partially developed and rarely followed to address sporadic conveyor belt deviations	No Process developed to address sporadic conveyor belt deviations	4
Are chronic breakdowns flagged to plan for elimination/ improvement initiatives	Chronic deviations flagged to plan for improvement initiatives on maintenance processes	Chronic deviations partially flagged to plan for improvement initiatives on maintenance processes	Chronic deviations flagged with no follow up plans for improvement on maintenance processes	Chronic deviations not flagged for improvement on maintenance processes	4
Is there flexibility/agility in the current maintenance practices to allow for continuous improvement	Exceptional agility to allow and embrace continuous improvement initiatives	sufficient agility to allow and embrace continuous improvement initiatives	Little agility to allow and embrace continuous improvement initiatives	No agility to allow and embrace continuous improvement initiatives	4
Are the findings of deviations and solutions shared across the team to note as lessons learnt	extensive sharing and implementation of lessons learnt across the team	sufficient sharing and implementation of lessons learnt across the team	low sharing and implementation of lessons learnt across the team	no sharing and implementation of lessons learn across the team	4
Pillar total	24	18	12	6	24

The aggregate scores were once again subjected to the hybrid expectation scale. The highlighted column reflects subsequent scores.

Table 7:Autonomous maintenance and focused improvement-Hybrid expectation scale

Hybrid expectations category	**Met few expectations**	**Met some expectations**	**Met Most expectations**
	1-6	7-14	**15-24**
		Autonomous Maintenance	
Description of adoption control **expectation**	Established basic conditions of the equipment and maintain those conditions	Assessment of the wear on the conveyor belts and development of activities to address it	**Autonomous management and standardization**
Adoption enablers	-Initial clean-up by maintenance crew and with established cleaning schedule at critical points	-Developed measures to address root causes of deviations/dirt requiring frequent clean up at critical points. -Established standards of cleaning and inspection process	**-Standardized and established maintenance activities with autonomous control**
		Focused improvement	
Description of adoption control **expectation**	Areas of improvement identified to address waste on the conveyor belts maintenance process	Continuous improvement techniques in place to address waste.	**Conveyor belts management techniques visualized supported with data enabling the team to make decisions to optimize processes**
Adoption enablers	View of the conveyor belt structure and clear visibility of critical areas with persistent deviations from belt standard	Visual boards to improve stakeholder engagement point of reference.	**FMEA analysis** **Why-why structure**

4 RESULTS

Table 8 below illustrates pre and post intervention performance statistics of the conveyor belt section under study.

Table 8: comparative performance

Key Performance Indicator	June-August	September-November	Improvement
Number of failures	63	54	14% reduction in failure occurrence
MTTR	156	93 Minutes	40% reduction in time taken on repairs
MTBF	1235	1313 minutes	6% increase in operational time before failure
R/Ton	278.34	130.68	R147.84/Ton savings
Actual throughput	99 607 tons	116 754 tons	17 147 tons production increase
Availability	87%	92%	5% increase in conveyor belt availability
OEE	18%	25%	7% increase in the overall equipment effectiveness of the conveyor belt

The implementation of Autonomous Maintenance and Focused Improvement TPM pillars resulted in significant performance improvement and cost reduction across a range of KPI's. The results are proof of the effectiveness of TPM as a performance improvement strategy in mining operations.

5 CONCLUSION

The goal of this study was to optimize the availability of conveyor belts and improve the productivity of CM sections in an underground coal mine. The adoption levels of autonomous maintenance and focused improvement were evaluated through observation studies and assessment of maintenance standard operating procedures. The study analysed the as-is data and highlighted gaps within the implemented pillars using a hybrid expectation scale on a section conveyor belt as a pilot.

The intervention process involved partial implementation of TPM principles over a 10-week period, while monitoring performance. Favourable results were recorded.

Practical and theoretical implications of the study

The results of this study contribute to the application of Total Productive Maintenance techniques in the mining industry. The study further contributes to the scarce research of maintenance management in underground mining operations. The results of the study suggest that mining companies will benefit from full implementation and sustainability of TPM principles.

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ENHANCING EMERGENCY MEDICAL SERVICE EFFICIENCY: OPTIMISING AMBULANCE RESPONSE TIME IN GAUTENG PROVINCE

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ABSTRACT

Emergency Medical Services (EMS) are integral to healthcare delivery systems, providing critical medical attention during emergencies. Patient survival rates are heavily reliant upon response time. However, EMS operations face challenges in responding quickly and effectively to emergencies, especially with increasing populations. This study aimed to reduce ambulance response times in Gauteng by using linear programming to optimize response strategies and resource utilization. We investigate methods to improve EMS response times in Gauteng Province through a combined qualitative and quantitative approach. Using provincial EMS secondary data detailing EMS dispatching processes, resource utilization, emergency locations, ambulance locations, a Linear Programming (LP) based model was developed to minimise ambulance response time by optimising distances between random emergency sites and hospital dispatching sites. The model was tested against the baseline operating model. The LP model performed favourably against the baseline model. This research provides valuable insights into possible low-cost operational improvements within EMS systems, offering a data-driven approach to mitigate response time challenges and improve emergency healthcare delivery.

Keywords: emergency medical service, response time, medical emergency

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1 INTRODUCTION

The health sector provides different services namely preventive, emergency, and centralised services. Preventive services include providing services that are of preventive nature while centralised services consist of primary and advanced healthcare facilities. This study focused on the emergency services. The Emergency Medical Services (EMS) serve as the first responders to healthcare emergencies in Gauteng, tasked with ensuring the stabilization of patients and facilitating transportation to the nearest healthcare facility when necessary. This vital service is accessible to all citizens in Gauteng during medical emergencies.

Emergency medical conditions arise from natural illnesses, injuries, road, and workplace accidents etc. EMS response to medical emergencies must be quick and efficient. Failure by EMS to respond timeously to such emergencies may lead to unwarranted fatalities. The researchers held the hypothesis that the average EMS response time in Gauteng is higher than the global recommended standard time of 8 minutes and 59 seconds [1]. Understanding the complexity of EMS services is essential to improve the efficiency and quality of the service. Accordingly, the need arises to develop an improved EMS operational model to reduce response time.

In this study, we analyse the as-is Gauteng EMS crew despatch operational model to identify and eliminate wasteful practices. We also evaluate the impact of Linear Programming as a tool to develop an improved operational model to reduce EMS response time. In resource constrained public funded institutions, optimised resource allocation and scheduling systems are important, more so against the backdrop of increasing population and medical emergencies [2] .

EMS must adapt to a response time standard of eight minutes 59 seconds in at least 90% of all emergencies responded to in suburb areas [3]. This standard time was formed and adopted under the National Fire Protection Association's (NFPA 1710 standard). This response time was based on the average recovery rate of cardiac-related medical emergencies.

This study encompassed the development and implementation of linear programming models for optimizing ambulance dispatching processes in the context of emergency medical services. It included the analysis of factors such as distance, dispatching rules and analysis of emergency locations and hospitals to improve response times and resource allocation. Additionally, the research investigated the potential impact of optimization efforts on overall efficiency of emergency response systems.

This research did not delve into the operational aspects of ambulance services beyond dispatch optimization. The research did not address patient care service times, ambulance return times, clinical protocols, and medical treatments. Furthermore, while the study acknowledged the importance of broader healthcare systems, it did not explore systemic issues such as hospital capacities, healthcare policy frameworks, or broader public health interventions. The focus remained specifically on the mathematical optimization of ambulance dispatch processes and its immediate implications for emergency medical service delivery.

The limited access to Department of Health data due to clearance constraints posed a significant limitation to the depth and breadth of the analysis in this study. To mitigate this challenge, the researcher collaborated closely with the Gauteng EMS department and accessed necessary data.The researcher further explored relevant literature, supplementing the institutional data. These measures enhanced the validity and comprehensiveness of the analysis, mitigating the impact of the initial limitations on the study.

2 LITERATURE REVIEW

In the recent past, numerous studies have explored the optimization of medical emergency response time. The review focuses on a few key topics namely, the importance of response time in EMS, Linear Programming, Resource Allocation, Resources constraints in EMS, Travel Time forecasting and Optimisation Models in EMS.

Emergency Medical Services (EMS) prioritize swift patient care and transportation to hospitals, crucial for improving outcomes, especially in critical situations. Response time serves as a vital metric for evaluating EMS efficiency, although challenges exist in comprehensively measuring effectiveness. Beyond response times, factors like care quality, patient and personnel safety, and system design influence EMS performance. [4] developed an optimization model considering vehicle unavailability, emphasizing strategic resource allocation. Literature reviews offer insights into diverse approaches for improving EMS operations. Addressing system design, resource allocation, and real-time decision-making challenges is key to enhancing EMS effectiveness. Ongoing research aims to innovate and integrate validated indicators to optimize EMS performance, ensuring timely and efficient care delivery in emergencies.

According to [5]), Linear Programming (LP) is a mathematical technique used to optimize unforeseen circumstances. LP involves one or multiple objective functions that are either minimized or optimized subject to constraints placed on the model [6]. The fundamental idea behind LP is to find the best possible outcome in each mathematical model whose requirements are represented by linear relationships. LP can be applied to several types of problems, such as maximizing profit, minimizing costs, or optimizing resource allocation. This technique is widely used in fields like economics, military planning, transportation, and telecommunications, among others.

The historical development of linear programming dates to World War II, a period that saw a significant rise in the need for optimal resource allocation. A team of British scientists studied ways to optimize the use of raw materials and resources, leading to the development of operations research techniques that included linear programming [7]. Their work laid the groundwork for modern LP, demonstrating its effectiveness in solving complex logistical problems under constraints. Post-war, the field expanded rapidly, with contributions from mathematicians like George Dantzig, who developed the Simplex method, a pivotal algorithm in LP. Today, linear programming is an essential tool in both academic research and practical applications, providing a robust framework for decision-making and optimization.

Linear programming problems are characterized by a set of decision variables, an objective function, and constraints. The decision variables represent the choices available; the objective function defines the goal to be achieved (such as cost minimization or profit maximization), and the constraints represent the limitations or requirements that must be met. The feasible region, formed by the intersection of all constraints, contains all workable solutions that satisfy the constraints. The optimal solution is the point within this region that maximizes or minimizes the objective function. The Simplex method, introduced by Dantzig, is a widely used algorithm for finding the optimal solution by iterating through the vertices of the feasible region.

In the context of EMS ambulance response time optimization, linear programming plays a crucial role. Efficient allocation of resources and strategic positioning of ambulances can significantly reduce response times, which is critical in emergency medical services. By formulating the problem as a linear programming model, EMS can optimize the number and locations of ambulances to ensure the fastest possible response to emergencies. Studies have shown that using LP models can lead to substantial improvements in emergency response efficiency [5]. This application of LP not only enhances the effectiveness of EMS operations but also contributes to better health outcomes by reducing the time it takes to provide critical medical assistance.

Every organization aims to provide satisfactory results while ensuring the growth and expansion of future endeavours. To achieve these objectives, it is essential to make critical decisions about how scarce resources will be allocated [8]. Resource allocation involves determining the most effective way to distribute resources such as time, money, personnel, and equipment to meet organizational goals. Decisions in this domain include setting competitive prices, identifying necessary and relevant areas of need, maintaining quality and performance standards, integrating technology, and managing the workforce. Effective resource allocation ensures that resources are used efficiently and strategically, contributing to the overall success and sustainability of the organization.

Linear Programming (LP) is a powerful tool for optimizing resource allocation. According to [7], LP helps organizations find the best uses of their resources by formulating and solving mathematical models. These models consider various constraints and objectives, enabling decision-makers to identify optimal solutions that maximize efficiency and effectiveness. For instance, LP can be used to minimize costs, maximize profits, or achieve a balanced allocation of resources that meets multiple goals simultaneously. This capability is particularly valuable in complex environments where resources are limited and the demands on them are high.

In the healthcare sector, resource allocation is critical for ensuring that services are delivered efficiently and effectively. [8] demonstrates the application of Binary Programming, a specific type of integer programming, in allocating resources within a healthcare facility. In his study, Horvat developed a binary programming model to minimize costs associated with staffing requirements for ambulance crews. The model was implemented in the Ambulance Service Station in Subotica, Serbia, resulting in a more equitable and efficient rostering process compared to the ad hoc scheduling previously used. This example highlights how mathematical optimization techniques can significantly improve resource management and operational efficiency in healthcare settings.

Linear Programming not only assists in solving optimization problems but also provides a systematic approach to decision-making under constraints. It helps managers make informed decisions about the allocation of scarce resources, ensuring that the organization can achieve its desired objectives despite limitations. By applying LP and other optimization techniques, organizations can develop robust strategies for resource allocation that enhance performance, reduce waste, and improve overall outcomes. This is particularly important in fields like emergency medical services, where efficient resource allocation can directly impact response times and patient outcomes.

Whereas most papers utilize verifiable emergency call information as a direct estimate for future demand, a developing and more significant body of literature employs this data to create machine learning models that can anticipate future demands. Early approaches primarily considered spatial demand, using numerous linear regressions to relate the size of demand for ambulances with variables such as population and socio-economic factors [9]. This methodology laid the foundation for more advanced predictive models by highlighting the relationship between emergency service demands and demographic variables.

There are three main groups of focus when dealing with demand prediction: economic status (employment rate, poverty), population, and social status [9]. By examining these variables, researchers can better understand the underlying causes of emergency service demands. For instance, areas with higher poverty rates might experience higher rates of emergencies due to factors such as inadequate access to healthcare and higher incidences of health-related issues. Similarly, densely populated areas are likely to have higher emergency service demands simply due to the larger number of people.

Temporal approaches have also been developed to forecast the demand for emergency calls at various times, including daily and multi-hour routines. These approaches include the queuing model and mathematical programming [10]. Temporal models are crucial because the demand for emergency services often follows predictable patterns. For example, the demand might be higher during certain times of the day, such as rush hours, or on specific days of the week, such as weekends. By accurately predicting these patterns, EMS can allocate resources more effectively, ensuring that ambulances and personnel are available when they are most needed.

To date, other methods are used to predict the demand for emergencies using optimization models of linear programming [6]. LP leverages historical and existing data to estimate future demand, providing a robust framework for forecasting. Developed and populated countries have ample data to conduct research using this approach to develop advanced forecasting models. These models can incorporate a wide range of variables, including historical emergency call data, demographic information, and socio-economic indicators, to generate precise predictions of future demand.

The use of linear programming techniques represents a significant advancement in the field of demand prediction for EMS. Machine learning algorithms can process vast amounts of data and identify complex patterns that may not be apparent through linear regression alone. By combining these models with LP, researchers can develop hybrid approaches that offer both the accuracy of machine learning and the robustness of linear programming. This combination can significantly enhance the ability of EMS to anticipate and respond to emergency calls, improving service delivery and patient outcomes.

Models concerning facility locations have been extensively studied and applied to emergency medical services, with a significant focus on ambulances. Many studies have investigated ambulance responses in urban areas of developed countries, examining numerous factors that influence the efficiency and effectiveness of EMS [11]. These studies have been instrumental in understanding how best to position emergency response vehicles to minimize response times and maximize coverage.

Earlier research often detailed data and solutions focused on specific diseases, providing targeted strategies for common medical emergencies such as cardiac and respiratory arrests, and strokes. These studies offered valuable insights into how EMS can be optimized for health crises, ensuring that resources are allocated in a way that addresses the most prevalent and critical conditions. For instance, optimizing ambulance locations based on the incidence and distribution of cardiac arrests could significantly improve survival rates by ensuring rapid response times to these life-threatening events.

In contrast, more recent studies have shifted towards a broader approach, focusing on current emergencies without being specific to certain diseases. This approach considers the dynamic and unpredictable nature of emergencies, where new policies and circumstances must be considered. This shift reflects the need for EMS to be adaptable and responsive to a wide range of medical situations, rather than being tailored to specific conditions alone. By considering the general demand for emergency services, these studies aim to develop more flexible and resilient models that can manage several types of emergencies effectively.

One such study that exemplifies this broader focus is [4], which utilized Linear Programming (LP) to optimize the location and relocation of emergency vehicles. This study considered the uncertainty and variability in emergency incidents, ensuring that ambulances are strategically positioned to respond to a wide array of emergencies efficiently. By not limiting the scope to specific diseases, the study's model is more versatile and can be applied to different scenarios, enhancing the overall responsiveness of EMS.

In summary, while early studies on emergency response location models provided disease-specific solutions, contemporary research emphasizes a more holistic approach that considers the unpredictability of emergencies. This broader focus enhances the ability of EMS to respond promptly and effectively to a diverse range of medical emergencies, improving overall service delivery and patient outcomes. By leveraging advanced optimization techniques and real-time data, these models ensure that emergency response systems are both efficient and adaptable to changing conditions.

3 METHODOLOGY

The study aimed to achieve two primary objectives: first, to analyze the current operational model of the Gauteng Emergency Medical Services (EMS) and eliminate waste; second, to determine the impact of Linear Programming (LP) as a tool to develop an improved operational model to reduce EMS response time.

To address these objectives, a mixed-methods approach was employed, integrating both qualitative and quantitative research methods. This comprehensive approach was chosen to gain a deeper understanding of the factors affecting EMS response times and to evaluate the effectiveness of proposed improvements.

To address the first objective—analyze the current operational model and eliminating waste—qualitative data were crucial. These data, which expressed opinions and feelings not captured by numerical statistics, were used to identify factors contributing to delays in EMS operations. Data collection methods included secondary data from existing EMS database. Interviews were conducted involving management and operational staff of Gauteng EMS department to understand the as-is operational model. Document analysis reviewed existing protocols, standard operating procedures, and incident reports to gain insights into current practices and wasteful practices.

The qualitative analysis also scrutinized ambulance dispatching rules, including criteria for dispatching, priority levels, geographical distribution, and resource availability. The manual decision-making processes and consequent sub optimal resource allocation procedures were noted. Detailed process mapping of emergency reporting procedures and communication protocols were done.

To address the second objective—evaluating the impact of Linear Programming as a tool to develop an improved operational model to reduce EMS response time—quantitative data were essential. Secondary data were used. Quantitative analysis provided measurable insights into factors influencing EMS operational efficiency. An LP based operational model was suggested to minimize average response times while satisfying constraints such as crew availability, ambulance capacity, and geographical coverage. The model was iteratively refined by incorporating data from the EMS department to ensure accuracy and validity

Formal authorization was obtained from the National Health Research Council (NHRC) and Gauteng Department of Health (GDoH) to utilize data related to EMS and medical services involving human subjects.

3.1 Formulation of Linear Programming Model

The present model was developed based on several key assumptions:

- The ambulance fleet size is known.
- Each dispatched ambulance requires three crew members.
- An ambulance that has been dispatched to one accident cannot respond to another accident.
- All emergencies are treated as having equal priority.
- Ambulances are dispatched to serve demand and return to the hospital afterward.
- Hospitals are the locations from which ambulances are dispatched.
- Emergencies can occur at any point in the province.
- Only the response time was minimized.

The objective function is:

$$Min\ Z\ = \sum_{\boldsymbol{i,j=1}}^{\infty} \boldsymbol{d_{ijt}} \qquad (1)$$

Where:

H_{ij} = Hospital location H_{ij} indexed by $i = 1 \ldots\ldots, I$

E_{ij} = Emergency Hospital location H_{ij} Indexed by $j = 1 \ldots\ldots, J$

t_{ij} = The response time of ambulance a_{ij} from Hospital location H_{ij} to emergency location E_{ij}

t_{ij} $= \frac{d_{ij}}{S}$

d_{ij} = Distance travelled by ambulance from hospital location H_{ij} to emergency location E_{ij} at a particular point in time

a_{ij} = Number of ambulances that respond to an emergency from Hospital location H_{ij} to emergency location E_{ij}

y = if an ambulance is assigned at Hospital location H_{ij}, otherwise = 0

S = Speed travelled by ambulance from hospital location H_{ij} to emergency location E_{ij}

A = Set of ambulances available at hospital location H_{ij} at a particular point in time.

T = Current average response time of ambulance a_{ij} to emergencies in Gauteng

C = 3, Set of Crews in an ambulance a_{ij} responding from Hospital location H_{ij} to emergency locationE_{ij} at point in time.

Subject to constraints:

$y = 1 \qquad \forall i, \forall x_{ij} \qquad (1)$

$C = 3 \qquad \forall x_{ij} \qquad (2)$

$\sum a_{ij} \leq A \qquad (3)$

$A \leq 1926 \qquad (4)$

$a_{ijt} \geq 0, \qquad t_{ij} \geq 0, \qquad d_{ijt} \geq 0 \qquad (5)$

Constraint 1 state that one ambulance will be assigned at ambulance Hospital location H_{ij} to respond to an emergency at emergency location nE_{ij}. Considering that the ambulance crew is proportional for each ambulance, where one ambulance requires three paramedics, constraint 2 caters for the fact that there is always enough assigned to ambulances that are responding to emergencies.

Constraint 3 state that there should always be enough ambulances at Hospital location H_{ij} to respond to an emergency at location E_{ij}. This caters for the logic that one emergency may require more than one ambulance at a time. Constraint 4 accommodates the fact that there 1926 ambulances counted in the period in Gauteng, the number of ambulances in various locations should therefore not exceed the total counted ambulances. Constraint 5 accommodates the non-negativity constraint.

4 RESULTS

4.1 Data on Emergencies

During September 2023, 62,344 accidents were addressed in Gauteng, out of which 36,478 required hospital transfers. This data provides a foundational understanding of the magnitude of emergency incidents in the region, crucial for informing resource allocation and planning.

4.2 Response Times

Response times for emergency calls in Gauteng were analysed across three categories and five districts to evaluate the efficiency of emergency services. By categorizing response times and district-wise comparisons, insights into the effectiveness of emergency response strategies were gained. Table 1 and Table 2 below show the number of calls that were taken during different time intervals.

Table 1: Calls and Average Response Times

Description	Description	CoJ	CoE	CoT	Westrand	Sedibeng
Calls within 30 Minutes	1<T<30	542	934	435	632	532
Calls within 60 Minutes	30<T<60	1738	2966	1609	1704	1810
Calls within 90 minutes	60<T<90	18544	13859	10966	2985	3088
Total Calls serviced	calls serviced	20824	17759	13010	5321	5430

Table 2:Average Response Time

Description	Midpoint	Total Calls	Midpoint *frequency
Calls under 30 minutes	15	3075	46125
Calls within 60 minutes	45	9827	442215
Calls within 90 minutes	75	49442	3708150

The average response time (T) for emergency calls in Gauteng was calculated using the formula:

$$T = Average\ Response\ Time = \frac{\sum(Midpoint * Frequency)}{\sum(Total\ Calls)} \qquad (2)$$

$$T = Average\ Response\ Time = \frac{\mathbf{4196490}}{62344} = 67{,}31 \text{ Minutes}$$

4.3 Resource Planning

Effective resource planning is essential for optimizing emergency response capabilities. Analysis of data on vehicles used for emergency response in each district during September 2023 facilitated an understanding of resource utilization and allocation patterns. Table 3 below shows the total number of ambulances that were utilised per each district per week in September 2023.

Table 3: Ambulances available per week per district in September 2023

Ambulances	**CoJ**	**CoT**	**CoE**	**West-Rand**	**Sedibeng**
Week 1	134	110	115	71	71
Week 2	124	113	110	67	67
Week 3	113	118	117	64	64
Week 4	130	108	111	62	65
Total Ambulances per month	501	449	453	267	256

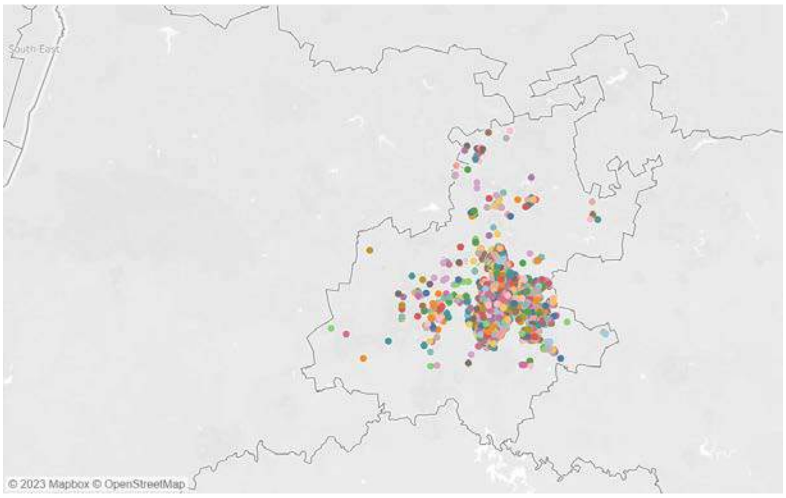

Figure 1: Map of Emergency Locations

4.4 Hospital Locations

The availability and distribution of hospital facilities are crucial factors influencing emergency response strategies. Analysis of hospital location data, encompassing 29 district hospitals, provided valuable insights into the geographical distribution of healthcare facilities across the province. Understanding the spatial relationship between hospitals and emergency locations informs decisions related to patient transport and destination selection.

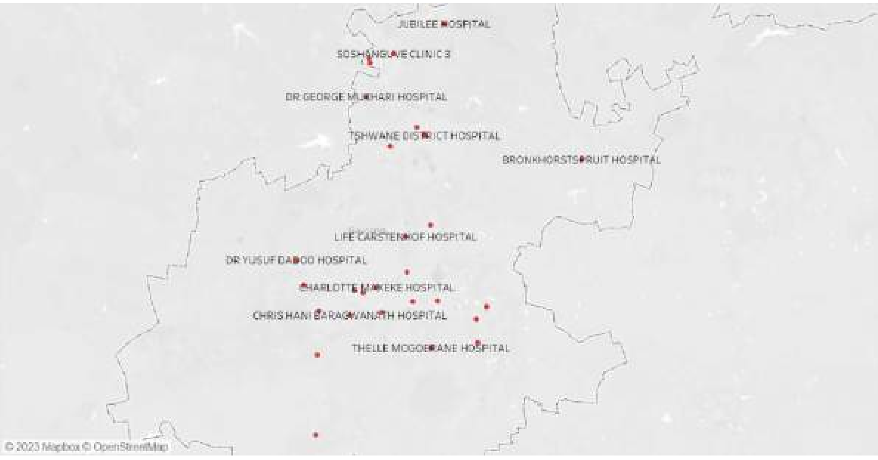

Figure 2:Map of hospital locations

4.5 Method of Dispatching Ambulances

Ambulance dispatching is a critical component of emergency response operations. The process begins when an emergency call is received and logged into the dispatch system, capturing crucial information about the incident. Dispatchers communicate detailed information about the emergency to the available ambulance crews. Any crew that is available to respond to the emergency provides feedback. The crew will inform the dispatchers of their location.

The dispatcher monitors the situation, provides updates, and coordinates with other emergency services if needed. Upon arrival, the ambulance crew assesses the situation, provides immediate care, and communicates findings back to the dispatch center. Continuous communication and record-keeping are essential for maintaining an efficient and effective emergency response system.

4.6 Discussion of Results

The researcher employed the Excel Solver tool to tackle the linear programming problem and optimize distances between hospitals and emergency locations. The Haversine formula was used to compute distances accurately.

Current Model: The total distance was 1202.187378 KM, and the average distance was 41.45474 KM. At an average speed of 60 KM/H, the response time was 41.45 minutes.

Optimized Model: Using the Excel Solver, the total distance was reduced to 291.857475 KM and the average distance was 10.06 KM. This resulted in a response time of 10.06 minutes.

To address the operational issues faced by the Gauteng EMS, the study proposes automated dispatching systems using real-time GPS data to optimize ambulance allocation and identify the nearest ambulances to emergency scenes. Periodic training for dispatchers was also recommended to enhance their decision-making skills under pressure

The study recommended streamlined reporting protocols and advanced communication tools to facilitate faster and clearer exchanges between all paramedics and ambulance dispatchers.

5 CONCLUSIONS AND RECOMMENDATIONS

This study has effectively met its goals to analyze the current operational model of the Gauteng Emergency Medical Services (EMS) and eliminate waste and to determine the impact of Linear Programming (LP) as a tool to develop an improved operational model to reduce EMS response time. Analysis from the Department of Emergency Medical Services (EMS) indicated that ambulances typically took around 67 minutes to respond to emergencies. Using random sampling, we evaluated various hospitals and locations, calculating distances and optimizing them through linear programming, which resulted in a dramatic decrease in response times from 41 minutes to just 10 minutes after applying Excel Solver. Key constraints identified included the availability of ambulances, crew, and external factors.

The findings underscore the importance of efficient EMS in densely populated areas where timely medical assistance is critical. This research demonstrates not only the potential for significant enhancements in ambulance deployment but also the substantial impact these improvements can have on patient care. Furthermore, it highlights the complex interplay of factors affecting response times, including traffic patterns and resource allocation.

Future research should explore advanced modeling techniques beyond linear programming and integrate real-time data to create more responsive deployment strategies. Additionally, studying community education's role in reducing unnecessary ambulance calls and evaluating emerging technologies can provide further insights. Collaborative efforts among stakeholders and cost-benefit analyses will also help optimize ambulance deployment systems, ensuring effective healthcare delivery in the community. Finally, strategies for sustaining these systems, including workforce training and ongoing performance evaluation, are crucial for long-term success.

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STATISTICAL ANALYSIS OF PROPERTIES OF SOUTH AFRICAN FOUNDRY CHROMITE SAND USED FOR ADDITIVE MANUFACTURING APPLICATIONS.

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ABSTRACT

Previous studies used the Quality by Design (QbD) approach to conceptual engineer the manufacture of chromite sand suitable for additive manufacturing (AM) using the binder jetting process. To this effect several chromite sand specifications were generated, and the findings published. The present paper collects secondary data and statistically analyses it to uncover underlying variable relationships and effects using Design of Experiments (DOE) technique on SigmaXL software. The programme provides streamlined, cost-effective, user-friendly approach that includes targeted features for quality improvement that are built-into it that assist with improving the QbD manufacturing process for bulk production of chemically coated chromite sand.

Keywords: statistical analysis, design of experiments, variables, quality by design, continuous improvement.

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1 INTRODUCTION

1.1 Quality Assurance - QA

The American Society for Quality (ASQ) expresses Quality Assurance (QA) as "planned and systematic activities implemented in a quality system so that quality requirements for a product or service will be fulfilled" [1]. Quality assurance methods are procedure driven and are largely concerned with the improvement of manufactured goods and service delivery as depicted in Figure 1 below to guarantee a quality high-grade product or service that consistently satisfies customer needs and specifications according to their objectives this in turn gives customer confidence in services and product supplied by the manufacturer [2].

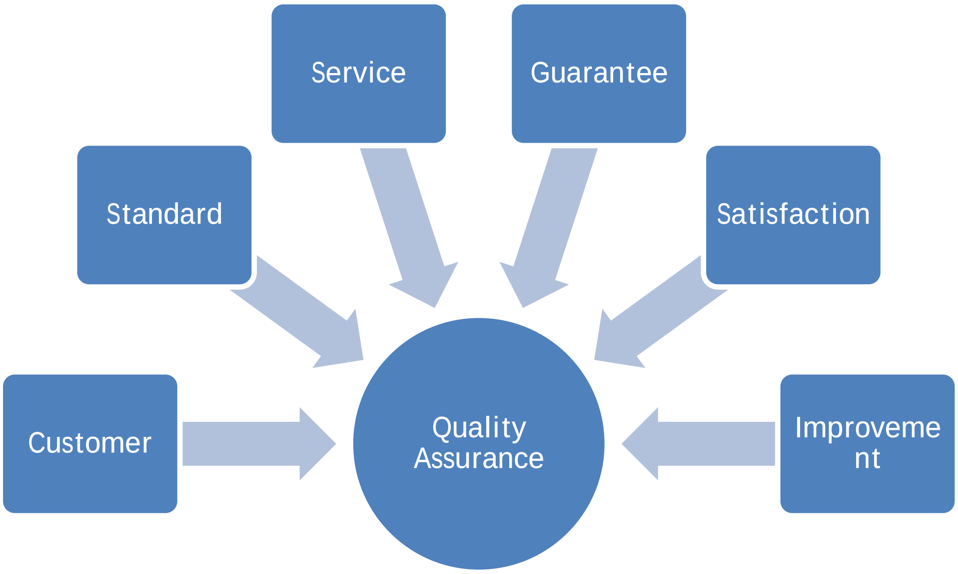

Figure 1: Diagram showing QA principles this in turn gives customer confidence in services and product supplied by the manufacturer.

These objectives namely (1) meeting industry standard, (2) guaranteeing product performance, (3) providing customer satisfaction and (4) delivering quality services, are realized by examining how well the performance of your product compares alongside industrial standards plus ensuring best operating practices. Employing quality controls that monitor any non-conformities from the outlined scope that ensure preventative action is taken to maintain the desired outcome as per specifications.

A good quality management system expressed by ISO 9000:2015: Quality management systems - Fundamentals and Vocabulary and echoed by the American Society for Quality has quality control (QC) and quality assurance (QA) at its centre, whereby QA is supported by controls that are put in place to ascertain that the standard operating procedures (SOPs) are followed, this in turn gives customer confidence in services and product supplied by the manufacturer [3], [4].

Various QA methods have been used across industries for decades. The most common include Kaizen, operations analysis, benchmarking, specifications, business process re-engineering, ISO accreditation, SOPs, Ishikawa diagrams, cost-benefit analysis, statistical sampling, and quality management approaches like QbD, Six Sigma, and lean manufacturing [5]. An investigative approach termed "spiral methodology" which is a high-level methodology incorporating the gradual improvement model zeroing in on risk identification and mitigation as depicted in Figure 2 below. It continues through iterative cycles involving four principal stages are Planning, Risk analysis, Build and Evaluation respectively.

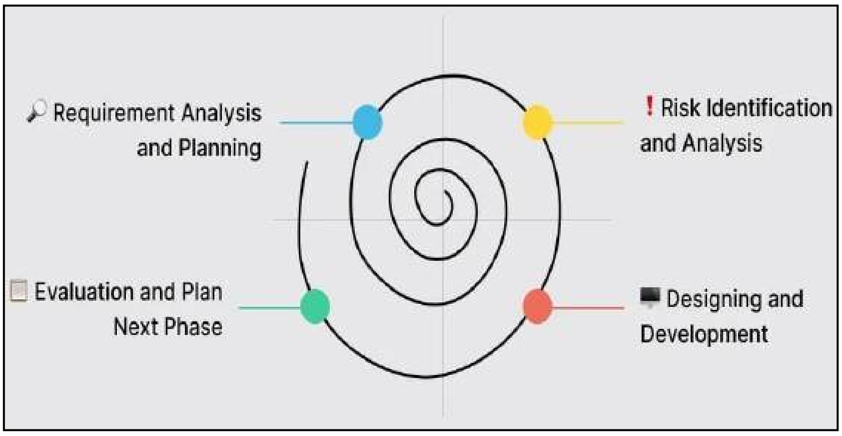

Figure 2: Phases of spiral model [6].

A fundamental element of this systematic approach is its emphasis on point-by-point risk examination at each stage of the manufacturing process, thus enabling unanticipated challenges to be addressed as they arise. This approach improves the quick identification of potential mistakes and affords swift resolution, enabling a comprehensive overview of issues for more effective investigating, which is also a core principle of the QbD approach.

1.2 Quality by Design - QBD

In his 1992 book entitled *Juran on quality by design: The new steps for planning quality into goods and services,* Juran describes QbD as “a systematic approach to development that begins with predefined objectives and emphasizes product and process understanding and process control, based on sound science and quality risk management” [2]. This approach is used in several industries due to its robust techniques, which offers product improvement methods for process readiness, growth of the organization, monitoring schemes and continual process improvement. The procedure consists of eight continuous steps, namely:

- Quality Target Product Profile (QTTP)
- Critical Quality Attributes (CQA)
- Process Flow Diagram (PFD)
- Critical Process Parameters (CPP) and Material Attributes (MA)
- Quality Risk Assessment (QRA)
- Design Space (DS)
- Control strategy (CS)
- Continuous Improvement Strategies (CIS)

QbD focuses on understanding the links between an item’s CQAs and the CPPs affecting them. This is achieved through trial and error, statistical analysis, and risk evaluation. By examining these links, manufacturers can establish a design space where the product consistently meets quality standards [8]. This enables optimization while maintaining quality, where manufacturers can establish controls and QA frameworks to ensure consistent performance. Tools-like design of Experiments (DOE) and process analytical technology (PAT) identify key factors, ensuring high-quality products that meet client needs and expectations [9]. QbD creates superiority in the product from the design and development phase by determining the degree of procedural deviation. It uses various tools to facilitate decision making, like design of experiments (DOE), which leads to system improvements [7].

1.3 Design of Experiments - DOE

DOE is a multipurpose statistical tool that can be utilized in different circumstances to provide recognizable proof of significant input factors or input variables and how they relate to the resulting reaction variable. Moreover, the regression analysis that can be utilized in different circumstances as a very suitable tool for process performance and product quality improvement in applications such as variable screening, transfer function identification, comparison, robust design and system optimization [2]. The basic experimental setup for DOE is shown in Figure 3 below.

The major steps followed in this study were: identifying the lowest number of experimental runs needed to examine the observations' upper control limits (UCL) and lower control limits (LCL), conducting the experiment, gathering data, analyzing data and documenting observations, establishing the design-space and, finally, giving practical conclusions and recommendations [10].

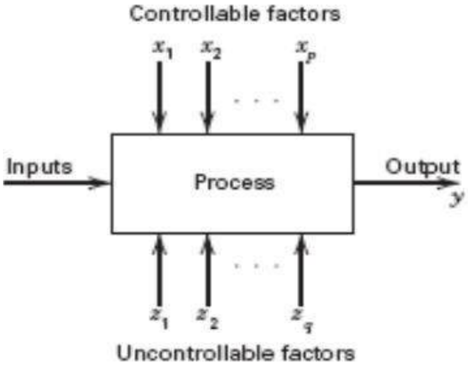

Figure 3: Typical DOE experimental set [10].

DOE assessments can be implemented effortlessly in Microsoft Excel, using pre-programmed processes and formulas. To execute any DOE examination, both linear regression and analysis of variance (ANOVA) is essential. Moreover, the data that is collected from experiments, both industrial trials and simulated events, can be quickly designed and analyzed with the assistance of suitable statistical software packages as well as platforms which are free and commercially available.

1.4 Statistical Analysis

Statistical analysis is the process of collecting, organizing, interpreting, and presenting data to uncover patterns, trends, relationships, or differences among variables. It plays a crucial role in research and decision-making across a wide range of fields, including science, engineering, medicine, social sciences, and business [9]. It is employed in several research fields as a foundation when it comes to analyzing the data that is collected from experimental runs, ranging from social sciences all the way through to biology, chemistry, physics as well as engineering [10]. Applying academic databases like Google Scholar, Scopus, Web of Science, IEEE Xplore, or specific repositories like those for journals and conferences published in the last 10 years show an increase in the use of statistical analysis tools with "ANOVA", "Design of Experiments (DOE)" and "statistical analysis" as search parameters across a multitude of industries.

1.4.1 Applications of statistical analysis

- **Research:** Validating hypotheses, discovering new insights, and supporting scientific conclusions.
- **Quality Control:** Monitoring and improving manufacturing processes.

- **Business:** Making data-driven decisions, forecasting sales, and understanding customer behaviour.
- **Medicine:** Analyzing clinical trial data and understanding the effectiveness of treatments.
- **Engineering:** Optimizing processes, product design, and reliability testing.

1.4.2 Key Components of Statistical Analysis

1.4.2.1 Data Collection:

Gathering relevant data through experiments, surveys, observations, or existing databases. The data can be quantitative (numerical) or qualitative (categorical).

1.4.2.2 Data Organization:

Structuring the data into a usable format, often in tables or spreadsheets, to facilitate analysis. This may include cleaning the data by removing errors or inconsistencies.

1.4.2.3 Descriptive Statistics:

Summarizing the main features of the data using measures such as:

- **Mean:** The average value.
- **Median:** The middle value when data is ordered.
- **Mode:** The most frequently occurring value.
- **Standard Deviation:** A measure of the dispersion or spread of the data.
- **Range:** The difference between the maximum and minimum values.

1.4.2.4 Exploratory Data Analysis (EDA):

Investigating data sets to discover patterns, anomalies, and relationships without making prior assumptions. This often involves visualization techniques such as histograms, scatter plots, and box plots.

1.4.2.5 Multivariate Analysis:

Analyzing more than two variables simultaneously to understand complex relationships. Techniques include Principal Component Analysis (PCA) and Cluster Analysis.

1.4.2.6 Inferential Statistics:

Making predictions or inferences about a population based on a sample of data. Common techniques include:

- **Hypothesis Testing:** Assessing whether there is enough evidence to support a specific claim about the data.
- **Confidence Intervals:** Estimating the range within which a population parameter lies with a certain level of confidence.
- **ANOVA (Analysis of Variance):** Comparing means among multiple groups to determine if there are significant differences.
- **Regression Analysis:** Modelling the relationship between variables to predict one variable based on another.

1.4.3 Statistical Software

The most common software used in different industries for planning and analyzing experimental data are Statistical, SPSS, SAS, Design-Expert, Statgraphics, Prisma R, Minitab, SigmaXL, JMP or *Python; that is particularly used in conjunction with libraries like pandas, scipy*, and stats models for data analysis. SigmaXL is an impressive Microsoft Excel add-on software that assists Lean Six Sigma heads examine and enhance practices which can generate control charts, map correlations and regressions, measure process capability and run root-cause analysis. This is the major reason for using SigmaXL software, it is specifically designed for Six Sigma and quality improvement projects. It includes a comprehensive suite of tools for process improvement, making it particularly suitable for QbD initiatives.

1.5 Previous studies on chromite sand for rapid casting applications

An acceptable size data bank suitable for foundry 3D printing is available on the local South African chromite sand website. The QbD approach was used to conceptually engineer chromite sand suitable for binder jetting. Optimisation and evaluation experiments were conducted by various authors [12], [13], [14], [15], [16], [17] and [18] to produce 3D printed moulds and cores made from chromite sand, more specifically looking at transverse strength development. In the process, several chromite sand properties and specifications were established. As summarized in Table 1 below:

Table 1: Table showing important 3DP chemical and mechanical properties

Properties	Specification
Fine-aggregate angularity	32% ≤ 45%
Acid demand value	≤ 6 ml
Resting period	≥ 2 days
Coating ratio	0.1% - 0.3%
Moisture content	≤ 0.2%
Grain fineness number	50 - 60
Angle of repose	$30^o \leq 45^o$
Chemical composition (XRF)	$Si0_2 < 1\%$
Sintering temperature	> 1577.55 ^oC
Sand distribution screens	2 - 5
Turbidity	0.05 NTU - 400 NTU

The secondary data used was obtained from laboratory experiments. The purpose of gathering data was to conduct a comparison between the various local chromite sands that are available. The study compared the existing data with the data that was accumulated from foundry best practices, three-dimensional printing requirements and ASTM standards so that differences between the previous model and the present model could be evaluated. The control strategy critical to the production of good quality chromite sand for rapid sand casting was established. This paper reports on the use of this secondary data for statistical analysis.

2 METHODOLOGY

The software to be used for data analysis is SigmaXL in conjunction with DOE Full Factorial Design, it provides a streamlined, cost-effective, user-friendly approach that includes targeted features for quality improvement that are built-into the software that will assist in improving the QbD process for bulk production of chromite sand. They offer specialized tools for quality improvement, making them suitable for organizations looking to enhance their production processes without the need for extensive statistical or programming expertise. A literature review of published case studies assisted in this regard. Figure 3 shows the process followed in this paper.

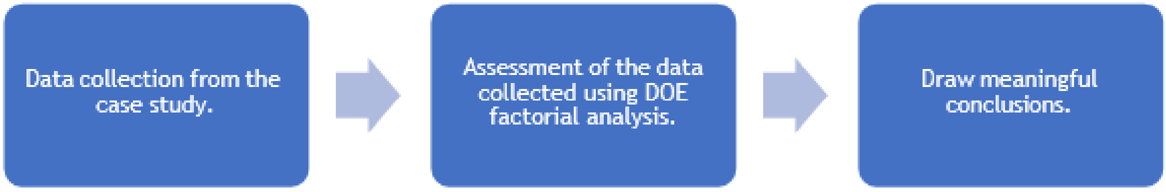

Figure 3: Diagram depicting the process followed in this study.

For this paper, the results generated using the SigmaXL software included, but were not limited to (1) main effects - which focus on the individual variables' effects on the measured variable, (2) interaction effects - which focus on the relationship effects of a combination of the variables on the measured variable, and (3) the Pareto chart - which offers a mixture of line and bar graphs that outline the individual qualities in From highest to lowest whereby 80% of output variables arise from 20% of input variables. For example, this principle highlights that 80% of a business's return is produced by 20% of its consumers. Lastly, (4) R-square - characterized as a number that lets you know how well the independent variable(s) in a factual model make sense of the variation in the dependent variable. It goes from 0 to 1, where 1 shows an ideal fit of the model to the data.

2.1 Collection of data

An inventory of the high-risk factors that were statistically analyzed using DOE full factorial design are shown in Tables 2, 3 and 4, respectively as shown in the experimental work on several chromite sands obtained from well-known local suppliers for rapid sand casting and foundry applications, and that have an impact on the final product produced.

Table 2: Table showing 3D-P process high-risk factors

	Factor	Low	High
A	Angle of repose (degrees)	33.66	40.25
B	Sulphonic acid (%)	0.10	0.30
C	Furfuryl alcohol (%)	1.00	4.00

Furthermore, three key factors were identified for statistical analysis, namely angle of repose, sulphonic acid and furfuryl alcohol, which are more likely to affect the cured transverse strength of the final 3D printed components. The factors and levels are given in above table. The statistical analysis included a full factorial analysis with each factor considered at two levels, i.e. low and high.

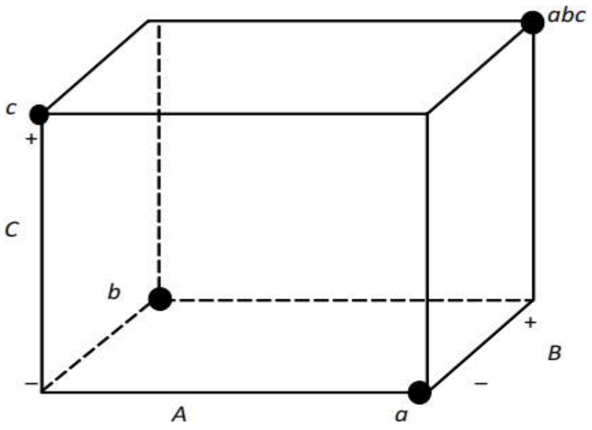

Figure 4: The 2^{3-1} factorial design orthogonal representation.

The key factors that were identified were those most likely to affect the quality of the chemically coated sand prepared for rapid sand casting. The factors and their levels are provided in Table 2. A full factorial experimental design with each of the **3 factors** at **2 levels** was conducted using formula $\mathbf{L^{(F)}}$. Thus, the number of treatments was $\mathbf{2^3 = 8}$ as shown in Figure 4 as an orthogonal representation, and further extrapolated in Table 3.

Table 3: Number of treatments to be analysed

Angle of repose	Sulphonic acid	Furfuryl alcohol	Transverse strength
33.66	1	0.1	90.50
40.25	1	0.1	108.25
33.66	4	0.1	10.00
40.25	4	0.1	223.75
33.66	1	0.3	118.00
40.25	1	0.3	128.70
33.66	4	0.3	541.66
40.25	4	0.3	618.75

This full factorial design allows for an analysis of the effect of each factor on the response variables, as well as the effects of the interaction between factors on the response variables. The analysis uses the steps of DOE, and the relationships are determined by using code values to calculate the interactional effect, which will be in the range of -1 low level to +1 high level for each factor identified**.** The thorough analysis of the data collected was carried out using DOE full factorial analysis. The coded data is shown in Table 4 in randomized order.

Table 4: Coded table of values and variable interactions

Run Order	A	B	C	AB	AC	BC	ABC	Transverse Strength
6	-1	-1	-1	1	1	1	-1	90.50
8	1	-1	-1	-1	-1	1	1	108.25
1	-1	1	-1	-1	1	-1	1	10.00
4	1	1	-1	1	-1	-1	-1	223.75
2	-1	-1	1	1	-1	-1	1	118.00
5	1	-1	1	-1	1	-1	-1	128.70
3	-1	1	1	-1	-1	1	-1	541.66
7	1	1	1	1	1	1	1	618.75

2.2 Assessment of the data using DOE

Figure 5 is a snapshot of the main effects of the different input variables, namely: A - angle of repose, B - furfuryl alcohol, and C - sulphonic acid. These were investigated using the SigmaXL statistical software tool. The main effects of the different input variables (independent variables) on the measured variable (dependent variable) are depicted in Figures 6, 7 and 8 below in the results and discussion section. Also depicted are the interactional effects of combined factors on the measured variable.

Different graphic and statistical analytical tools are available on SigmaXL statistical software as add-ons indicated with a red square box on figure below. These provide a generous number of templates for ease of data analysis. The software can generate control charts, map correlations and regressions, measure process capability and run a root-cause analysis.

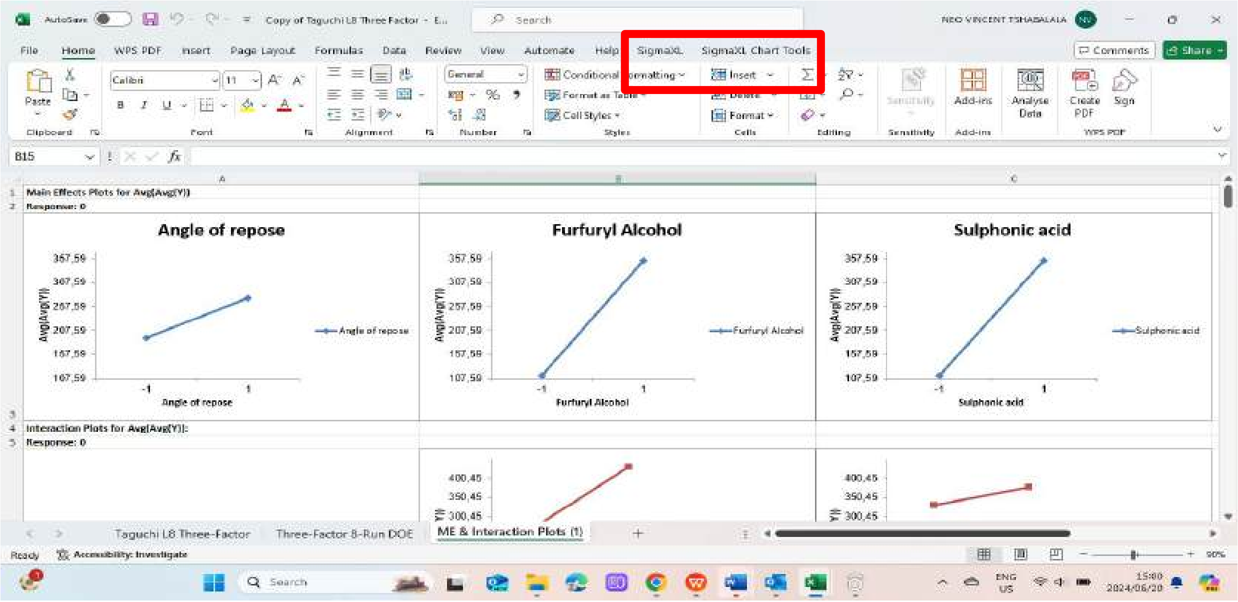

Figure 5: Interaction effects plot for the bank application process.

3 RESULTS AND DISCUSSION

3.1.1 Effects of factors

A summary of the main and interactional effects of the different input variables, A, B and C, are given below. The target or response variable is transverse strength, and the results are shown in Table 5. The interaction of all the factors involved (A, B and C) as well as their combined (or interactional) effects on the transverse strength have been fully factorized.

Table 5: Main and interactional effects of the input variables

	Main effects			Interactional effects			
	A	B	C	AB	AC	BC	ABC
Average High	269,86	348,54	351,78	262,75	211,99	339,79	213,75
Average Low	189,88	111,38	108,13	197,15	247,92	120,11	246,15
Effect	**79,99**	**237,17**	**243,65**	**65,60**	**-35,93**	**219,68**	**-32,40**

3.1.2 R square of the data

The R^2 for the data is 99.91%. This result indicates how well the independent variable(s) in a factual model make sense of the variation in the dependent variable. The range is from 0 to 1, where 1 shows an ideal fit of the model to the data. The data shows an R^2 of 0.99, which means that the model's estimated variation and its goodness-of-fit curve compare favorably with the actual data points.

3.1.3 Main effects plots

Figure 6 shows the main effect plots for each of the factors studied. They show which variable has a greater effect on the overall transverse strength, as plotted on the Y-axis of each of the graphs. The graphs indicate gradients between the low-risk and high-risk factors of the respective variables being analysed, as indicated in Table 5. All graphs have a positive gradient.

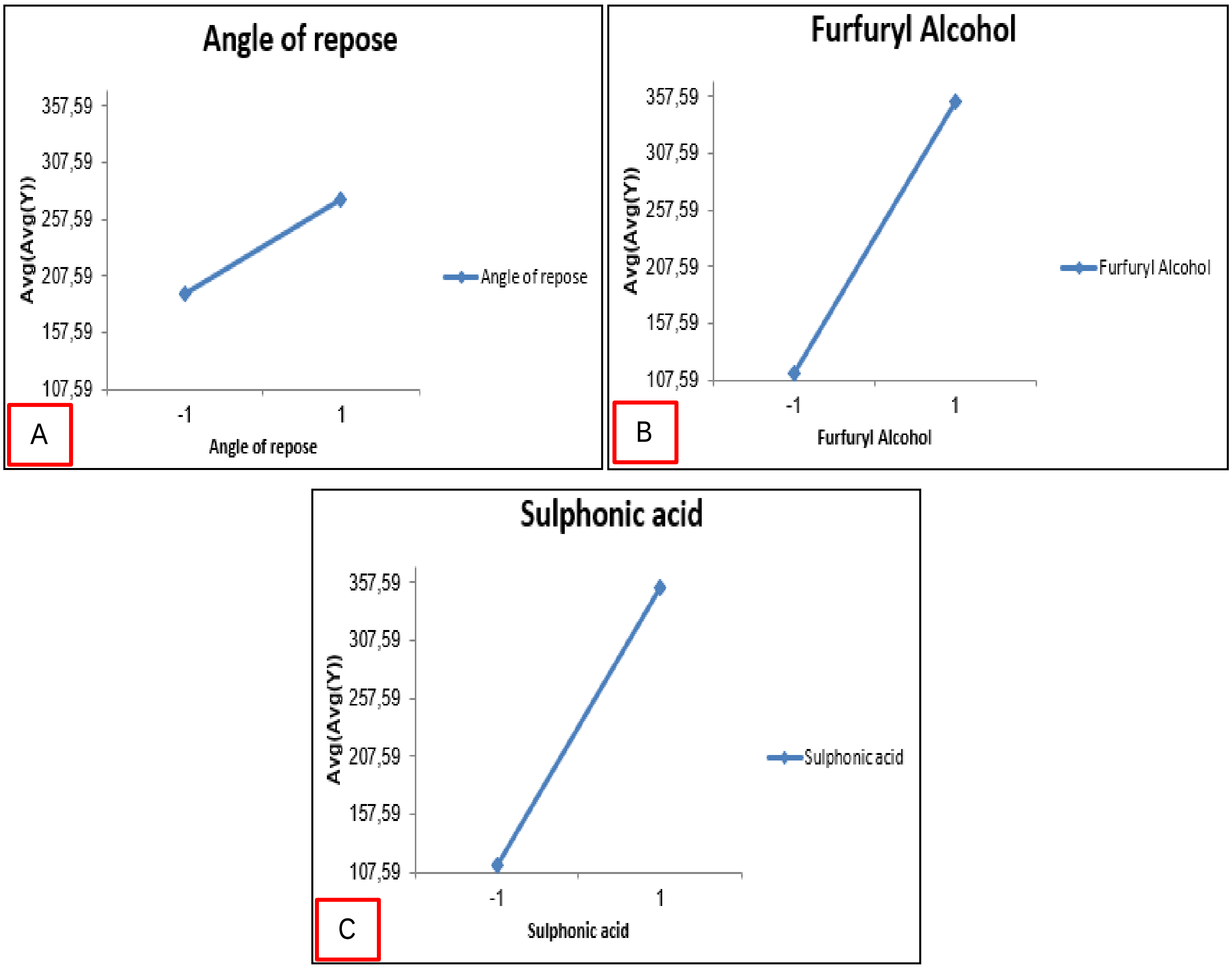

Figure 6: Diagrams showing main effects plots for (A) Agnle of repose, (B) Furfuryl alcohol and (C) Sulphonic acid on transverse strength.

The gradient of the graph is used to evaluate the relationship between two variables. A positive gradient implies that 2 variables are positively linked, meaning once the variable on the x-axis increases, the variable on the y-axis also increases, and vice versa. The gradients of the graphs can be seen displayed on the graphs as 82.60, 239.08 and 240.48, respectively. The steeper the straight line, the greater the gradient. This is evident in Graphs B and C (Figure 6) as they have very steep lines compared to Graph A. These results indicate that Variables B and C are more significant than Variable A. Thus, furfuryl alcohol and sulphonic acid have a greater impact on the overall results than angle of repose.

As a quality control instrument, the Pareto chart works according to the 80-20 rule. A graphical representation of the full factorial design study of the data is shown in Figure 7 below. The figure above indicates that factor C (furfuryl alcohol) has the largest effect on the evolution of transverse strength in the samples that were tested, with factor B (sulphonic acid) also having a considerable effect on transverse strength. This means that changes in the amounts of these factors will greatly affect the outcome of the strength observed with a certain type of configuration, and thus the quality of the final product produced.

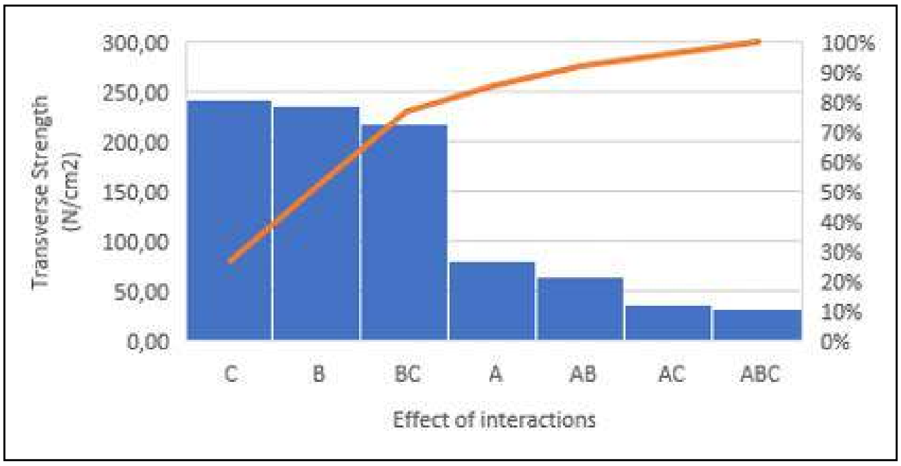

Figure 7: Pareto chart showing interactions of factors.

Factor A (angle of repose) has less of an effect on the evolution of strength compared to Factors C and B. Moreover, it can be observed that B and C are significant. This observation is consistent with the conclusion that was reached: Factor BC is a significant interaction, as the combined effect of these variables has a significant impact on the ultimate transverse strength achieved. Importantly, this conclusion was only reached because statistical analysis was performed on the data; and cannot be readily observed from the experimental results. This means that during the process, efforts need to focus on those factors with major influences on the system.

3.1.4 Interaction effects

Figure 8 shows the interactional effect plots for each of the factors studied. The plots show which combination of variables a negative or positive impact on the overall transverse strength has observed. The effect of the combined or interacting variables are shown as straight-line graphs on the same axis. Interaction can be classified as having mild, strong, very strong or no interaction relation.

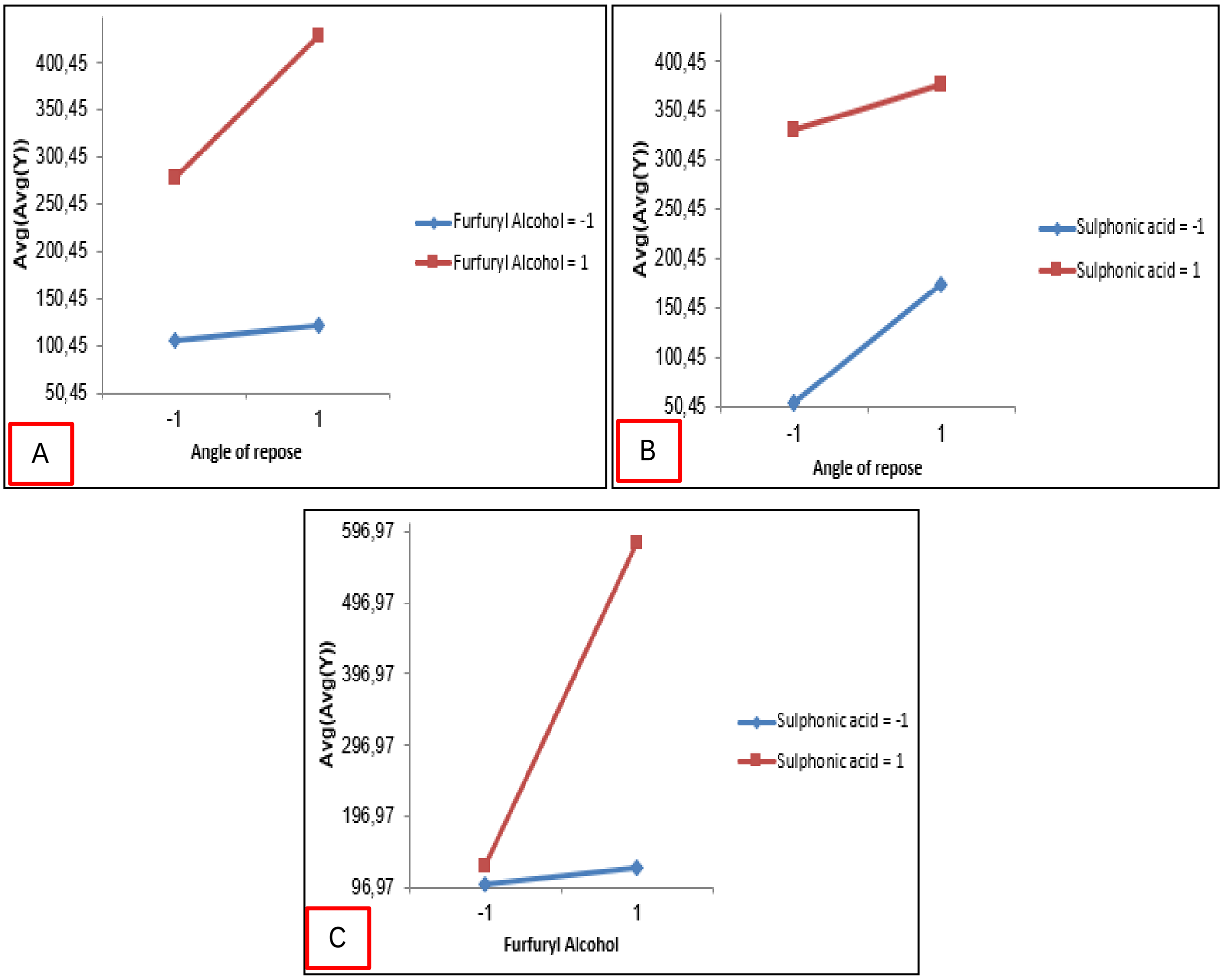

Figure 8: Diagrams showing interactional-effect plots for (A) angle of repose with furfuryl alcohol on transverse strength, (B) angle of repose with sulphonic acid on transverse strength and (C) furfuryl alcohol with sulphonic acid on transverse strength.

The effects of the interaction between angle of repose and sulphonic acid concentration are depicted in Graph A (Figure 8). The graph shows a mild interaction with the lines almost parallel to each other. The same interactional effects were observed with the factors angle of repose and furfuryl alcohol, as depicted in graph B. This indicates that the interaction between these two sets of factors have an influence on the results observed, i.e. transverse strength, but that it is not a significant influence.

The more significant effect of the interaction of factors furfuryl alcohol and sulphonic acid, as depicted in Graph C, is indicated by the lines that slope up at different gradients to each other. This means that their interaction has a greater influence on the results observed as compared to Graphs A and B. As such, the two factors collaborate to have an impact that is more than the sum of their parts on the transverse strength.

4 CONCLUSION

The analysis demonstrates that the recommended approach effectively evaluates how each design variant influences the variance of the final transverse strength observed for chemically coated chromite used in 3D printing with a Voxeljet VX1000 printer. The results obtained using SigmaXL software align with the initial conclusions and interpretations of the primary data.

The study confirms that these new insights enhance the QbD process for bulk production of quality chromite sand by providing detailed information on selecting and treating factors that control the desired property variance. This leads to a stronger understanding of these variables, resulting in a more robust QbD framework for reliable and effective rapid sand-casting applications.

4.1 Reflection and Future Directions

While the study successfully applied the recommended approach, additional measures could have been taken, such as incorporating a broader range of experimental conditions and exploring alternative statistical tools for comparative analysis. Additionally, extending the scope to include real-world industrial settings could provide more practical insights.

This approach can be applied to similar cases in other industries, such as metal casting, ceramics, and polymer manufacturing, where controlling material properties is crucial. By leveraging DOE methodologies and quality management tools, manufacturers can optimize their processes and improve product quality.

4.2 Future research could expand on this study by:

4.2.1 Exploring Different Software Tools

Comparing SigmaXL with other statistical software like R, Python, Minitab, and JMP to determine the most effective tools for specific applications.

4.2.2 Extended Case Studies

Applying the approach to other types of 3D printers and materials to generalize the findings.

4.2.3 Industry Collaboration

Partnering with industries to validate the approach in real-world production environments.

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BUILDING A SUSTAINABLE HIGHER EDUCATION MODEL FOR SOUTH AFRICA

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ABSTRACT

The current discussion paper looks at higher education funding in South Africa. The paper aimed to come up with recommendations on how South Africa can build a sustainable higher education funding model. The paper made use of a desktop research methodology. Literature on higher education funding in South Africa was sourced and reviewed. Recommended solutions for South Africa to build a more sustainable higher education funding model include diversification of funding sources, introduction of income contingent loans, performance-based funding, research and innovation funding, and introduction of education impact bonds. Making use of the Quadruple Helix recommendations for government, industry, community and higher education institutions were offered. It is recommended that higher education institutions diversify funds to reduce reliance on government funding and alternative sources of funding such as income contingent loans, performance-based funding, and education impact bonds be used.

Keywords: Higher education, Income contingent loans, Performance-based funding, Education impact bonds.

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1 INTRODUCTION

Higher education is an important tool to advance economic and social development [1]. Countries with effective and efficient higher education systems tend to have developed economies [2]. In the case of South Africa, higher education is an important tool in ensuring economic equality, especially for formerly marginalized groups [3]. A key component of a successful higher education system is the funding model used in the system [4]. Funding models determine the levels of resources higher education institutions have and the accessibility of higher education for students [5,6]. In countries where there is little public funding for higher education, students are presented with significant impediments to participate [6]. While countries that offer higher education public funding significantly reduce barriers to participation. South Africa in its quest to reduce inequalities due to the Apartheid system has committed to government being the main funder of higher education. While the system reduces barriers for students, it also carries challenges. The main challenge is the long-term sustainability of a government-funded higher education system. This paper is a discussion paper which uses a desktop research methodology to identify possible solutions for South Africa to build a sustainable higher education funding model.

The search for articles reviewed in the study focused on keywords such as (“tuition”) AND ("free") AND ("higher education"), AND, “sustainable” AND ("South Africa"). The search only focused on studies undertaken in English. The search for grey literature was done by inputting the keywords in the Google Scholar search engine. The articles reviewed were from the years 2008 to 2022.

2 CURRENT STATE OF HIGHER EDUCATION FUNDING IN SOUTH AFRICA

South Africa has made strides in improving higher education funding since the dawn of democracy [7,6]. The democratic dispensation in South Africa resulted in massive shifts in the funding of higher education [8]. This was to rectify the adverse effects of the Apartheid Era higher education funding policies which neglected the majority of South African citizens [9]. A key impediment for most students was the lack of funding to attend university and other higher education institutions.

In 2017 the South African government committed to funding higher education for students from low-income households, i.e. those from households with an annual income of less than R350 000 [10]. While this decision was met with hope and happiness by some, some viewed it with scepticism as this required a huge commitment of scarce resources [11].

The current higher education funding is designed in such a way that universities receive funding in the form of subsidies [12,13]. These subsidies are earmarked for research and teaching. The number of subsidies a university receives are based on the student graduation rates, student enrolment, and research output [10]. Recent years have seen universities facing increased costs which have not been met with proportionate increases in government subsidies [14].

Universities are also indirect recipients of government funding in the form of tuition and accommodation fees paid by the government through the National Student Financial Aid Scheme (NSFAS) [10]. The NSFAS, a bursary and loan scheme for students from low-income households, was born out of the NSFAS Act (no. 56) of 1999 [15] . While the NSFAS was beset by several issues such as poor management and low repayment rate, it did play a pivotal role in ensuring students from low-income students managed to attend higher education institutions [16]. In 2018 the NSFAS loan and bursary scheme was transformed into a full bursary scheme catering for students from households earning less than R350 000 [17,10]. The funding for students also includes funds for transport, rent, and books.

The shift to a full bursary scheme in 2018 opened opportunities for more students to access higher education, however, it also presented several challenges which threatened the sustainability of the funding model. The first challenge is the sudden increase in students attending university and other higher education institutions, without a proportionate increase in resources and staff [14]. This means universities find themselves understaffed and under-resourced, faced with a larger student body. The lack of resources means in some cases universities have to let go of staff [18]. This means less staff for a higher number of students, affecting the quality of higher education. In some cases, highly skilled staff are deciding to leave for developed countries with more resourced institutions, impacting the quality of staff left in South African institutions.

South Africa has a larger number of its population dependent on social welfare [19]. This presents the second challenge faced by the shift in 2018; that of the possibility of reduced social welfare funding for other members of society. With the NSFAS becoming a bursary scheme, it means a significant portion of resources are committed to higher education. In a country like South Africa with limited resources, which means resources committed towards the NSFAS are taken from other parts of the budget. With expected increases in students enrolling for higher education, the concern is that if the current higher education funding model is sustainable in the long term.

Of question is also the long-term commitment of the government to maintain the current funding model. For example, during the COVID-19 crisis, the government reallocated higher education funds towards South African Airways [20]. This brings to the fore concerns on whether the government would be committed to the current model when faced with other crises, natural or man-made. It is therefore important for the government to build a new sustainable higher education funding model that can withstand the vagaries of economic downturns.

3 EXAMPLES OF SUCCESSFUL HIGHER EDUCATION FUNDING MODELS

While the South African government may have been well-intentioned when it committed to fee-free higher education for those coming from households earning less than R350 000, the unintended effects point to the model being not sustainable in the long term [10,21]. Adopting the fee-free higher education model was partially based on observing the successes recorded in countries with fee-free higher education which include Denmark, Egypt, Finland, France, Germany, Greece, Hungary, Iceland, Italy, and Luxembourg [22]. However, most of the countries with fee-free higher education are in the developed world, thus are faced with differing economic realities from those faced by South Africa, a developing nation. It is important to consider countries with other higher education funding models which have had relative success. The following countries were selected for review as they have been successful to a certain extent in implementing cost-sharing models. The United Kingdom provides an example of a developed nation, while Malaysia and Kenya provide examples of developing nations.

3.1 United Kingdom

In the United Kingdom, higher education is primarily funded through tuition fees [23]. The government provides income-contingent loans to students attending university; these loans are repaid upon employment [24]. The payment conditions are relatively favourable, with the aim being not to impose burdens on graduates. The model has led to increased access to higher education for students, as it allows for students from low-income households to get loans to fund their higher education [25]. The loans have the benefits of not being burdensome as students do not need to repay them until they are employed. The income contingent loans in the UK, have been viewed as being fair due to the state and the individual sharing the cost of higher education [26]. This is in line with the belief that higher education provides both private and public benefits. However, it is important to note that the UK higher education funding model is faced with several challenges. There is rising student debt which has resulted in some raising concerns over the long-term impact on the loan system on the welfare of loan takers [22]. The model has the unintended consequences of being favourable for high-income earners, while low-income earners struggle to repay the loan [27].

3.2 Malaysia

Malaysia provides an example of a developing country that has been able improve its higher education funding model (reference). Part of the funding for higher education comes from the government which provides funds for infrastructure, research, and teaching [28]. Malaysia has also adopted performance-based funding. Performance-based funding in Malaysia means that higher education institutions receive funding based on their graduation rates, research output, and employability of graduates [29]. Malaysia has also been able to diversify sources of higher education funding through greater private-sector involvement in the higher education sector [30]. Malaysia's multifaceted funding model also involves the provision of loans to students, with these loans carrying favourable repayment conditions, making them affordable for students from low-income households [31].

3.3 Kenya

Kenya's funding model has been successful to a certain extent; however, many challenges are still faced. The Kenyan government provides the bulk of funding for higher education; however, these funds are often inadequate [32]. This is due to the rise in the number of students in higher education institutions without a corresponding increase in funding [33]. Higher education students in Keya also have the option to get student loans. Loans in Kenya are provided through Higher Education Loans Board (HELB). Kenya has a research endowment fund focused on providing funding to for research and innovation projects [34]. The research endowment fund has been successful in providing funding for projects in science and technology. The cost-sharing model instituted by Kenya whereby the government foots the bulk of the bill in higher education funding while students have access to loans has worked to encourage greater participation in higher education [32]. However, challenges in the repayment of loans persist due to a poor labour market.

4 PROPOSED SOLUTIONS TO BUILD A SUSTAINABLE FUNDING MODEL

In the context of higher education, the quadruple helix provides a framework for understanding and enhancing the interactions between academia, community, government, and industry [35]. The quadruple helix highlights the importance of society in the innovation process. It focuses on the four major forces or factors needed for successful innovation in a country: science, policy, industry and society [36]. Each proposed solution will look at the four forces under the quadruple helix. The quadruple helix is shown in Figure 1:

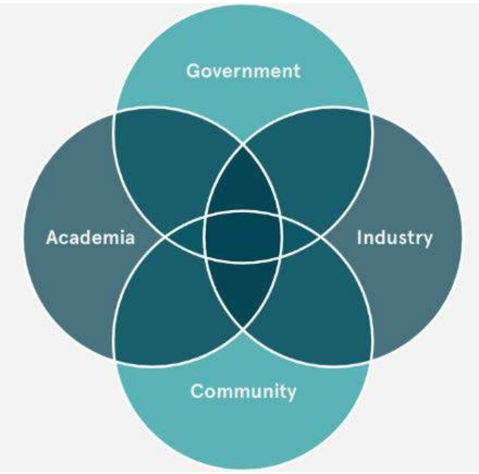

Figure 1: The Quadruple Helix Source:[37]

4.1 Diversification of Funding Sources

The vulnerability of depending on the government as a major source of funding was exposed during the COVID-19 pandemic when the government decided to use higher education coffers to support South African Airways [19]. This revealed the need for a higher education funding model that provides a diversified source of funds. Diversifying funding sources reduces reliance on the government. A funding model with less reliance on the government is more sustainable and resilient to economic shocks. Diversifying sources of funds also reduces the influence of politicians on academia. To diversify funding sources, universities can approach private sector players such as banks, businesses, foundations, and individuals.

4.1.1. Government

The government is the major driver of policy in South Africa; thus, it is incumbent upon it to design policies that promote the diversification of funding sources. The government can design a policy that offers incentives such as tax benefits to private sector players that help fund educational activities and infrastructure. Government can ensure it improves public-private partnerships in the area of higher education. Government can also play a role in ensuring universities have access to alternative sources of funding, this can be done by relaxing regulations which may be currently hindering universities from accessing funding.

4.1.2. Industry

Industry plays a pivotal role in providing a diversified source of funding for higher education. Industry, which includes banks, foundations, and businesses can provide funding to higher education institutions through endowments, research funding, and sponsorships. Industry can ensure the funding of higher education is part of their corporate social responsibility initiatives. Industry can collaborate with higher education institutions in research and innovation. This ensures universities receive funding for research, while industry receive benefits in the form of research and innovative ideas.

4.1.3. Community

The community can play a role in ensuring that higher education receives more funding. The community can play a role in raising awareness of the lack of adequate funding for higher education in South Africa. Through campaigns and community events, the community can highlight the need for improved funding of higher education. The community can engage in fundraising events to support educational programs.

4.1.4. Higher education institutions

Higher education institutions should diversify sources of funds by sourcing funds from alumni donations, private sector partnerships, research grants, and international funding bodies. South African higher educational institutions can improve funding through improving the management of endowments. Having a large endowment helps higher education institutions to access funding such as loans at favourable rates and it also indicates to potential funders that higher education institutions are able managers of resources.

4.2 Income-Contingent Loans and Grants

Several countries have successfully used income-contingent loans and grants as a source of funding for higher education. South Africa can utilize income-contingent loans in building a more sustainable higher education funding model. Income contingent loans are loans that have repayment conditions that are based on the income earned by the borrower when they get employed [38]. Grants are financial aid without repayment conditions. Income contingent loans in South Africa can be provided to students who qualify for places in higher education institutions. This can be done without consideration of the household economic conditions of the student. This will allow more students to access higher education and will encourage responsible borrowing as students will be cognizant of the need to pay the loan in the future. Income contingent loans also carry the benefit of reduced default risk as the loan repayment is based on the income of students. The Heher Commission on the Feasibility of Fee-Free Higher Education in South Africa also proposed the use of income-contingent loans [10]. The Commission reasoned that they would not lead to a reduction in funding of higher education institutions and that students receive private benefits from higher education and thus need to also bear part of the burden [39].

Grants can be offered to specific students, for example, those coming from specific backgrounds or the disabled. Another option is to make grants based on academic merit thus encouraging excellence. The combination of income-contingent loans and grants can provide a sustainable model for higher education funding, as income from loan repayments can be used to fund more students. Grants encourage excellence and give relief to deserving students thus encouraging excellence and promoting upward social mobility.

4.2.1 Government

The government can take its policy role by creating policies that are supportive of the use of income-contingent loans. The government can play a role in setting up a regulatory environment that ensures loans are properly used. It can also ensure that students are not taken advantage of by defining the repayment rates, income thresholds, and interest rates. The government can offer resources such as seed funding or subsidies for interest payments to ensure the success of income-contingent loans.

4.2.2 Industry

The industry, banks and financial institutions can offer income-contingent loans for students with favourable conditions by leveraging government support of the loans. Banks and financial institutions are knowledgeable in the management of loans thus they can play a role in providing management expertise to government and higher education in relation to income-contingent loans.

4.2.3 Community

The adoption of income-contingent loans requires broad support thus the community can play a role in raising awareness of the importance of this funding source. Experts in the community can volunteer to guide students in the loan application and repayment process. A key aspect of income-contingent loans is repayment which ensures other students are funded as well, the community can play a role in encouraging recipients to repay loans.

4.2.4 Higher education institutions

Higher education institutions play a central role in the disbursement of income-contingent loans. Higher education institutions can provide financial literacy education that helps students responsibly manage their loans. Higher education institutions can monitor and report on the success of loans.

4.3 Performance-Based Funding

Some countries such as Austria and Finland have found success using performance-based funding [40]. Performance-based funding entails allocating funds to universities based on their performance. The performance can be measured based on metrics such as research output, graduation rates, and student success. The use of performance-based funding promotes excellence, optimal use of resources, innovation, and greater research output [41]. Performance-based funding requires constant monitoring of universities' outputs thus it also promotes more accountability and transparency. For universities to perform well they will need to be good at strategic planning and to optimally utilize their resources. Performance-based funding leads to universities improving their strategic planning and optimally using their resources [42]. Performance-based funding can be done by using global rankings of universities, this will improve the competitiveness of South African universities on the global stage [40].

4.3.1 Government

The government can promote performance-based funding by establishing clear performance metrics for funding allocation. Performance metrics to be used include graduation rates, research output, and other relevant indicators. Performance-based funding can be used for research, faculty training and infrastructure. The government can offer incentives that encourage competitiveness while also considering that historically disadvantaged institutions may not have the ability to compete at the level of historically advantaged institutions.

4.3.2 Industry

Industry can play a role in the promotion of performance-based funding. Industry can engage in strategic partnerships whereby it provides funds to improve the performance of higher education institutions, and it receives research and development outputs in return. Industry can provide incentives for higher education institutions that exceed set performance metrics. Industry can offer feedback that has deep industry-specific insights, this can help higher education institutions focus on research and education suited to industry needs.

4.3.3 Community

The community can play a role in the promotion and monitoring of performance-based funding. The community can play a role in ensuring performance-based funding is distributed in a manner fair and transparent. The community can ensure that performance-based funding is distributed based on higher education institutions providing outputs that cater to community needs.

4.3.4 Higher education institutions

Higher education institutions should strategically position themselves to be constantly evolving to improve performance. Higher education institutions should invest their funds wisely to ensure they promote their performance in areas such as graduation rates, research output, and staff training. Higher education institutions should adopt best practices to ensure they competitively compete against international players.

4.4 Research and Innovation Funding

The increase in research and innovation funding can reduce reliance on the government. Research and innovation funding relates to funds provided to universities to conduct research and innovation [43]. These funds can originate from businesses, individuals, and non-governmental organizations. Research and innovation have the potential benefits of leading to revenue streams from licensing of innovations, patents, and new companies. Research and innovation can result in greater collaborations between universities and businesses. Research and innovation have the societal benefits of helping address issues such economic inequality, health, climate change, and energy issues.

4.4.1 Government

Research and innovation are important for the development of a country such as South Africa, it is incumbent upon the government to ensure it promotes research and innovation through providing funding earmarked for it. The government can promote research and innovation funding by providing tax incentives for companies that fund research and innovation in higher education. Government should also monitor the impact of research and innovation funding to ensure funding is being used for what it is intended for.

4.4.2 Industry

Industry can play a role in research and innovation funding by partnering with higher education universities in undertaking research projects that meet industry needs. Industry can play a role in helping higher education institutions license patents and innovations. This helps create revenue streams for both universities and industry. Industry can provide employment or tuition funding for students engaged in products considered of benefit to the industry.

4.4.3 Community

The community can advocate for research and innovation funding to be disbursed towards projects that contribute towards solving major problems in South African society. The community can crowdfund for research projects that address societal challenges.

4.4.4 Higher education institutions

Higher education institutions can work towards getting funding that is earmarked for research and innovation. This requires higher education institutions to identify areas in need of research. After identifying these areas higher education institutions can approach the government and industry to solicit to funds for identifying research projects. Higher education institutions should invest in research infrastructure, including technology, skilled personnel, and infrastructure. This signals to the government and industry that they are ready and capable of undertaking research projects that add value.

4.5 Education impact bonds

Recent years have seen growth in use of impact bonds designed for social and sustainable causes [44]. A possible way of universities to build a sustainable higher education funding model is incorporating education impact bonds as part of their revenue source. Education impact bonds are bonds that a debt financial instruments that is designed to fund specific education programs. The repayment of the bond is based on the outcomes of the program being funded. This means investors in the education bonds are only repaid in the case of set educational outcomes being met.

4.5.1 Government

The government plays a pivotal role in the promotion of education impact bonds through creating an enabling environment. The South African government can support education impact bonds by creating a policy framework that encourages investment in education. The government can ensure any regulatory hurdles that discourage investment in education are removed. The government can also monitor the use of capital from education impact bonds to ensure higher education does not engage in incidences of impact washing. The government can provide support to programs higher education institutions undertake using education impact bonds to ensure these projects meet public policy goals related to education.

4.5.2 Industry

Industry players such as banks and other financial institutions can help higher education institutions in the design and issuance of education impact bonds. Industry can share information with higher education institutions to signal projects that they are willing to fund and are relevant to their sectors. This has the advantage of educational impact bonds providing much-needed capital to higher education institutions while educational projects undertaken meet industry needs.

4.5.3 Community

Members of the community can help in the design and evaluation of educational programs funded using educational impact bonds. Involvement of the community ensures higher education institutions have support when sourcing funding and that educational programs address societal issues. Ensuring educational programs address broader societal issues leads to more groups in society participating in educational impact bonds. Educational impact bonds can be designed to allow for investment from community members thus ensuring ownership of educational programs funded by educational impact bonds.

4.5.4 Higher education institutions

Higher education institutions can use educational impact bonds as an alternative source of funding. Higher educational institutions can partner with external stakeholders in the design and issuance of educational impact bonds to ensure the bonds are aligned with market demand and societal needs. By aligning funding with specific educational outcomes and fostering collaboration among universities, industry, government, and civil society educational impact bonds can enhance the relevance of educational programs.

5 RECOMMENDATIONS FOR FURTHER RESEARCH AND PRACTICE

It is recommended that research projects undertake a comparative analysis of funding models. Studies can compare nations using similar models to assess the outcomes. Studies can look at countries in similar economic conditions using different models to assess the outcomes. Future studies can conduct case study research focused on successful funding models. For example, a case study focused on Finland's funding model. Studies can be undertaken focused on understanding the impact of new sources of funding such as educational impact bonds.

It is recommended that policymakers and educational leaders should engage with financial experts to gain insights into ways to better raise and manage higher education funds. It is recommended that stakeholders engage in frequent workshops and seminars that gather government, community leaders, industry leaders, and education leaders to discuss trends in funding and share best practices.

It is recommended that educational leaders learn from international counterparts on ways to source and manage funding. For example, educational leaders in the United States of America have been successful in building endowments, and South African educational leaders can learn best practices on endowment from them. Higher education institutions should create and implement systems for monitoring and evaluating the effectiveness of their funding models.

6 CONCLUSION

The paper was designed to provide recommendations for building a sustainable higher education funding model in South Africa using the quadruple helix. The current state of South Africa higher education is seemingly not sustainable in the long term, given the overreliance on government funding. The paper provided several possible solutions to build a sustainable higher education funding model. These include diversifying funding sources, introducing income contingent loans, performance-based funding, research and innovation funding, and introducing education impact bonds.

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FRAMEWORK FOR DEVELOPING PEDAGOGY SKILLS FOR TEACHING AND LEARNING IN THE FOURTH INDUSTRIAL REVOLUTION (4IR): A SOUTH AFRICAN PERSPECTIVE

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ABSTRACT

Education 4.0 is characterised by responding to the needs of the fourth industrial revolution. This concept harnesses the potential of digital technology, open educational resources, globally connected education, and lifelong learning. South Africa's educational teaching and learning paradigm must be revisited and reframed to fit into the global perspective and application of education 4.0. The study aimed to analyse the current gaps in the pedagogy skills applied in higher education. One hundred-and-five lecturers were analysed using descriptive analysis focusing on their use of technology, pedagogy and digital skills. It was found that many lecturers need more understanding of pedagogy and are further limited in applying computational and digital skills. The study proposed a framework exposing lecturers to shifting learning approaches, innovative pedagogies, and advanced digital skills. Although the literature explores the framework for education 4.0, this study provides a deep dive into the realities and gaps within the scope of South African higher education, focusing on the Community Education and Training Colleges.

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1 INTRODUCTION

The Department of Higher Education and Innovation in South Africa is made up of three divisions, namely, Universities, Technical Vocational Education and Training (TVET), and Community Education and Training (CET) [1]; see Figure 1 below. South Africa is recorded to have many adults who are illiterate or unskilled [2]. Therefore, the CET's role is to provide basic literacy and skills to adults, and it is largely dominant in previously disadvantaged areas. CETs have nine colleges in total, structured as one college in each province of the country, and incorporate 3,279 adult education and training centres, (CETCs) [4]. These colleges target post-school youth and adults who wish to improve their employability and those who want to progress to TVET and Universities.

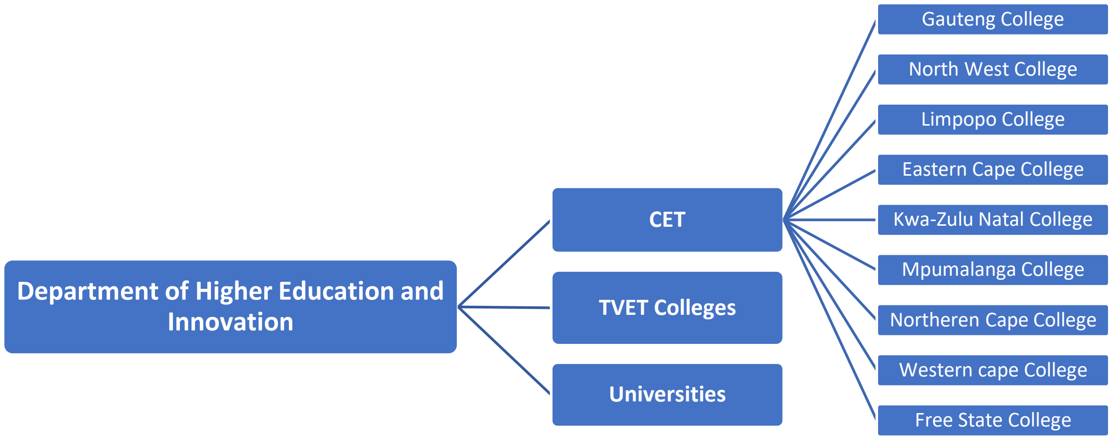

Figure 1: Placement of CET in the Department of Higher Education and Innovation

The CET sector faces a variety of challenges including insufficient resources, inadequate funding, and curriculum relevance. However, the greatest challenge that the sector faces is the need for digital skills and digital adaptation for its lecturers and learners [5]. The sector has been unable to bridge the digital gap and integrate technology into colleges and classrooms. It has been further stated that the sector still needs to develop effective E-learning platforms to ensure that educators and students are skilful in using them [6]. It has been emphasized that the CETC's lecturers have inadequate skills and qualifications, and college leaders need to improve their professional preparation [5]. This finding has led to this research which focused on analysing the skills gaps in CET's lectures.

1.1 Aim and Objectives

The study aimed to analyse the current gaps in the pedagogy skills applied in CETC's

The study's objectives are the following:

- Investigate the Teacher's understanding of 4IR in teaching and Learning
- Analyse the Teacher's exposure to pedagogies of teaching and learning in a higher institution
- Examine the Teacher's digital skills in CETC's
- Develop a framework for the pedagogy skills required for teaching and learning in a CETC

2 LITERATURE REVIEW

The world economic forum provided a guideline to promote the application of education 4.0 [7]. Education 4.0 is the concept of combining technological resources and infrastructure, and the advanced pedagogies in teaching and learning with the aim of adopting characteristics of the fourth Industrial Revolution [8]. The guideline indicated that the fourth industrial revolution in education rests on the following criteria: Global citizenship skills, Innovative and creativity skills, Technology Skills, Interpersonal skills, Personalised and Self-paced learning, Accessible and inclusive learning, Problem based learning, collaborative learning, lifelong and student driven learning [7]. It was through this guideline that the adoption of the fourth industrial revolution in education was clearly outlined as a world standard. It was found that South African Higher Education Institutions were falling behind the in adopting the 4IR, due to the lack of technological infrastructure and the limited knowledge in technology [8]. Given that South Africa is a developing country, the advancement in technology, specifically in community colleges has not yet evolved to meet the requirements of 4IR. The guideline by the World Economic forum further states that advancement in technology is at the centre of 4IR in education, and that none of its requirements may be met without technological infrastructure and resources being developed. This means that it is important for the HEI's to adopt the use of technology in teaching and learning so that they may remain competitive based on global standards.

For the adoption of technology in South African HEI's it is imperative that the teachers understand the concept of 4IR in education, their pedagogies are centred around the use of technology, and that they have the necessary digital skills required to facilitate innovation in teaching and learning [9] it is therefore vital that there is a specific focus on the teacher's readiness for 4IR, assessing their basic digital skills, and identifying their use of technology in teaching and learning.

2.1 Lecturer's readiness for 4IR in Teaching and Learning

The 4th Industrial Revolution (4IR) involves advancements in artificial intelligence (AI), robotics, Internet of Things (IoT), machine learning, and other cutting-edge technologies. The concept of 4IR was to signify the impact of the technological revolution on our daily lives, also known as Industry 4.0 [10]. In the context of South Africa, 4IR is still a relatively new phenomenon. It is agreed that the integration of the new curriculum aims to equip students with advanced technological knowledge encompassing the physical, digital, and biological aspects of 4IR [11][12]. However, this goal is difficult to achieve, as the current era of 4IR presents both opportunities and challenges that can impede students' effective technological progress [13].

Many studies have assessed the lecturer's readiness and knowledge of the Fourth Industrial Revolution. A study [14] found that although African lecturers may have a basic understanding of 4IR, there is still a need to lack of basic technologies in Africa, and the application of 4IR cannot be fully realised, specifically in education. The application of 4IR in education plays a vital role in both the learners and the lectures and has a positive impact on the classroom and eventually the community [15][16][17].

Several studies have investigated the preparedness of lecturers to incorporate the Fourth Industrial Revolution (4IR) into their lesson plans. A study found that despite having a moderate level of 4IR knowledge, new lecturers must be sufficiently equipped to integrate 4IR into their teaching practices [18]. The study revealed there is a need for more preparedness among new lecturers when incorporating 4IR into their lesson plans. New lecturers were further recommended to engage in training activities, such as workshops, to deepen their understanding of 4IR [18]. Additionally, to enhance 4IR preparedness, it is suggested that educational institutions offer additional resources to enable lecturers to access the Internet more efficiently [19].

2.2 Integrating technology in Teaching and Learning

Research has shown that it is essential for lecturers to have pedagogical knowledge [20]. This type of knowledge specific to the lecturer is based on how they relate to the discipline and subject matter [21]. Understanding what they know about teaching and what they know about what they teach impacts the lecturer's skill in transferring knowledge.

Previous research suggests that new lecturers have a basic understanding of educational content, while experienced lecturers tend to rely on unchanged subject matter expertise [22]. Additionally, new lecturers often make general teaching decisions without considering their students' background knowledge, skill levels, or preferred learning methods [23]. It has also been shown that experienced lecturers struggle to explain the connections between teaching concepts and subject matter concepts. Furthermore, using straightforward and factual recall questions is linked to low levels of pedagogical content knowledge [24]. These studies indicate that new lecturers find it challenging to represent and adapt ideas and concepts in meaningful ways to their students and are concerned about their teaching expertise.

Integrating technology into higher education teaching and learning requires changing both the instructors' knowledge of educational technology and their beliefs, stances, and pedagogical perceptions [25, 26]. In recent years, universities worldwide have significantly expanded distance learning, using integrated video-based technological means, such as online homework, lectures, and lessons that complement traditional classes [27]. Numerous higher institutions have been offering entire courses open to the public on the internet [26][28]. Most instructors adhered to the traditional lecture mode, using technology only to support frontal teaching [25]. However, the Covid-19 outbreak caused all higher education instructors to switch to online teaching immediately and without preparation [27]. This enabled the examination of the instructors' beliefs and knowledge when they switched to online teaching with the Covid-19 outbreak.

Professional development is the primary means for capacitating academic staff members at higher education institutions and is considered a mechanism and a platform for academics to continuously improve their teaching skills with a view to improving student success [25]. Professional development is defined as an ongoing and systematic process that includes activities such as discussion, investigation, experimentation with new practices, learning, expansion of knowledge, acquisition of new skills, and the development of approaches, stances, knowledge, and work tools [26]. Academics improve their pedagogy through professional development programs, and students learn more as a result, and there is a growing need for professional development for lecturers teaching in disciplines due to the changing nature of learning and teaching in universities [27][28]. Given the dynamics facing higher education, academics require massive professional development support to successfully navigate this complex and ever-changing landscape in higher education [25]. This applies to both newly appointed and experienced lecturers. Therefore, the teacher's approach and conceptions to teaching are central to student success.

2.3 The importance of Digital skills Teaching and Learning

Digital competence refers to a set of knowledge, skills, and attitudes that enable a person to achieve various life goals using digital technologies [26]. In the education system, teachers are required to develop their digital competencies and to impart the necessary skills to students for functioning effectively in the digital world, specifically for them to participate actively in education 4.0 [26]

The use of digital skills is a crucial factor for the competitiveness of a professional teacher, Therefore, the education system needs to anticipate future demands and prepare students for them [27]. As a result, a modern teacher must stay current with various modern technologies, possess them, and be able to apply them in practice based on the goals and objectives of the training [28]29].

With most sectors relying increasingly on technology, digital skills are essential for lifelong Learning. Individuals must continually acquire new digital skills to remain competitive as the digital and workforce landscapes evolve [29]. Universities and community colleges increasingly use technology to rethink learning paradigms, make online Learning more accessible, and transform what can be accomplished in the classroom [30]. Instructors are utilising learning technologies to adapt to these changes [29]. It is therefore equally vital that the CETs in South Africa adapt to these trends and are not left behind in innovations and developments.

Using technology effectively in the classroom is crucial for teachers today because it is an integral part of the educational environment. Developing teachers' digital competencies ensures that students have access to the best education. By providing ongoing professional development, access to technology and resources, and a supportive culture, higher learning institutions can help lecturers develop the skills, knowledge, and attitudes needed to integrate technology effectively into their teaching practices [31][32]. Digital literacy for lecturers also includes understanding digital safety, digital citizenship, and data privacy. Digital competence is broader, encompassing a comprehensive range of abilities, including information literacy, communication literacy, problem-solving and critical thinking, and digital content creation. It also includes the attitudes and mindset needed to use digital technologies responsibly and ethically [33]

The integration of digital technologies into teaching practices has the potential to enhance teaching and learning, but it requires thoughtful and strategic implementation. There are several challenges associated with teaching using digital technologies, including adapting teaching practices, providing professional development and training, ensuring equity and access, integrating technology effectively, addressing pedagogical concerns, managing assessment, and navigating time constraints [32]. Introducing a Digital Technology Curriculum presents both challenges and opportunities for educators and addresses the critical skills shortage in the digital technology industry, but requires addressing teacher readiness, limited resources, and curriculum integration.

2.4 Current Framework

The Learning Ecosystem Framework (LEF) has been suggested for institutions [9] and consists of two main parts. The first part includes academic stakeholders like policymakers, instructors, institutional staff members, and students. The second part includes non-living components like technology, the internet, course content, educational policy, structures, culture, strategies, and digital learning tools [9]. In an educational ecosystem, all stakeholders are expected to engage in learning, unlearning, relearning, and co-learning for self-improvement [9]. The framework addresses the concept of transformation in teacher pedagogy but does not provide the specific skills required from teachers to effectively engage in technology-based teaching and learning environments.

3 METHODOLOGY

The study followed a quantitative approach. Convenience sampling was used. A total of 105 lecturers in Gauteng CETCs were involved in the study, see table 1 below. Data was collected through closed-ended questionnaires that were analysed using descriptive analysis.

Table 1: Number of lecturers engaged in CET

Area	**N**	**%**
Johannesburg	19	18%
Sedibeng	9	9%
West Rand	26	25%
Tshwane	34	32%
Ekurhuleni	17	16%
Total	**105**	**100%**

The study was based in Gauteng, including Johannesburg, Tshwane, Ekurhuleni, Sedibeng, and West Rand. Lecturers from the various CETCs in Gauteng were involved as participants in the study. The study included only permanent lecturers through the different academic and skills programs.

4 RESULTS

4.1 Basic understanding of Education 4.0

The lecturers were asked how they would describe their understanding of 4IR in the classroom, the results are depicted in the figure 2 below.

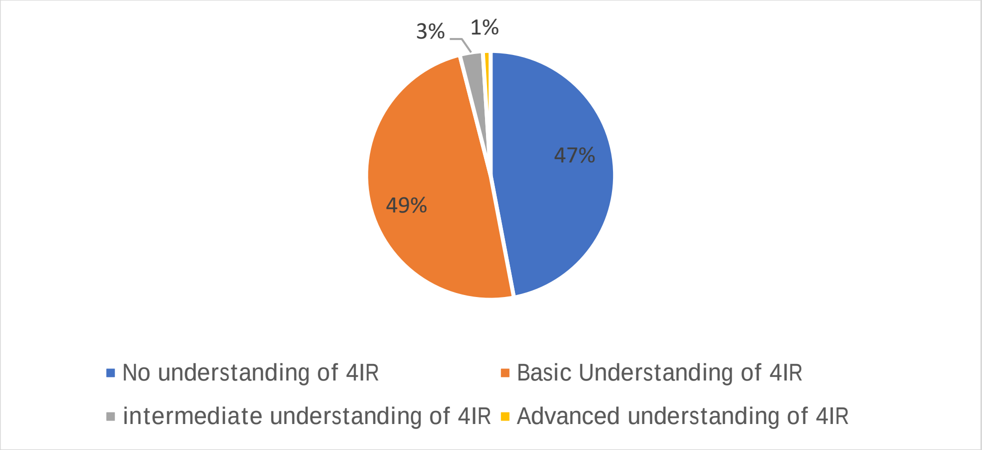

Figure 2: Teacher's understanding of 4IR

Most lectures indicated that they had no understanding of 4IR ranking at 49% or a basic understanding of 4IR in teaching and learning at 47%. This means that a total of 4% understand 4IR. This result is concerning because it means that lecturers are still applying traditional teaching methodologies that do not align with the developments in education. This also means that students are not exposed to technology at this level, which further disadvantages them in terms of employment and further studying in other institutions of higher Learning. The dominant lack of knowledge in 4IR clearly shows that there is a great need to educate and train these lecturers to ensure that they are on par with the development in education and equip the students with the necessary technological exposure to function effectively in the current era.

4.2 Lecturer's exposure to Teaching and Learning Pedagogies training

Figure 3 below reflects the teacher's responses to the question "Have you received any training on the 4IR teaching and Learning pedagogies?"

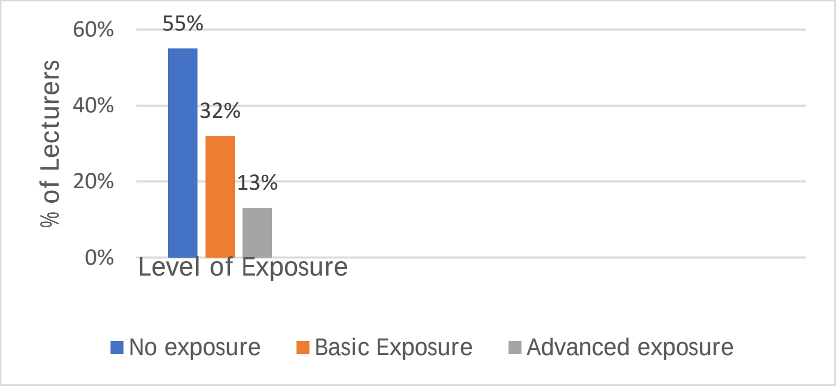

Figure 3: Lecturer's exposure to Teaching and Learning Pedagogies training

The study found that 33% and 13% had basic and advanced exposure to Teaching and Learning pedagogies. This is relatively good, given that most lecturers are senior citizens and close to retirement. This means that although 55% of the lecturers had no exposure to pedagogies, there is still some indication that lecturers take the time to reflect on their teaching practices in the classroom. This also shows that almost half of the lecturers have beyond basic knowledge of their teaching content. There is a need to still educate and train the 55% of lecturers who have no exposure at all to teaching and learning pedagogies.

4.3 Technology Centred Teaching Pedagogy

The teachers were asked if their teaching pedagogy promotes the use of technology to enhance learning, the responses are depicted in figure 4 below.

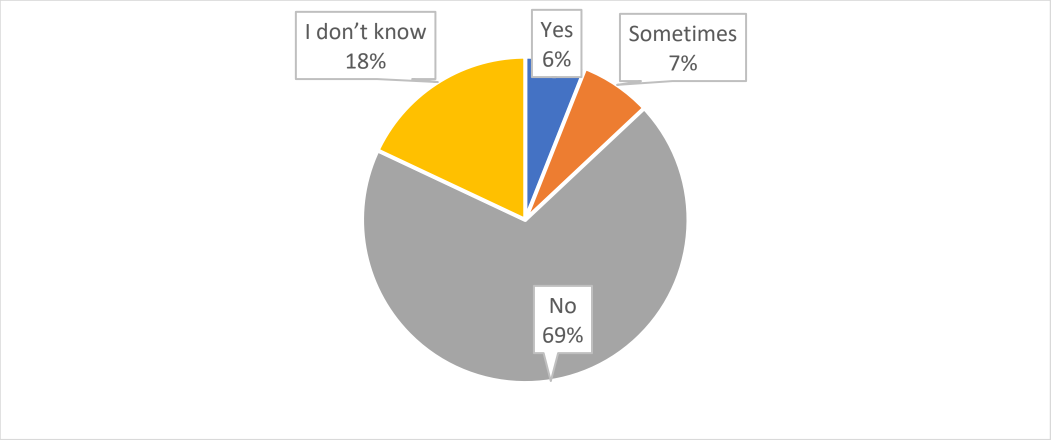

Figure 4: technology centered teaching pedagogy

It was found that most of the teachers acknowledge that their teaching pedagogy does not promote the use of technology to enhance learning. This means that they do not consider the integration of technology in their teaching. 18% of the teachers indicated that they did not know if they their pedagogy involves the use of technology as they do yet understand the concept of pedagogy. 6% and 7% of the teachers stated that they use YouTube videos and online platforms for their classes, these also include Facebook pages and WhatsApp groups, however the usage of these platforms in infrequent.

4.4 Teacher's knowledge in using technology in Teaching and Learning

Figure 5 below, shows the teachers responses to how they would you rate their current knowledge with regards using technology for teaching and learning,

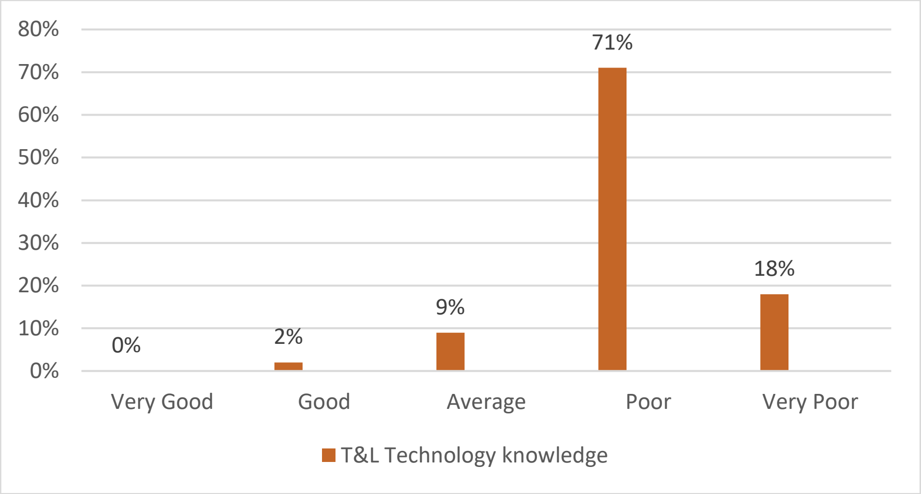

Figure 5: Teacher's knowledge in using technology in Teaching and Learning

It was found that only 2% of the teachers rated their knowledge on the use of Technology in Teaching and Learning as good, while 9 % rated themselves as average. This means that a total of 89% of the teachers believed that they were either Poor or Very Poor knowledge and exposure regarding the use of technology for Teaching and Learning. This means that there is not much exposure provided to the teachers in this regard, and very limited expectations from them to use technology for their teaching and learning. This further means that their students are not exposed to the various forms of technology in learning from the college, and therefore are misaligned with the concept of 4IR in the classroom.

4.5 Digital Skills for CET Lecturers

Table 2: Digital skills for CET lectures

	No Knowledge	Basic Knowledge	Advanced Knowledge
Gradebook	7%	78%	15%
Lesson Planner	81%	10%	9%
Calendar and Schedules	79%	17%	4%
Data import and Export	84%	11%	5%
Online communication	1%	71%	28%

In terms of digital skills, it was found that the CET lecturers have basic knowledge about managing a gradebook. This was because they used manual spreadsheets to capture marks, which were then transferred to an online gradebook by the college administrator. This means that although 78% know a gradebook, they do not personally use it for their marks. Above 79% of the lecturers do not have any knowledge of a lesson planner, data import and export, and managing online calendars and schedules, see Table 2 above, However, 71% and 28% had basic and advanced knowledge of online communication. This was an impressive result; however, most lecturers reported that they communicate online using online group chats through social media platforms and do not actively use organizational online communication platforms such as emails. These results have indicated that lecturers need to be exposed to various digital platforms that can facilitate teaching and Learning.

4.6 Quality of Technological resources as CET colleges

The lecturers were asked what the quality of the colleges WIFI, Computers and Electronic devices, Electronic Learning Materials and Online learning Platforms. Table 3 below, shows the responses from the lectures.

Table 3: Quality of Technological resources as CET colleges

Resources	Good	Fair	Poor	Not available
WIFI	2%	9%	6%	83%
Computers/ Electronic Devices	13%	11%	2%	74%
Electronic Learning Material	5%	1%	0	94%
Online learning platform	0%	0%	0%	100%

It was discovered that most of the colleges do not have WIFI, computers, electronic learning materials or an online learning platform. 11% of the participants stated that the WIFI was good or fair, 24% stated that the quality of the computers or electronic devices in the college was either good or fair. The teachers further stated that the electronic learning materials is largely not available, and only 5% found the that the quality of the learning materials was good. All the teachers stated that there is currently no online learning platform in any of the colleges. This means that the students are only taught physically using the traditional methods of teaching.

5 RECOMMENDATIONS

According to the World Economic Forum, there are basic skills required for teachers to promote the application of 4IR in education, as discussed previously in literature [7] the focus for South Africa has been to improve the technology and digital skills of teachers amongst infrastructure and other technological resources [8]. The framework recommends that a higher institution's level of readiness for 4IR, relies largely on the teacher's ability to evolve and transform the classroom to be compatible with the technology needs of the current age. This framework was developed based on the skills requirement of lecturers' in HEI's as recommended by the World Economic Forum, however specifically focuses on the CET current lecturers' skills profile and their limitations in the application of technology in teaching and learning.

Based on the findings on this study, the CET lecturers lack the understanding and application of 4IR in teaching and learning. It can also be concluded based on the findings that they do not have enough training on innovative pedagogical knowledge and lack technology skills. The framework below seeks to address the areas of focus to improve the lecturers pedagogy and technological skills, which will in turn improve the college's competitiveness and ability to foster 4IR in its teaching and learning practices [7]

The recommended framework for CET comprises three categories namely, The evolution of teaching and learning, Innovative teaching pedagogies, and technology skills. See Figure 6 below.

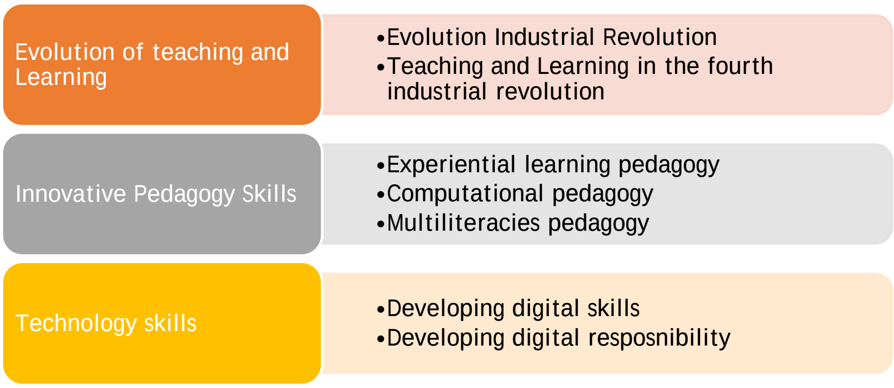

Figure 6: Framework for teaching and learning in 4IR in a CETC

5.1 Evolution of Teaching and Learning

The lecturers in higher education must be provided with a basic understanding of the Industrial Revolution, primarily from the first, second, third, and fourth, see table 4 below.

Table 4: Evolution of Teaching and Learning, Adapted [33]

	STAGE	LEARNER	EDUCATOR	RELATIONSHIP	ORGANISATION	GOVERNANCE
EDUCATION 1.0	Authority and Input centric	Passive recipient	Authoritarian	Teacher Centric	Centralised, Closed	Machine bureaucracy: No feedback loop
EDUCATION 2.0	Output and Testing-centric	Memorising input	Expert	Testing (Input - Output)	Decentralised, less-closed	Professional bureaucracy: Slow-feedback loop
EDUCATION 3.0	Learner and Student Centric	Explore new questions	Facilitator	Dialogic	Networking, opening	Learning system: An institutionalised feedback loop
EDUCATION 4.0	Co-creation and Innovation centric	Co-sense and shape the future	Midwife: generative coaching	Co-creative	Eco-system, breathing-in, breathing-out	Innovation Eco-system: Shared awareness of the whole

The basic knowledge of the Industrial Revolution in the context of teaching and learning allows lecturers to consider their teaching methods and how they must adapt to address the present requirements of the Fourth Industrial Revolution. [33].

5.2 Innovative Pedagogy Skills

Lecturers should be exposed to the various innovative pedagogy skills that are available to them. There are various types of innovative pedagogies that lecturers can be trained and exposed to, such as experiential learning pedagogy, computational pedagogy, and multiliteracies pedagogy.

- Experiential learning pedagogy: Involves engaging learners in an experience, followed by prompting them to reflect on the experience in order to cultivate new skills, attitudes, or ways of thinking. [34].
- Computational Pedagogy: This is done by constructing an artificial system (typically implemented on a computer), which is given a (simplified) learning environment and a learning rule that adapts the system to its environment [35].
- Multiliteracies Pedagogy: Designed to captivate the learner by taking into account their experiences and hobbies and getting them ready to handle the complexities of the world. The core of multiliteracy pedagogy consists of four essential concepts: contextualized practice, over-instruction, critical framing, and transformed practice [36].

5.3 Digital skills

There is a need to provide training in basic digital skills. This includes training in online grading, lesson planning, managing an online calendar, imparting and exporting digital data, and online communication using formal organizational platforms.

[37][38] Defined the basic digital skills needed in a day-to-day teacher and learner context. These skills include the following.

- Fundamental digital skills involve the ability to utilize digital technologies, such as browsing the internet, connecting online, and maintaining password security.
- Handling information and content requires the use of search engines, understanding that not all online content is trustworthy, and accessing content on various devices.

- When transacting online, one should create accounts for using or purchasing goods/services, use secure payment methods, and complete online forms.
- Problem-solving online involves finding solutions through tutorials, or chat, presenting solutions using software, and enhancing productivity.
- Being safe and lawful online entails understanding best practices for data storage and sharing, updating and securing passwords, and taking precautions against viruses.

6 CONCLUSION

It can be concluded that the absence of technology in the CET does not add value to the institution's innovation and development. Teaching and Learning in 4IR requires that the lecturers are equipped with the necessary skills and knowledge that align with the advancement in education. The CET must focus on the upskilling of its lectures. The framework provided would serve as a guideline for implementation. This framework would ensure that there is some exposure provided to lectures in terms of pedagogy and digital skills.

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AN OVERVIEW OF FUZZY LOGIC TRAFFIC SIGNAL CONTROLLER

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ABSTRACT

Arterial roads connect residential urban areas to economic centres and therefore carry high amount of traffic. Signalised intersections on arterial roads bear the predominant traffic congestion. Traffic congestion is a major issue as it not only causes frustration to motorists, but it also affects productivity and quality of life itself. Traffic signals are put in place to control traffic and give right of way to motorists from opposing directions. When the traffic signal fails to adequately solve the problem of traffic congestion, optimization strategies are then necessary to improve the traffic signal control and give the signal the intelligence to make a decision when faced with a problem of congestion. In this current study, we explore the use of Fuzzy Logic in traffic signal control. Fuzzy logic is a suitable concept in transportation since it combines subjective knowledge and objective knowledge.

Keywords: Fuzzy Logic, Traffic signal control, Transportation

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1 INTRODUCTION

According to Hausknecht et al. [1], traffic signals do not always reduce delay or congestion especially at intersections and they further outline that signalized intersections experience congestion, leading to delay despite the presence of a traffic signal. The congestion and delays experienced have a negative impact on road users. A large amount of time is wasted in congestion, which adversely contribute to reduced productivity at work and associated economic activity since more time is spent on the road than at work.

Various strategies are employed to optimize signal control with an aim of reducing congestion. Different strategies, techniques and algorithms have been developed and tested in several countries, more especially the developed countries. There have been several standard studies focusing on various approaches of modelling and predicting the behaviour of traffic [2]. The utilization of deterministic models is employed to depict the actual situation, as it offers the advantage of stability and ease of handling [3]. Nevertheless, these models are limited in their ability to promptly respond to unforeseen changes in driver behaviour [4]. The fuzzy theory, on the other hand, presents the potential to address both significant changes that quickly impact traffic flow continuity and minor changes that may pose statistical challenges but are of significant importance [5]. Over time, numerous stochastic methodologies have been introduced; however, the integration of fuzzy logic continues to demonstrate the highest level of reliability [6].

Zadeh [7] introduced the concept of fuzzy logic, which is based on fuzzy sets. The application of fuzzy set theory has been widespread in addressing uncertainty, imprecision, and complexity in various domains. Given the inherent uncertainties and imprecisions in the real world, fuzzy set theory is particularly well-suited for tackling real-world challenges and deriving precise conclusions [8]. The fundamental components of fuzzy set theory include a knowledge base that stores the operations of the fuzzy system as if-then rules, crisp inputs, crisp outputs, and an inference system that matches the input with the knowledge in the knowledge base to determine the output [9]. The utilization of linguistic variables and fuzzy if-then rules is a distinctive feature of fuzzy logic [10]. The core concept underlying these linguistic variables and rules revolves around the utilization of information compression [11].

The application of fuzzy logic in the transportation systems has contributed an additional framework in solving the uncertainties faced in this discipline [12]. Fuzzy logic is an extremely suitable concept in transportation since it combines subjective knowledge and objective knowledge [13]. It has been applied in the evaluation of traffic control strategies, operational transportation planning and the design of traffic controls [13]. Using fuzzy logic to control traffic flow affords a capability to convert human thinking process into an algorithm using mathematical models [14].

This study explores the use fuzzy logic in traffic signal control which is designed to optimize traffic signal control at a fourway intersection.

2 LITERATURE REVIEW

2.1 Signalised intersections

A signalized intersection is governed by traffic signals, which are utilized in intersections characterized by high volumes of traffic to regulate the interaction and sequence of movement from various directions [15]. These signals play a pivotal role in mitigating traffic conflicts, enhancing drivers' decision-making regarding turns, and dictating the permissible movements in a specific order [16]. The effectiveness of a signalized intersection in facilitating traffic flow is contingent upon both the physical attributes of the intersection and the employed signal timing plan.

2.2 Traffic signal control

The principal aim of a traffic signal control system is ensuring safety by implementing a temporal separation between the movements of individuals and vehicles traversing an intersection, thereby preventing conflicts [17]. A secondary yet significant objective of this system is according priority to specific groups or users to accomplish established goals or objectives related to system performance [18]. Numerous arterial roads are specifically engineered to facilitate the smooth movement of various users, such as motorists, public transport passengers, cyclists, and pedestrians, with minimal interruptions [18]. These integrated systems often prioritize particular users, such as public transport passengers, based on predefined performance objectives or desired outcomes of the system [18]. Intersection traffic management can be categorized as either fixed-time control or actuated control [18].

Each traffic signal control system is developed with the aim of fulfilling the particular social and political objectives of individual communities [19]. Nevertheless, according to Diakaki et al. [20] these systems are oriented towards accomplishing the subsequent goals: (1) Enhancing the efficiency of traffic flow and ensuring public safety. (2) Effectively monitoring traffic patterns and making well-timed traffic management decisions. (3) Mitigating fuel consumption and the environmental repercussions of stop-and-go traffic by enhancing traffic flow efficiency.

The advantages of advanced traffic signal control systems have been evidenced in various aspects such as travel duration, velocities, vehicle halts, delays, energy usage, and ecological effects [21]. Furthermore, they have exhibited capabilities in alleviating traffic congestion and diminishing the occurrence of road accidents [21].

Traffic signal control can be a fixed-time signal control or actuated signal control. A fixed-time traffic signal is a signal that utilizes a timer to transition at established intervals, rather than adjusting based on traffic flow [22]. It establishes a structured and foreseeable traffic flow in the vicinity where they are positioned through the employment of an electro-mechanical signal controller that can be modified and employs a rotary timer to guarantee the signal changes at the designated interval determined by a traffic designer [22].

The primary benefit of fixed-time traffic signals lies in their lower initial expenses and maintenance requirements compared to alternative traffic signal systems [23]. Conversely, a drawback associated with them is the potential for unnecessary delays, as vehicles may be compelled to wait at intersections for extended periods in the absence of traffic [23]. Consequently, fixed-time signals are predominantly utilized in metropolitan regions characterized by consistent and heavy traffic volumes [23].

2.2.1 Actuated Traffic Signal Control

Actuated traffic signals, unlike fixed-time signals, adjust according to traffic patterns through sensor detection [24]. The primary objective is to optimize traffic flow efficiency by making prompt adjustments. Various detectors are utilized to interface with the control system of actuated signals, such as embedded road sensors like pressure plates and inductive loops, as well as overhead devices like non-video and video sensors [24].

The advantages of these traffic signals are numerous, as they excel in adapting to traffic dynamics and mitigating congestion [24]. They are most effective in areas with fluctuating traffic patterns, such as suburban or rural regions. Nonetheless, the drawback of this signal type lies in the initial and ongoing expenses associated with both detectors and control systems [24]. There are three basic types of actuated control: (i) semi-actuated control, (ii) fully-actuated control (iii) volume-density control [24]. Their objective is to keep the junction busy and to eliminate idle green time, thus minimising delay to vehicles.

2.3 Fuzzy logic

Fuzzy logic is a methodology utilized for formalizing the human capacity for reasoning imprecisely or approximately [25]. It serves as a means of computational processing involving linguistic variables, wherein the values are words or sentences rather than numerical figures. The foundation of a fuzzy logic control system is rooted in a collection of rules that qualitatively articulate the connection between inputs and outputs in a "natural language" manner [25]. These rules, akin to knowledge-based expert systems, offer a simplistic elucidation of the input/output correlation [25]. In contrast to expert systems, a fuzzy logic rule framework can be concise and direct due to the mapping of discrete input and output values onto user-defined fuzzy sets [25]. These sets are instrumental in constructing a model that accomplishes the requisite non-linear mapping while evading undesired "steps" in output values caused by the mere utilization of thresholds in input values [25].

The fuzzy logic process follows basic steps in developing a fuzzy logic controller. The steps are outlined in the section below.

2.3.1 Input/ Linguistic Variables

A linguistic variable is a fundamental concept within fuzzy logic that holds significant importance in various applications, especially in the domains of fuzzy control and fuzzy expert systems [26]. As indicated by its name, a linguistic variable comprises values that are words or sentences in a natural or artificial language [26]. For instance, the linguistic variable "Queue Length" qualifies as such if its values include terms like "long," "not long," "very long," "short," "not short," "very short," and others. Linguistic variables serve as a means to articulate significance and contextual information. They convey precise information suitable for the given problem [26].

The potential values associated with a linguistic variable depict its universe of discourse [27]. For instance, the universe of discourse for the linguistic variable "speed" could range from 0 to 220 km/h, encompassing fuzzy subsets like extremely slow, moderate, medium, rapid, and very fast. Linguistic variables encompass the notion of fuzzy set modifiers, commonly referred to as hedges [28]. Hedges are terms that alter the structure of a fuzzy collection [28].

2.3.2 Fuzzification and Membership Functions

The process of fuzzification involves the conversion of a precise input into a fuzzy function, thereby establishing the 'degree of membership' of the input to an ambiguous concept [29]. In numerous controllers, the input variable values are aligned with the value ranges of the respective universe of discourse [30]. The scope and precision of input-fuzzy sets, alongside their impact on the fuzzification process, are recognized as factors influencing the overall efficacy of the controller [30].

Membership functions enable the quantification of linguistic terms and the graphical representation of fuzzy sets [29]. A membership function for a fuzzy set A on the universe of discourse X is defined as $\mu A: X \rightarrow [0,1]$ [31]. Each element within X is assigned a value between 0 and 1 [31], denoted as a membership value or degree of membership. This value signifies the extent to which the element in X belongs to the fuzzy set A [31].

2.3.3 Fuzzy Rule Base

The knowledge base encompasses a collection of fuzzy implications in the form of rules that outline the necessary actions to be executed. The intelligence of fuzzy reasoning algorithms lies in the fuzzy rule base [30]. According to Atlas [30], these rules embody the operational dynamics of a system, decision-making processes, and the insights of an expert. Establishing a robust rule base system is crucial for making accurate decisions [30]. This system incorporates the ideas, knowledge, intuitions, and strategies of experts in the decision-making process [30].

The inference system is a computational framework that is grounded in the principles of fuzzy set theory [32]. The primary role of the inference engine is to apply the inference rules to the fuzzy input in order to produce the fuzzy output [32]. These inference rules are utilized for assessing the linguistic values and associating them with a fuzzy set, necessitating the defuzzification process to convert it into a precise value [32]. This system emulates the cognitive process of human reasoning [32]. Consequently, a fuzzy inference system is an intelligent system capable of computing through verbal means to draw inferences utilizing knowledge presented in a linguistic format of IF-THEN structure {IF (conditions are met) THEN (consequences are inferred)}. There exist two prevalent types of inference models, namely the Mamdani and Sugeno inference approaches [33].

2.3.4 Defuzzification

Defuzzification is the process of transforming a fuzzy output into a precise value [30]. The resulting defuzzified value guides the Fuzzy Logic Controller (FLC) on the necessary decision or action to be executed to regulate the process [30]. For instance, in applications of real-time control systems, the output manifests as a precise signal utilized to activate real-time apparatus like electronic switches and relays [30]. Various methods are applied in the defuzzification process, with the most recognized methods being lower maximum (LM), upper maximum (UM), mean of maxima (MOM), equal areas (EA), and center of gravity (COG)/ center of areas (COAs). The COG/ COA method is predominantly employed in fuzzy logic control scenarios [30].

2.4 Fuzzy logic traffic controller

A fuzzy logic traffic controller is an advanced system crafted to enhance traffic flow through the adjustment of signal timings according to real-time traffic conditions [34]. Numerous research works have introduced fuzzy logic controllers for traffic signals, incorporating elements such as pedestrian crossing allocation, estimation of traffic density, and management of incidents on expressways. These controllers employ fuzzy inference systems to analyze input variables, modify signal intervals, and make decisions aimed at improving traffic efficiency [34]. Furthermore, there have been proposals for distributed modular fuzzy logic-based control strategies for multi-stoplight road networks, demonstrating the potential to alleviate congestion by directing traffic independently based on localized sensor data [34]. Through the integration of fuzzy logic principles into traffic management systems, these controllers strive to enhance road safety, decrease energy consumption, and optimize overall traffic flow [34].

Aziz [35] introduced a viable model for the deployment of a fuzzy Logic-based system for traffic control. The model involved the placement of eight sensors at a four-way junction to monitor the flow of vehicles. The system underwent testing in various traffic scenarios, ranging from heavy to light traffic, with car densities observed at different times of the day. A comparison was made between the performance of this system, a traditional controller, and a human expert. The evaluation criteria focused on the number of vehicles allowed to pass simultaneously and the average waiting time.

The results indicated that the fuzzy controller outperformed the conventional controller by allowing 31% more cars to pass and reducing the average waiting time by 5%. Furthermore, the performance index saw a 72% improvement. In comparison to a human expert, the fuzzy controller facilitated the passage of 14% more cars with a 14% shorter waiting time and a 36% higher performance index. Tan et al. [36] conducted a similar study based on the model proposed by Aziz [35].

Zhang et al. [37] presented a traffic signal control approach utilizing a layered Fuzzy Neural Network (FNN) for learning the rules of a Fuzzy Logic control system. The FNN combines the benefits of Fuzzy Expert Systems (fuzzy reasoning) and Artificial Neural Networks (self-learning). The paper details the integration of fuzzification strategies, decision-making logic, and defuzzification strategies into the network's nodes, with the fuzzy rules represented by the adjustable weights of the input connections on a specific layer of the network.

Czogolla [38] devised a fuzzy logic controller for a four-way intersection aimed at deciding whether to conclude or prolong the current phase and opt for the transition to the subsequent phase of the signal control. The primary constituents of the controller system encompass the signal processing unit, responsible for transforming binary raw detector data into traffic parameters. The fuzzy controller is presented with the input parameter set and identifies the optimal moment for concluding the ongoing phase. The state machine retains the current state of the systems. The security unit assesses the feasibility of fuzzy output to maintain minimal and maximal phase durations. The resultant signal specifies the succeeding phase number when the preceding phase is terminated. In the event that no public traffic is incoming from any direction and demands from individual traffic flows are identified, a predefined fundamental order of the phase sequence is implemented.

Chou & Teng [39] design a fuzzy logic controller that can be used in multiple junctions with multiple lanes. The fuzzy logic controller is able minimize congestion by reducing the queue lengths from all directions. Hoyer and Jumar [40] presented simulation results acquired for an intersection with twelve main direction traffic flows. The controller operated with ten fuzzy input variables and two output variables. Compared to currently used design processes, fuzzy control leads to a more effective and transparent design of traffic signal systems. Zaied and Othman [41] develop a fuzzy logic traffic system that considers the two two-way intersections and is able to adjust changes in time intervals of a traffic signal based on traffic situation level. The results show that their proposed cycle length is shorter than the one proposed by the current system, the cycle length of the proposed system is accelerated by 3% to 7%. Additionally, the suggested system results in less latency per cycle than the current system does. With a percentage range of 4-16%, the proposed system reduces delay (improves cycle).

Tunc et al. [42] use fuzzy logic controller to optimize the traffic light in a fourway intersection. The queue length values of the vehicles at the traffic intersection are used as input values, with the green phase duration being the output value. The aim was to minimise the waiting time at the traffic intersection. The researchers used seven membership functions and 49 fuzzy rules. A simulation was carried out using SUMO program with different scenarios simulated. The simulation results show that the proposed fuzzy logic controller yielded better results than the fixed time traffic light control, where the green phase was extended based on the queue length. Boneva et al. [43] design and implement a fuzzy controller that uses expert knowledge to derive its fuzzy rules. The proposed controller is simulated and compared to conventional traffic light controller. The authors used nine fuzzy rules. The control parameter was the duration of green light within the cycle length. Their results show that the fuzzy controller outperforms the conventional controller.

3 METHODOLOGY

The aim of this study is to design a fuzzy logic traffic signal controller for a four-way intersection where traffic flows from the North, South, East, and West directions, excluding right and left turning movements.

Vehicles arrive at the intersection signal randomly and are halted by the red light signal. Upon receiving the green light signal, vehicles proceed until the subsequent red light cycle, where they are once again halted, as depicted in Figure 1. While awaiting the green light signal, vehicles are subjected to an influx of additional vehicles joining the queue, thereby causing traffic congestion. The initiation of the green light prompts the vehicles to commence movement until the subsequent activation of the red light signal. In scenarios where the green light signal remains active for a short duration, numerous vehicles within the queue encounter challenges in traversing the intersection and thus necessitate prolonged waiting periods. This predicament contributes to congestion and subsequent time lags. An astute approach involves the design and implementation of a traffic signal controller that possesses the capability to protract the green light signal in accordance with the queue's vehicle count, thereby ensuring efficient clearance without inducing congestion. The allocation of an elongated green light signal is proposed for the traffic direction experiencing heightened traffic flow.

Figure 1: Queueing system

The process of designing a fuzzy logic controller is detailed in section 2.3. This section elaborates on the steps involved in designing the traffic signal controller using fuzzy logic. Section 3.1 outlines the input variables, section 3.2 describes the fuzzification process and membership functions, section 3.3 focuses on the development of fuzzy rules, and section 3.4 addresses the defuzzification process.

3.1 Input Variables

To develop the fuzzy controller, it is imperative to define the linguistic variables to be employed. Two linguistic input variables, Queue Length (QL) and Vehicles Arriving (VA), are utilized, while the output variable is denoted as Green Light Extension (GE).

The queue length is then computed as the number of vehicles stopped during each red signal phase. A total of ten sets of queue counts were documented and aggregated within a 15-minute time interval. The number of incoming vehicles (Vehicles Arriving) is tallied as they enter the intersection. The delay experienced by motorists at signalised intersections is calculated using Webster’s model presented in equation 1.

$$d = \frac{C(1-\lambda)^2}{2(1-\lambda X)} + \frac{X^2}{2v(1-X)} - 0.65\left(\frac{c}{v^2}\right)^{\frac{1}{3}}\left[X^{2+5\lambda}\right] \qquad (1)$$

where:

$d = average\ overall\ delay\ per\ hevicle\ (seconds),$

$\lambda = prportion\ of\ the\ cycle\ that\ is\ effective\ green\ \left(\frac{g}{c}\right),$

$C = cycle\ length\ (seconds),$

$v = arrival\ rate\ (vehicles/hour),$

$c = capacity\ for\ lane\ group\ (vehicles/hour),$

$X = volume\ to\ capacity\ ratio\ of\ lane\ group,$

$g = effective\ green\ time\ (seconds).$

3.2 Fuzzification and Membership Functions

In this study, triangular membership functions have been employed due to their efficiency, ease of modeling, and simulation capabilities given their inherent linear characteristics. Table 1 showcases the membership functions assigned to each input and output fuzzy variable.

Table 1: Fuzzy membership functions

Variable	**Membership Functions**		
Queue Length (QL)	Short (S)	Medium (M)	Long (L)
Vehicles Arriving (VA)	Low (Lo)	Medium (M)	High (H)
Green Light Extension (GE)	Short (S)	Medium (M)	Long (L)

Triangular membership functions are carried out through the integration of line equations presented in equation 2.

$$\mu_A(x;x_1;x_2;x_3) = \begin{cases} 0, \\ \frac{x-x_1}{x_2-x_1}, \; for\; x_1 \leq x \leq x_2 \\ \frac{x_3-x}{x_3-x_2}, \; for\; x_2 \leq x \leq x_3 \\ 0, \quad otherwise \end{cases} \tag{2}$$

where the parameters $x_1, x_2 \; and \; x_3$ give the location of fuzzy membership function A in the universe of X.

Therefore,

$$\mu_A = QL = \tilde{A} = \{QL, \mu_{\tilde{A}}(QL) |\; QL \;\epsilon X\} \tag{3}$$

$$\mu_A = VA = \tilde{A} = \{VA, \mu_{\tilde{A}}(VA) |\; VA \;\epsilon X\} \tag{4}$$

3.3 Fuzzy Rules

The number of rules corresponds to the potential input combinations derived from the number of membership functions per input. The proposed fuzzy controller entails two inputs and one output, with each featuring three membership functions; hence, resulting in a total of nine fuzzy rules.

3.4 Defuzzification

Defuzzification represents a crucial procedure aimed at converting the fuzzy output values from a fuzzy inference into precise output values. The method adopted in this research involves the application of the center of gravity (COG)/ center of areas (COAs) defuzzification technique.

4 RESULTS AND DISCUSSION

In this paper, the fuzzy logic toolbox within Matlab has been utilised to execute the proposed fuzzy logic traffic signal controller for a fourway signalised intersection, in addition to the fuzzy rule set. By utilizing the Mamdani fuzzy inference system, the implementation encompasses the membership functions assigned to input and output variables, alongside the integration of fuzzy rules.

The depiction of membership functions for Queue length is visible in Figure 2. The illustrated graph shows the membership degree ranging between zero and one, where zero signifies non-membership and one signifies full membership. For a short queue length, the vehicle count falls within the range of 0 to 10, while a medium queue length corresponds to 5 to 25 vehicles, and a long queue spans from 20 to 50 vehicles. Consequently, the controller must calibrate the Green time according to the queue's vehicle count, with longer queues necessitating prolonged Green time.

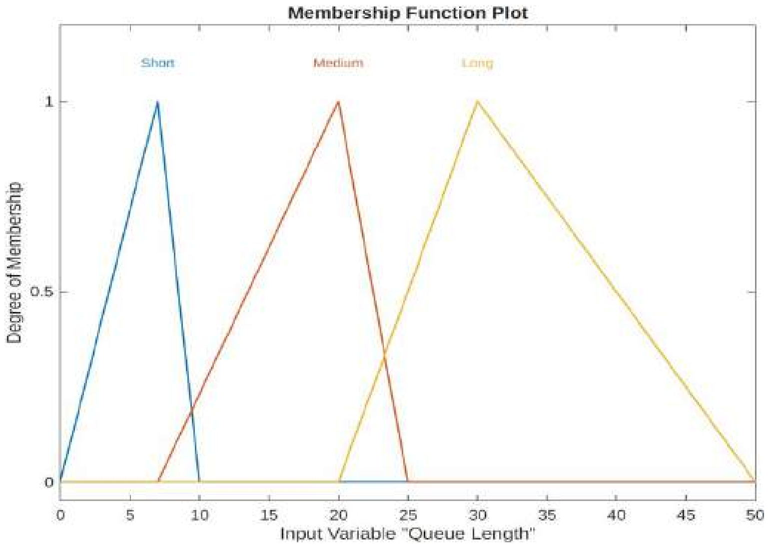

Figure 2: Queue Length Membership Function

The membership functions associated with Vehicles Arriving are presented in Figure 3. The extension of green time is contingent upon the influx of vehicles at the intersection during either green or red light signals. A higher volume of arriving vehicles warrants an elongated green light duration aimed at mitigating queue length and delays.

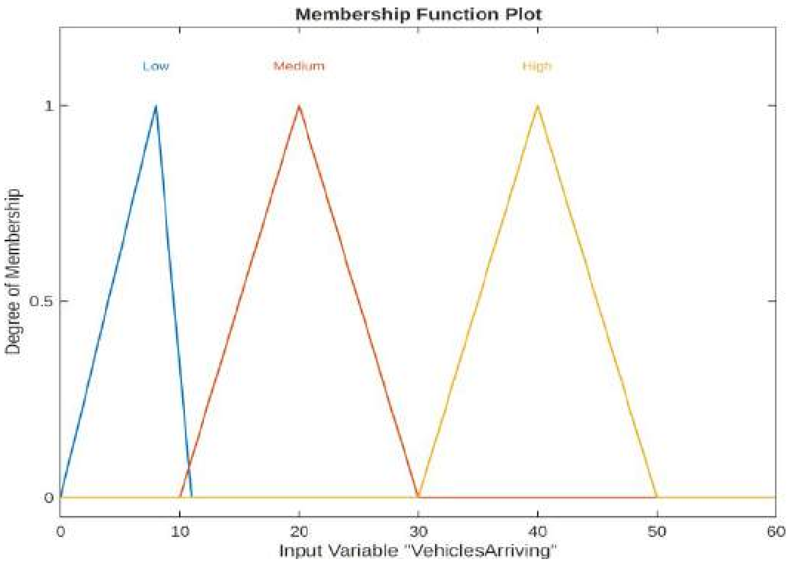

Figure 3: Vehicles Arriving Membership Functions

The formulated fuzzy rules are outlined in Table 2, with a total of nine rules having been derived. These rules govern the controller's directives based on the queue length and incoming vehicle count. For instance, rule number 1 stipulates that "If Queue Length is Short and Vehicles Arriving are Low then Green Time Extension is Short." Rule number 9 for instances stipulates that "If Queue Length is Long and Vehicles Arriving are High then Green Time Extension is Long." Subsequently, the green signal duration adjusts in response to the queue length and incoming vehicle count, thereby enhancing the intersection's operational efficiency and reducing delays for motorists.

Table 2: IF-THEN Fuzzy rules

Rule no.	Queue Length	Vehicles Arriving	Green Time Extension
1	Short	Low	Short
2	Short	Medium	Short
3	Short	High	Medium
4	Medium	Low	Medium
5	Medium	Medium	Medium
6	Medium	High	Long
7	Long	Low	Long
8	Long	Medium	Long
9	Long	High	Long

Figure 4 shows the surface viewer depicting the proposed traffic signal control system. This visual representation offers a 3-Dimensional output surface exhibiting queuing vehicles and incoming vehicles, thereby enabling the generation of diverse surface views for varying outputs.

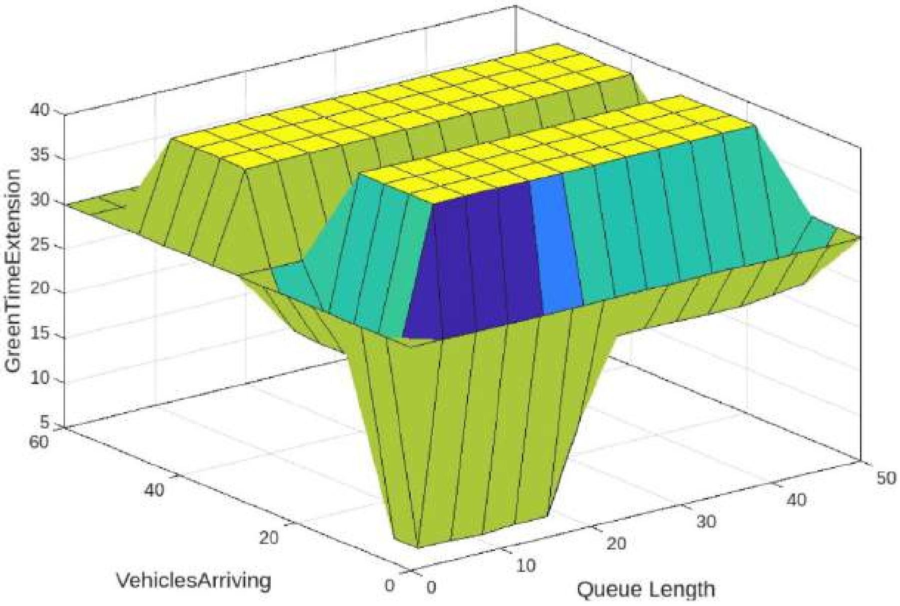

Figure 4: Surface viewer

5 CONCLUSION

In the present study, fuzzy logic was utilized for the development of a traffic signal controller. The utilization of If-Then fuzzy rules is aimed at providing directives to the controller regarding the extension or retention of the green light signal, which is contingent upon the number of vehicles present in the queue and those arriving either to traverse or join the queue. A direct correlation is observed, wherein the length of the queue and the influx of arriving vehicles dictate the duration of the green light signal extension. Consequently, this strategy is anticipated to reduce the time spent by motorists at the intersection, thereby mitigating delays and enhancing the efficacy of traffic signal management at the intersection.

The inherent characteristics of fuzzy logic offer a methodology for addressing efficiency, safety, and environmental goals in traffic signal control and multi-objective decision-making processes, thereby aiding in the enhancement of an effective and efficient Transportation Management System (TMS). Recent literature highlights the adaptability of initial parameters in fuzzy logic-based traffic signal controllers, along with the utilization of various fuzzy inference methods. Research in this area is driven by findings indicating superior performance compared to traditional traffic signal controls, particularly in high and fluctuating traffic volumes prevalent in numerous developed and developing nations. It is foreseeable that the application of fuzzy logic will not only advance adaptive traffic signal controllers but will also significantly enhance future TMS strategies by boosting the performance of adaptive controllers and overall decision-making processes within TMS frameworks. Scholars in developing regions, notably rapidly progressing countries such as South Africa, should explore the potential benefits of fuzzy logic-based traffic signal control.

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THE ROLE OF INDUSTRY 4.0 TECHNOLOGIES IN SUCCESSFUL ENTERPRISE RESOURCE PLANNING (ERP) IMPLEMENTATION OF PROJECTS IN SELECTED SOUTH AFRICAN ORGANISATIONS

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ABSTRACT

This research investigated the role industry 4.0 technologies, notably Cloud Computing and Big Data, play in data quality and integration with regard to the success at which Enterprise Resource Planning systems are implemented in selected South African companies. Current issues faced by software and information systems industries and the challenges of successfully implementing an ERP system were explored. Key themes prompted responses regarding the barriers that are preventing the successful implementation of ERP Systems in South African organisations. The study's findings suggest that South African ERP users are actively considering integrating a number of cutting-edge technologies into their current ERP systems, but the rate of actual adoption of these technologies is significantly slower due to economic considerations, security considerations, and lack of expertise. Strategies to successfully promote and implement ERP Systems are suggested.

Keywords: Enterprise Resource Planning, Industry 4.0, Cloud Computing, Big Data Analytics, Data Integration

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1 INTRODUCTION

The COVID-19 pandemic has led to a shift in business practices in South Africa, with many industries adopting remote work policies to minimize physical dependence. Enterprise Resource Planning (ERP) systems, which integrate a company's processes into a single data and IT architecture, are playing a crucial role in enabling remote operations and meeting consumer demands [36]. While large organizations have already implemented ERP systems, small and medium-sized enterprises are increasingly recognizing their cost-effectiveness and strategic importance [1]. ERP systems support remote access, automated reporting, data sharing, and real-time controls, sustaining businesses during the pandemic.

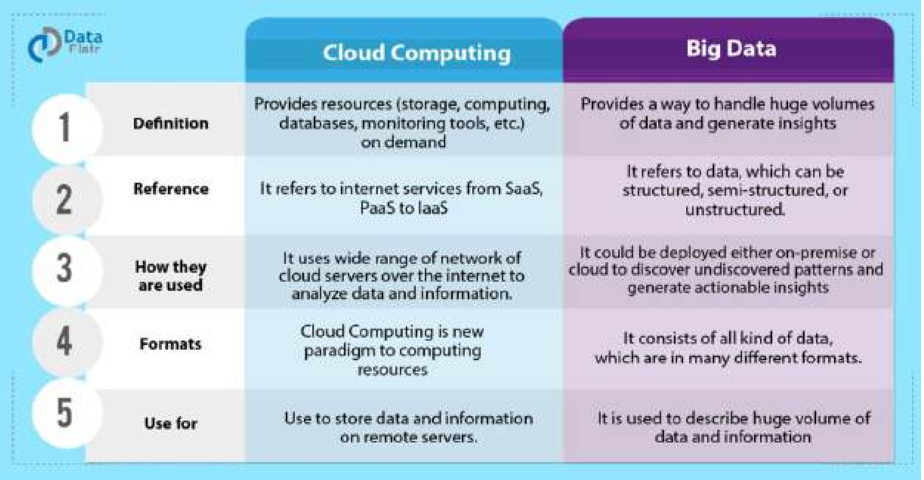
Industry 4.0, a digital transformation of manufacturing processes, is driven by emerging technologies such as sensor technology, artificial intelligence, and cloud computing. Industry 4.0 has revolutionized various aspects of business, including team management, digital platforms, contactless delivery, and customer relationship management [37]. This study focuses on the impact of Industry 4.0 technologies, specifically Cloud Computing and Big Data, on the success of ERP systems in South African organizations. The selected technologies are closely related to ERP system implementation and can help businesses leverage existing data sets and analyze unstructured data, preparing them for future ERP deployments.

Big Data Analytics is crucial for extracting value from large data sets, but managing such data can be challenging. Cloud computing provides a solution by allowing remote processing of data and continuous software evolution. Cloud-based systems offer benefits such as increased productivity and faster data recovery compared to traditional on-premises systems.

The importance of data quality and integration in adopting an Enterprise Resource Planning (ERP) system is often overlooked. Data migration, transferring data from older systems to the ERP database, is a crucial step but can be challenging due to scattered data sources. The need for data transfer to a cloud-based system goes beyond replacing outdated systems and includes factors like database growth, reliance on high-end servers, cost reduction, and data transferability [38].

1.2 Research Objective

The main objective of this research paper is to determine the role Cloud Computing and Big Data play in data quality and integration with relation to the success at which Enterprise Resource planning systems are implemented in selected South African companies.



		Cloud Computing	Big Data
1	Definition	Provides resources (storage, computing, databases, monitoring tools, etc.) on demand	Provides a way to handle huge volumes of data and generate insights
2	Reference	It refers to internet services from SaaS, PaaS to IaaS	It refers to data, which can be structured, semi-structured, or unstructured.
3	How they are used	It uses wide range of network of cloud servers over the internet to analyze data and information.	It could be deployed either on-premise or cloud to discover undiscovered patterns and generate actionable insights
4	Formats	Cloud Computing is new paradigm to computing resources	It consists of all kind of data, which are in many different formats.
5	Use for	Use to store data and information on remote servers.	It is used to describe huge volume of data and information

Figure 1 Differences Between Big Data and Cloud Computing [34]

2 LITERATURE REVIEW

2.1 Enterprise Resource Planning (ERP) Systems

ERP systems are software solutions that integrate an organization's processes and functions into a unified framework [1]. They support critical business functions such as communication, business process orchestration, data storage, and providing insights into organizational health [2]. According to Acar and companions. [3], ERP systems automate the movement of goods, information, and financial resources, ensuring smooth information flow within and outside the organization. Over the years, ERP systems have evolved and integrated various modules, including purchasing, inventory control, sales, production planning, quality management, cost control, fixed asset accounting, and human resources [4]. These systems offer improved customization and integration options, allowing organizations to tailor them to their specific needs [2]. There are two approaches to implementing ERP systems: best-of-breed, which integrates software from multiple vendors, and an integrated best practice approach, which embeds

business best practices into modules and implements them organization-wide [4]. Customization and interface with other applications may be necessary to meet unique requirements [5]. Traditional ERP systems are known as on-premise ERP, where IT expenditures are not considered as expenses under the licensing arrangement [5].

2.1.1 Implementing Traditional ERP

Conventional ERP systems can be categorized into two types: On-Premise and Hosted ERP [2]. In an on-premise ERP solution, the software is licensed and installed on the organization's own PCs and servers. The organization maintains control of the infrastructure, performs maintenance, and incurs the associated costs. This requires significant capital expenditures, and the organization is responsible for managing the server maintenance and IT infrastructure [4].

Alternatively, a hosted solution involves a third-party service provider hosting the licensed ERP application [6]. The service provider operates the service from a remote location and provides it to individuals or groups of organizations through a network connection, which may or may not be connected to the internet [7]. This type of deployment is known as a hosted or Application Service Provider (ASP) solution, where the third-party firm provides computer-based services [7]. It can be considered a private cloud-based solution.

2.2 Industry 4.0

Industry 4.0, a term coined by Kagermann and companions [8] refers to the increasing integration of information and communication technology (ICT) in industrial manufacturing. Key technologies associated with Industry 4.0 include big data analytics, IoT, digital modeling, cloud computing, and augmented reality. Industry 4.0 aims to enhance quality, productivity, and flexibility in manufacturing, enabling mass customization [9]. While there is no universally accepted definition, this study adopts the manufacturing perspective definition put forward by Kagerman and companions [8] as it encompasses all the essential elements of Industry 4.0.

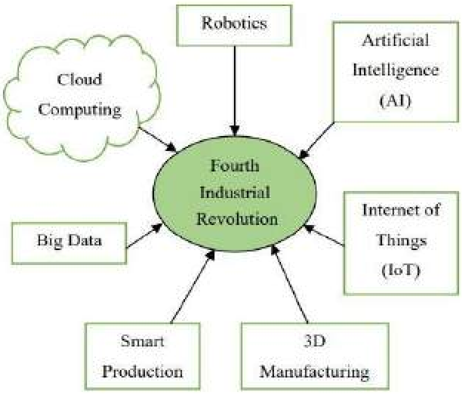


Figure 2 Elements of Industry 4.0 [35]

2.3 Cloud Computing

Cloud computing is a computing environment that provides high-level availability, scalability, and flexibility of computer systems while keeping operating costs low. It offers computing resources as a utility over the internet to meet the diverse needs of the business community. Cloud computing encompasses software, hardware, and services delivered through the internet [10]. It is categorized into three service models: Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS). These models are illustrated in Figure 2, representing different levels of cloud computing services [11].

2.3.1 Data Migration and Quality

The use of standard tools and processes in cloud computing enables streamlined integration and migration by facilitating interaction between system components, users, and other systems. Cloud migration involves transferring data repositories and other IT components to a provider-managed shared environment accessible over the Internet.

ERP systems are an excellent candidate for cloud migration because they serve as the information system's central hub, containing a large amount of data that local devices may struggle to process effectively, and because, unlike operational systems such as MES or WMS, they are not mission-critical applications that would completely shut down the business if they failed [12].

2.3.2 Cloud Based ERP

Cloud-based ERP (Enterprise Resource Planning) solutions operate in a cloud computing environment, where the ERP program is hosted on the internet and accessed through a browser without the need for local installation [13]. Cloud ERP offers advantages such as reduced costs, faster implementation, scalability, and easier updates compared to traditional on-premise ERP systems [14].

Moving to cloud ERP is crucial for organizations to stay competitive in the market, as legacy ERP systems become more expensive and new technologies like cloud computing and software as a service (SaaS) become available

[15] states cloud-based ERP provides benefits such as lower access costs, reduced IT support and maintenance, reliable information access, minimized data duplication, shorter adoption and cycle times, cost savings, scalability, and less maintenance. [16] explored the benefits of Cloud-based ERP for small and medium-sized enterprises (SMEs) in terms of cost reductions, improved performance, decreased maintenance and update costs, and easier software maintenance.

However, an article by Valdebenito and Quelopana [17], stated that despite these benefits organizations may still face difficulties with the user interface and capabilities provided by cloud ERP providers. Concerns about the availability and reliability of cloud services, as well as the integration of services and applications between traditional and cloud ERP systems, can also arise.

2.4 Critical Success Factors Impacting the Adoption of Cloud ERP Systems

2.4.1 Security of the system

Security breaches in cloud ERP systems can have severe repercussions for organizations, including the unauthorized access to sensitive data and the compromise of user account information [18]. Concerns regarding data security, encryption, accountability, and system maintenance are prevalent when using cloud ERP.

2.4.2 Senior management support

Senior management plays a vital role in the successful implementation of a new cloud ERP system. It is essential for senior management to encourage the deployment of cloud ERP systems, communicate their purpose and benefits to the company, and ensure that employees understand and embrace the technology [19].

2.4.3 Add-ons and customisation

When considering cloud-based ERP providers, companies should prioritize providers that offer significant customization capabilities to meet their automation needs. A survey mentioned by Nazari and companions [20] revealed that less than 20% of respondents created their ERP system with minimal or no modifications. This is because initial customizations tend to grow and eventually pose technical challenges that can derail implementation efforts.

2.4.4 Ease of integration

Integration plays a crucial role in cloud ERP systems as it enables businesses to enhance their operations. A comprehensive CRM and ERP integration solution is necessary to avoid a disconnected workplace that hampers productivity [21]. Integration ensures that the logic of cross-functional processes is appropriately represented, allowing data entered into any functional module to be accessible to other modules that require it.

2.4.5 User education and training

The success of cloud ERP systems depends on the people using them. Providing on-the-job training that allows users to apply real-world scenarios to all ERP modules is crucial for organizations [22].

*2.4.**6 Effectiveness of employees' ICT skills***

The development of Internet services and ICT technology has enabled ERP cloud providers to offer innovative ICT solutions, leading to the adoption of new operating models by organizations [23].

2.5 Big Data

Big data encompasses various data types generated from diverse sources, and businesses recognize the importance of extracting valuable insights from this data [24]. Cloud computing has evolved due to the use of big data technologies, transforming it into a critical component for the future [25]. Enterprises can leverage big data technology for centralized services, intelligent technology applications, automated analysis, comprehensive computing, and prediction, all of which drive corporate innovation [25]. To effectively utilize big data technology, organizations need robust data structures and capable ERP systems that can collect, store, and analyze vast amounts of primary data [26]. Big data technology and enterprise resource planning (ERP) systems are intricately connected, as ERP systems play a crucial role in managing and analyzing data for meaningful insights [26].

2.5.1 Big Data and Predictive Analytics (BDPA)

BDPA (Big Data Predictive Analytics) is a decision-making field that utilizes statistical tools, machine learning, artificial intelligence, and data mining to extract valuable insights from large datasets [19]. It aims to improve a company's market performance and operating profit. McAfee and Brynjolfsson [27] underline that decision-making is crucial for businesses of all sizes, as it allows executives to base their plans on factual information. Waller and Fawcett [28] state that predictive analytics initiatives require appropriate management and technical capabilities to succeed. As more business processes and data exchange move to the cloud, BDPA becomes increasingly important. BDPA is considered an organizational skill that can enhance competitiveness in terms of market performance and operating profit [29].

2.5.2 The Capabilities of Big Data and Predictive Analytics (BDPA)

Developing BDPA (Big Data Predictive Analytics) capabilities requires both managerial and technical skills. Managers need to foster shared objectives, form competent teams, and possess market forecasting and interpersonal skills [30]. According to Gupta and companions [31], there is a positive influence of cloud-based ERP on BDPA Cloud-based ERP. Gupta and companions [31], establish a link between an enterprise's internal departments and external firms along the supply chain, offering a holistic view of all the data and information impacting an enterprise's success.

BDPA in the CERP system provides proactive decision-making, resulting in improved operational performance and a more informed market, boosting an enterprise's competitiveness against competitors and analyzing the probability of a future opportunity [29]. It enables the CERP system to accurately reflect not just what has transpired, but also what is happening and will occur in the near future [4,31]. Predictive analytics is a vital branch of data mining and analysis that focuses on improving operations and anticipating future probabilities in a changing market [32].

3 RESEARCH METHODOLOGY

A mixed-methods research approach, both qualitative and quantitative methods were used. For qualitative interviews were used to collect information and for quantitative an online questionnaire was used in a survey via Google Forms to collect information.

For the interviews individuals were selected deemed by the study as experts in the subject matter of the research, being data analysts, ERP consultants or software engineers, had significant and appropriate years of experience in ERP System implementation and role of 4IR Technologies in South Africa, with substantial amount of expertise in the South African information technology business. There were eight interviewees, four being Information technology professionals and the other four from companies such as SAP, Oracle, and similar who are responsible for the development of ERP systems. All the interviews targeted large companies.

For the surveys a total of 50 information technology professionals and data science experts who work in 5 different firms were polled. By following the Snowballing method, the companies range from SME’s to large companies. Starting with a LinkedIn contact reference falling under the following criteria: Data analysts, ERP consultants or software engineers; or significant and appropriate years of experience related to the subject matter of this research, which is ERP System implementation and role of Industry 4.0 Technologies in South Africa. This was done by finding one person who qualifies to participate and ask him or her to suggest some other people who have the technological knowledge required, and the list of participants will expand from there.

4 DATA ANALYSIS AND RESULTS

This chapter will provide the findings from the analysis of the data that was gathered and analyzed. Each result is presented in lines with 5 main themes which are : Knowledge and experience of ERP Systems, issues faced when utilizing Cloud Computing and Big Data Analytics for ERP Systems, benefits of a cloud-based and big data-enabled ERP system, incorporating Industry 4.0 Technologies such as Cloud Computing and Big Data Analytics in businesses and the critical success factors impacting the adoption of Cloud Computing and Big Data enabled ERP Systems.

The table below shows the profiles of eight industry experts chosen from various information technology companies.

Table 4.1 Profile of interviewees

Interviewee	Age	Gender	Job Description	Years of Experience	Company Size
A	32	Female	Certified Information System Security Professional at a Software Company (Company 1)	10	Medium-sized
B	49	Male	Support Technician, Information Technology (IT) at an Industrial Operations company (Company 2)	27	Small
C	58	Male	Network Engineer at a Technology company (Company 3)	32	Small
D	41	Male	Data Analyst at a Financial Institution (Company 4)	15	Large
E	33	Female	Information Technology Manager at Professional/Consulting services firm (Company 5)	10	Small

Therefore, the participants all have a vast experience of greater than 10 years in the field, making them suitable for the research interviews.

Table 4.2 below shows a knowledge rating of each interviewee and how well they are familiar with ERP Systems. The higher the frequency of people mentioned the more knowledgeable.

Table 4. 2 Commonly Used ERP Systems

ERP Systems	Mentioned by interviewee	Frequency
SAP	A, C, E, F, G	5
ORACLE	A, E, F	3
NETSUITE	A, D,	2
AWS	A	1
PeopleSoft	C, F	2
Xero	H	1
SAGE	H	1
Epicor	B	1

As indicated in the table above, the most frequently utilized ERP system among the interviewees is SAP, while the least utilized is AWS.

Many of the participants, as indicated in figure 4.1, are fully knowledgeable on various ERP Systems and their preferred uses. It must be noted that Interviewee B rated himself low (knowledge rating of 3) in comparison to the rest of the interviewees.

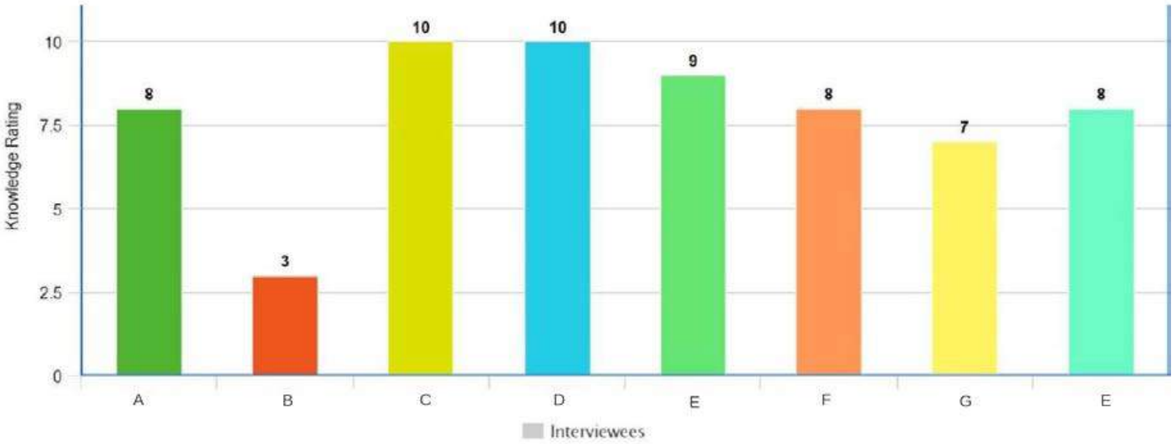


Figure 4.1 Interviewees' Responses to Knowledge of Various ERP Systems

In Figure 4.2 below, data collected from the online questionnaire reveals that slightly over 60% of the survey respondents are either sufficiently knowledgeable about ERP systems or are willing to acquire more information on the subject.

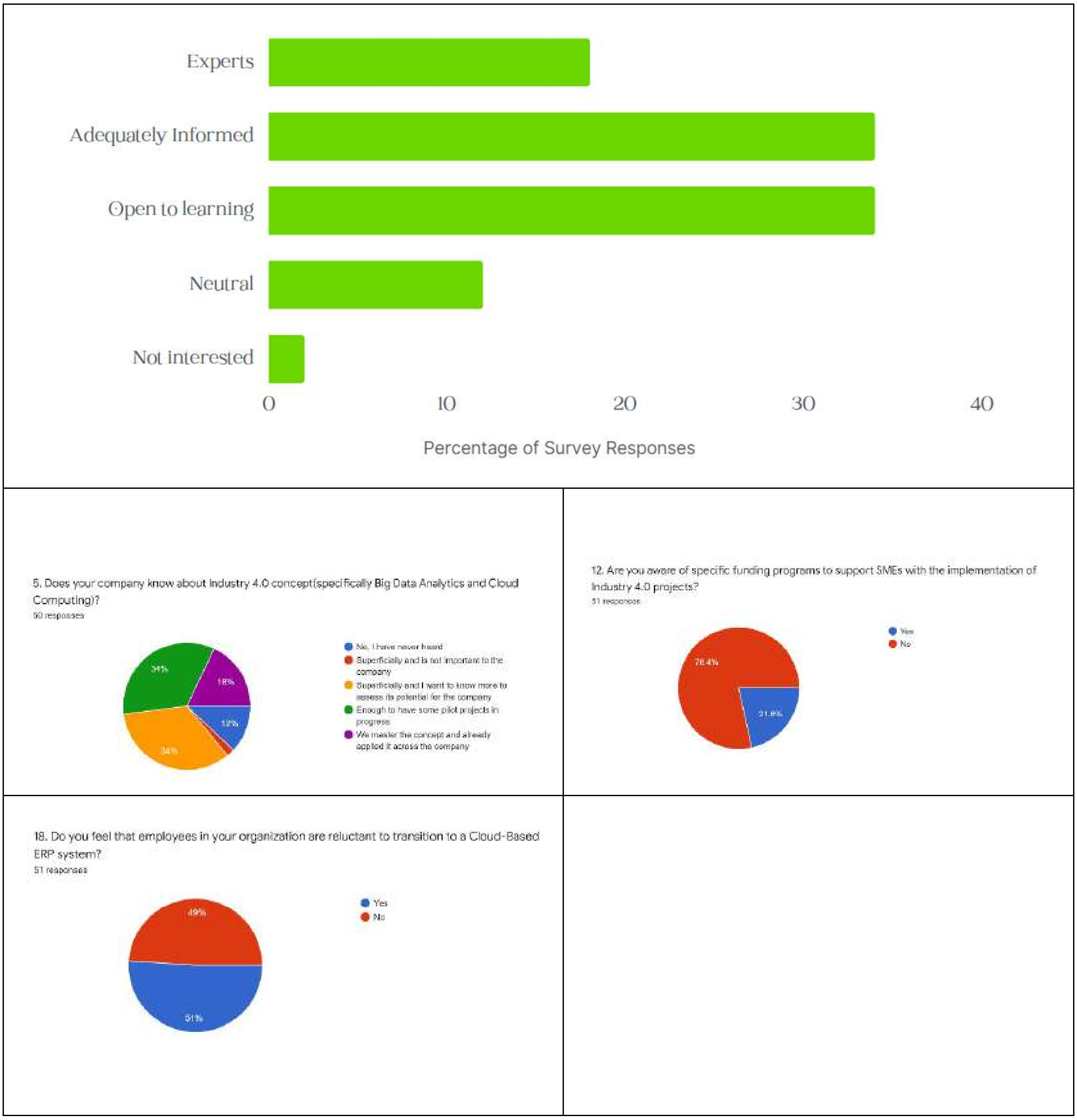


Figure 4.2 Participants' Overview of survey response

Figure 4.3 below illustrates that the primary challenge encountered when utilizing Cloud Computing and Big Data analysis for ERP systems is implementation. Additionally, it is evident from the information below that most organizations are still in the planning stage.

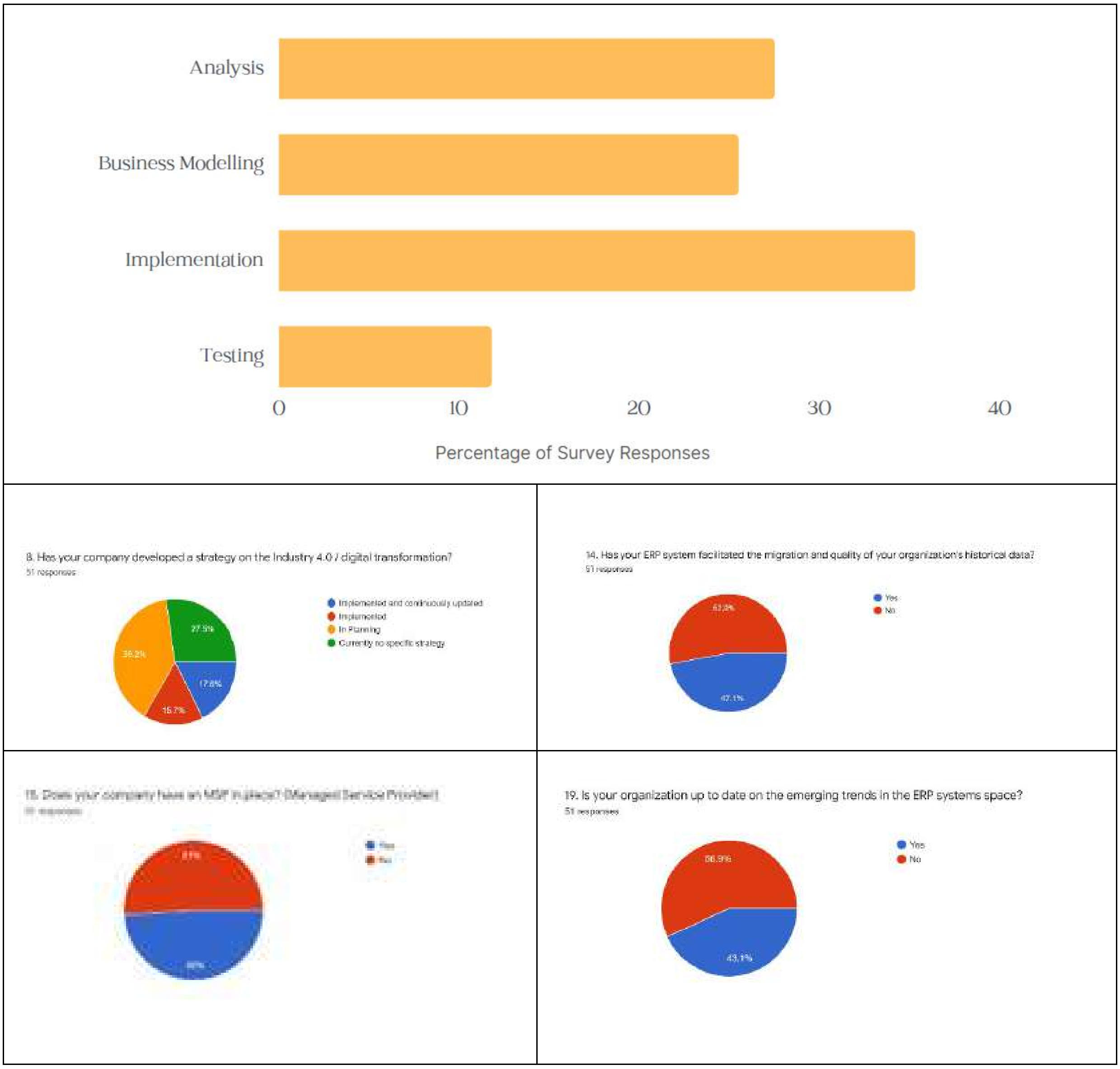


Figure 4.3 Current issues faced when utilizing Cloud Computing and Big Data Analytics for ERP Systems

According to Figure 4.4 below, the primary benefit organizations gained from implementing Cloud-Based and Big Data-Enabled ERP systems was ecosystem integration. The second most significant benefit was the use of customized adapters.

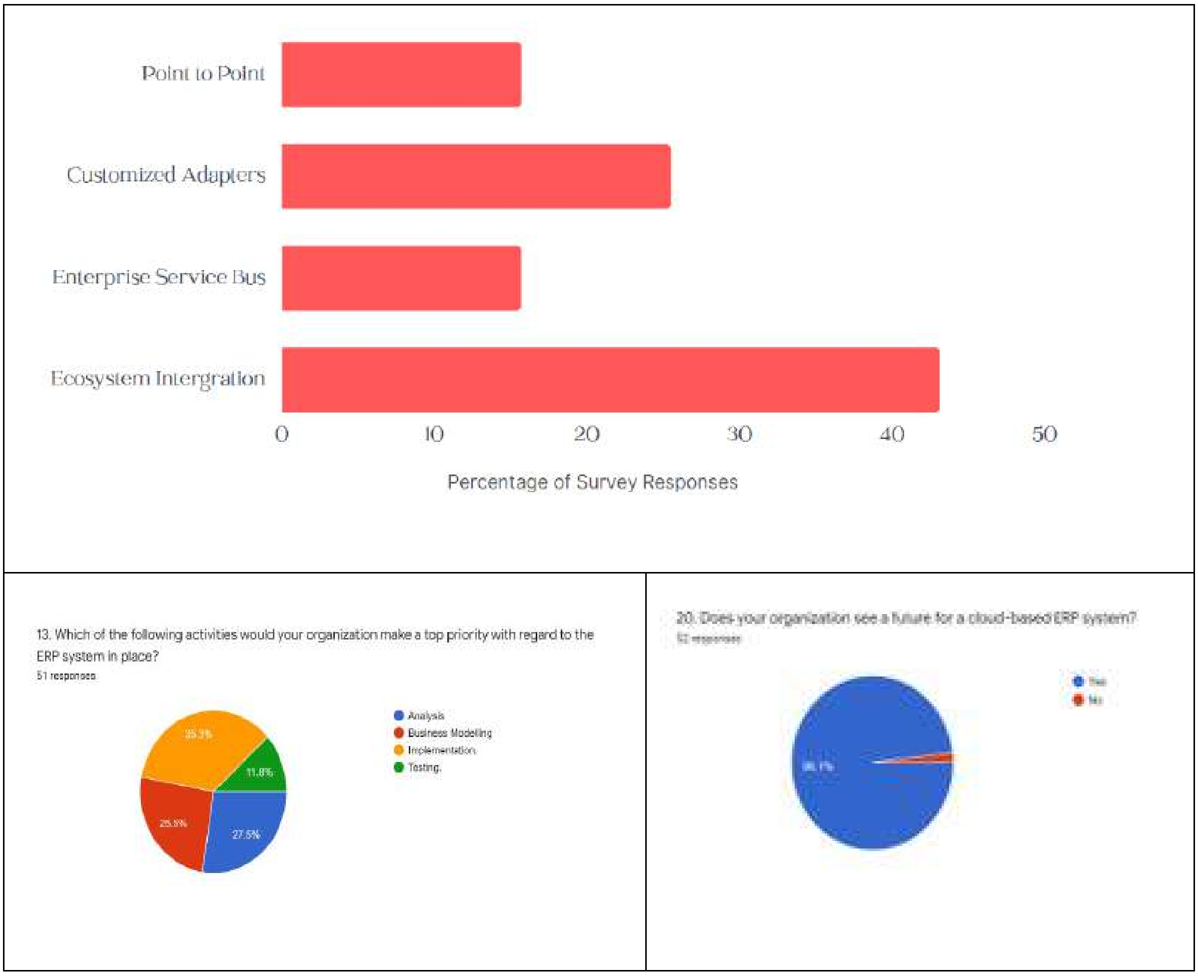


Figure 4.4 The Benefits of a Cloud Based and Big Data Enabled ERP System

Figure 4.5 below indicates that the primary use of these technologies by most companies was for implementation, rather than for analysis and business modelling. Additionally, it was found that 98% of organizations are open to adopting Cloud-Based ERP systems in the future.

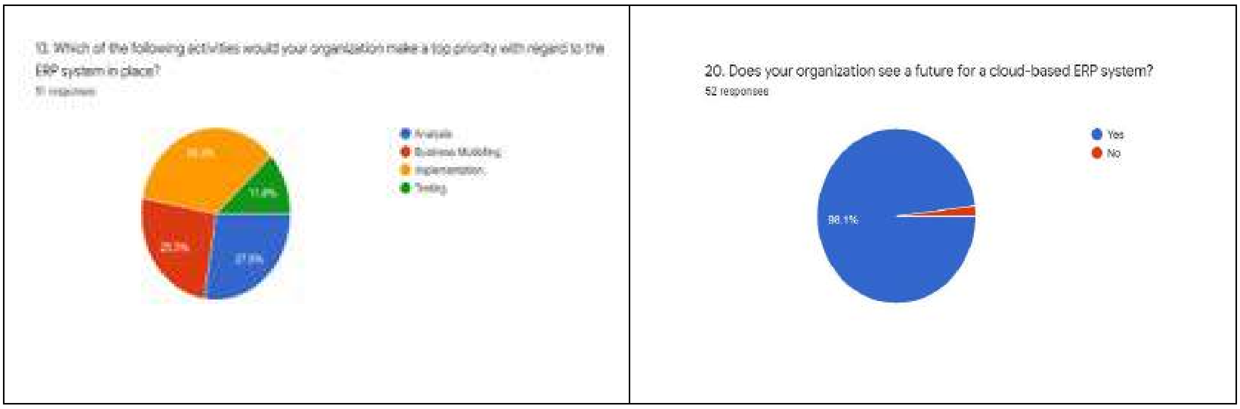


Figure 4.5 How Incorporating Industry 4.0 Technologies, such as Cloud Computing and Big Data Analytics can assist businesses in acquiring a better understanding of their business processes

Figure 4.6 below shows us that majority of organisations have opted to manage company data centrally versus through an on-premise ERP system.

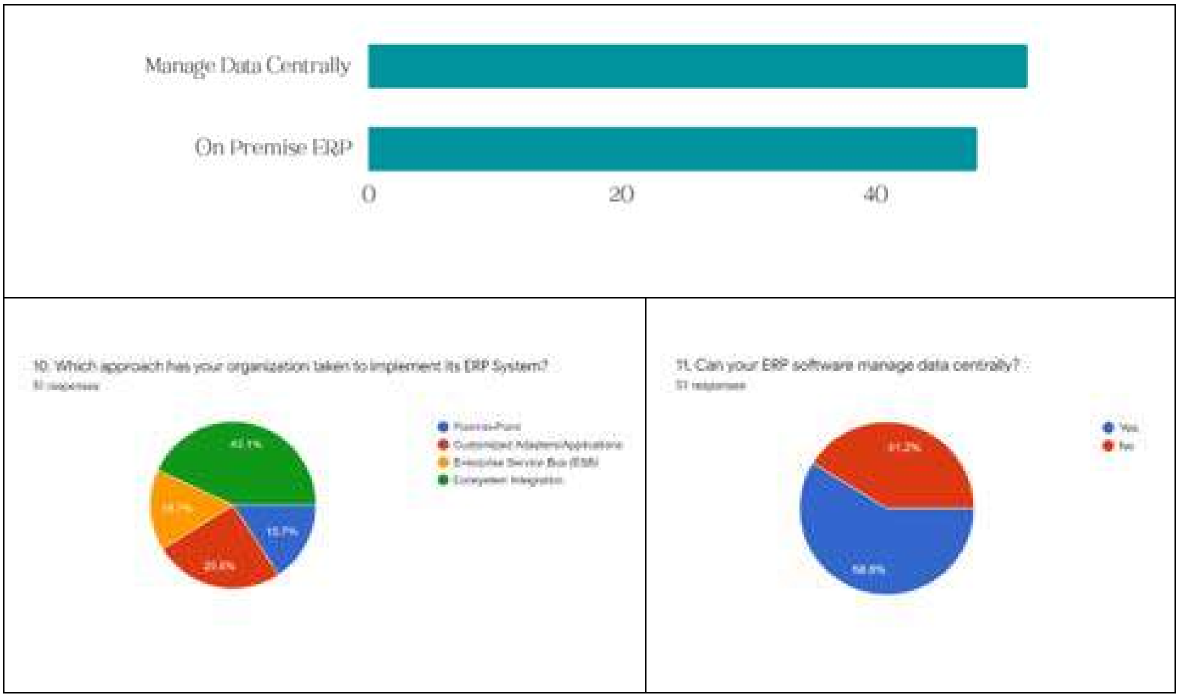


Figure 4.6 The Critical Success factors impacting the adoption of Cloud Computing and Big Data enabled ERP Systems

5 DISCUSSION

The discussions consider each theme beginning with a synthesis of interviewees perspectives and augmenting with the surveys done, providing insight on the respective theme.

5.1 Knowledge and experience of ERP Systems

Following the study of the literature and comments from the interviews, a recurring pattern emerged: the success rate of an ERP system is dependent on the business's understanding of the software and technology.

According to figure 4.2, 34% of respondents' organizations showed a basic level of understanding of Industry 4.0 technology. Lack of understanding in this area is a common reason for ERP implementation failure. 78.4% of respondents are unaware of financial programs designed to assist small and medium-sized enterprises (SMEs) with the deployment of ERP systems (fig 4.2). This indicates a lack of research and knowledge about ERP technologies among organizations.

59% of respondents expressed hesitancy in transitioning to a cloud-based ERP system (fig 4.2). This suggests a reluctance to adopt cloud technology in ERP systems, possibly due to concerns or reservations.

5.2 The Current issues faced when utilizing Cloud Computing and Big Data Analytics for ERP Systems

The development of business processes is dependent on both the administrator and the company in question's agreement on the consequences of licensing and authentication. Guaranteeing process improvement based on technological projections cannot be accomplished in a unilateral manner. Through time, users have a tendency to skip over the phases of a procedure that were originally planned.

According to figure 4.3, 51% of respondents' companies do not have a Managed Service Provider in place, which can become a long-term problem as relying on helpdesk or technical assistance for every issue can cause disruptions. Having a managed service provider tailored to the company's needs ensures prompt network and system management, allowing employees to focus on company development. 56.9% of respondents are not keeping up with the latest ERP system trends (fig 4.3), which poses a problem as organizations leverage emerging trends to enhance digital capabilities, drive growth, and improve profitability.

5.3 How Incorporating Industry 4.0 Technologies, such as Cloud Computing and Big Data Analytics can assist businesses in acquiring a better understanding of their business processes

In the aftermath of the SARS-CoV-2 (Covid-19) coronavirus pandemic, the degree of digitalization of business operations rose significantly. Manufacturing, commercial, technological, and other companies in South Africa have invested in the implementation of new information technologies and Industry 4.0, to improve specific spheres of their business activity as part of this increase in digitization and internationalization.

According to figure 4.5, 98.1% of organizations gained from implementing Cloud-Based and Big Data-Enabled ERP systems using ecosystem integration. The second most significant benefit was the use of customized adapters. The respondents' businesses see a future for a cloud-based ERP system. This demonstrates that South Africa's digital economy is still developing, and that cloud computing and data analytics are the way of the future for all types of businesses.

Modern-day businesses demand a roadmap that places a high priority on data analytics and cloud usage [33]. In turn, this has made and will continue to make corporate operations smarter thanks to the data obtained through big data and cloud-based ERP systems, allowing for hassle-free innovation for management [33].

5.4 The Benefits of a Cloud Based and Big Data Enabled ERP System

According to figure 4.5, Five out of the eight interviewees believed that these technologies outweighed the initial costs and bring long-term value to organizations of all sizes. However, the remaining three interviewees argued that the financial investment risk of implementing on-premise ERP systems, including Cloud computing and big data, did not guarantee a more successful ERP implementation. Factors such as longevity, business strategy, company size, and reporting requirements needed to be considered.

One interviewee emphasized that simply adopting an ERP system does not save money immediately but rather demonstrates how to transform the company, increase efficiency, and position it for future profitability. Implementing an ERP system incurs significant costs, but shifting to the cloud can save money on hardware and infrastructure maintenance. However, companies must consider data security and have confidence in cloud storage. The long-term benefits of ERP implementation include time savings and success in today's competitive market. The expertise of professionals can handle the technical aspects on behalf of the company.

5.5 The Critical Success factors impacting the adoption of Cloud Computing and Big Data enabled ERP Systems

According to figure 4.6, the customisation of the program, has been identified by the interviewees as a crucial impediment to a smooth adoption ERP systems have a reputation for being very restrictive since they only allow for a limited amount of customisation. Due to a reluctance to make changes inside the company, organizations that do not insist on customizing the application to fit their business processes often claim failures in their application implementations. As a result, businesses implementing ERP systems must take these considerations into account to guarantee a successful installation of the program.

The customized adapters/application approach is preferred by 25.5% of respondents (fig 4.6), allowing them to have an ERP system designed around their existing infrastructure and capabilities.

Both approaches have potential drawbacks, such as constraints, limitations, or incompatibilities with current databases, workflow systems, and communication tools. Adjustments or modifications may be necessary.

6 CONCLUSION

The goal of this study was to investigate the numerous elements that contribute to the adoption of big data and cloud computing inside an ERP environment. According to the study's findings, South African ERP users are actively considering integrating a number of cutting-edge technologies into their current ERP systems. However, because of a number of variables, such as economic considerations, security considerations, and a lack of expertise, the rate of actual adoption of these technologies is significantly slower. Many companies' employees were unwilling to transition to a Cloud-based and Big Data enabled environment, resulting in ERP system rollout difficulties. These technologies open up vast possibilities for forward-thinking manufacturers, system providers, and whole geographic areas. Cloud computing and big data, like past revolutionary developments, offer a significant danger to untrained users as well as the business as a whole. This study indicates the need for more industry-and academic-led research to generate the knowledge base required to assist organisations in making well-informed choices on the integration of these technologies into their ERP systems.

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AN EXAMINATION OF BARRIERS AND SUPPORT SYSTEMS FOR SMALL AND MEDIUM ENTERPRISES IN SOUTH AFRICA'S COAL MINING SECTOR

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ABSTRACT

South Africa's extensive coal deposits have long provided crucial energy inputs while enabling socioeconomic development. However, a complex interplay of financial, technical and regulatory dynamics has traditionally concentrated extraction and trade around large industry players challenging smaller and emerging coal mining companies. A quantitative method study analyses multi-dimensional constraints reported by 85 South African coal mining small and medium enterprises (SMEs) through a recent industry survey. Reliability analysis of perceptual scales provides unique empirical insights around external support, operational risks, common disputes, and procedural gaps inhibiting SME progress. Findings spotlight equipment shortages, planning issues, financing access barriers and upgrading lags as key determinants of SME success. Merging survey data with production records, licensing metrics and existing scholarship reinforces a targeted reform agenda enhancing inclusion for this critical constituency amidst South Africa's ongoing energy transition.

Keywords: Renewable Energy, Reliability Analysis, Energy Access, Coal Mining, Small and Medium Enterprise.

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1 INTRODUCTION

South Africa's sizeable coal deposits have long provided crucial energy inputs enabling industrialization and rural electrification efforts [1]. However, a complex constellation of financial, infrastructural, and regulatory dynamics has concentrated extraction and trade historically around a few large, established industry players. This poses barriers for smaller, emerging miners attempting to build self-sufficiency in this vital value chain [2].

Amid ambitions to catalyse socioeconomic inclusion, policymakers have recently prioritized nurturing fledgling mining houses through preferential licensing, stockpile set-asides and developmental financing. Yet bureaucratic complexity, narrow eligibility criteria and implementation gaps still constrain the translation of these well-intentioned mechanisms into robust SME growth multipliers to date [3].

This study aims to address the research gap concerning the specific challenges faced by SMEs in South Africa's coal mining sector. The primary objectives of this research are:

1. To identify and analyse the key barriers facing SMEs in the coal mining industry.
2. To evaluate the effectiveness of current support systems for these enterprises.
3. To propose recommendations for improving the operational environment for SMEs in the sector.

By addressing these objectives, this study aims to contribute to a more comprehensive understanding of the SME landscape in South Africa's coal mining industry, potentially informing more effective policy and support mechanisms.

2 LITERATURE REVIEW

2.1 Support Framework Perspectives

Industry support desks like the Junior and Emerging Miners Desk further reinforce financial, technical, infrastructure and administrative limitations dominating the SME mining experience in concluding assessments across multiple South African jurisdictions [4]. Through member dialogues, these coordination platforms consistently spotlight planning shortfalls, funding gaps, upgrading lags and contract management capabilities as recurring pressure points undermining fledgling miner maturation prospects.

While incremental state supports through preferential licensing, stockpile off take and developmental financing do appear periodically, bureaucratic complexity, eligibility exclusions and knowledge gaps still inhibit the translation of these well-intentioned levers into consistent SME growth catalysts [5]. So, in their totality, support ecosystem perspectives reiterate a wide minefield of multifaceted internal and external hazards undercutting the viability foundations essential for South Africa's precarious SME mining sector to ever stabilize and thrive.

Individual mining houses have also been prompted by the Mining Charter to develop emerging companies. This initiative requires mining houses to have a certain percentage of Black, Youth, and small enterprises working with the mine. However, the effectiveness of these programs in fostering sustainable SME growth remains a subject of debate and further research [6].

2.2 Operational Models

While contractor engagement can provide vital operational flexibility for smaller miners lacking their own technical expertise or equipment access, dependency risks around inflated charges, litigation liability and directional misalignment remain. As Rupprecht [7] notes, small firm contract mining forays have run repeatedly aground from poor partner selection, undefined deliverable specifications and risk miscalculations around everything from production metrics to environmental compliance.

Yet self-directed owner-operator models for SME coal miners bring their own complexities too in South Africa's stratified mining ecosystem, with financing, skills and infrastructure still largely controlled by dominant players [8]. Navigating this terrain thus becomes somewhat akin to choosing between dependence or exclusion risks, where neither operational path appears clearly optimal for aspirational junior miners.

Understanding the consequences of failing to deliver contracted coal is crucial for strategic planning and risk mitigation. The focus on warnings and delivery shortfalls aligns with the literature emphasizing the importance of understanding and managing the consequences of contractual breaches [9]. This section prompts further inquiry into the long-term implications of habitual delivery failures on SME viability, potentially through longitudinal case studies.

The failure to meet contractual obligations is a complex issue rooted in machinery breakdowns and inadequate planning. The identified emphasis on equipment maintenance and improved planning aligns with the broader literature on supply chain management and operational efficiency within the mining sector [10]. Theoretical frameworks such as the Resource-Based View (RBV) and Dynamic Capabilities Theory may provide a theoretical lens to explore how SMEs can develop and deploy resources to enhance their operational resilience [11].

2.3 Funding, Policy & Legislative Environment

Accessing start-up development capital and project financing poses another fundamental barrier, as most traditional investment channels gravitate toward larger, more established mining houses with operational runways to demonstrate concept viability [12]. And while state vehicles like the Department of Mineral Resources, Eskom and the Industrial Development Corporation have instituted specialized loan funds targeting qualifying SME miners, uptake remains muted with many smaller operators still foundering on bureaucratic prerequisites, limited expertise and infrastructure means to catalyse financing into operational [12].

Amid these financing struggles, compliance with elaborating legislative requirements around environmental and social protections driven by the Minerals and Petroleum Resources Development Act, the National Environmental Management Act and the National Water Act further strains already overloaded SME management, technical and accounting capacities. Here again, while regulatory evolutions capture necessary externality corrections through stricter rehabilitation planning, water licensing and impact reporting, thinly stretched juniors face disproportional new cost and complexity burdens relative to sector incumbents [11].

Contractual disputes represent a significant risk for SMEs, with disputes over legal issues, payment terms, tonnage produced, and contractual duties. The need for policy interventions to mediate these disputes aligns with studies highlighting the importance of legal frameworks in fostering a conducive business environment [13]. This section encourages further exploration into the impact of contractual disputes on the financial stability and sustainability of SMEs, with potential application of Transaction Cost Economics and Agency Theory.

2.4 Lifecycle Execution Barriers

These geological barriers only constitute the inception of a chronically obstructed progression for SME miners attempting becoming owner-operators. In fact, the high-risk exploration phase represents a common initial downfall point, as capital intensive sampling, assessments and permitting pursue mounting debts prior to realizing production revenues [14]. For entities successfully transitioning to extraction, new obstacles arise around technical expertise shortages for purchasing, operating and maintaining complex specialized equipment [10]. Beneficiation activities similarly assume advanced processing capacities and quality control diligence beyond most SME capabilities at slim profitability margins.

2.5 Geology & Extraction Legacies

Having cantered coal operations for over a century around Mpumalanga’s extensive deposits, decades of intensive mining by leading houses concentrating on higher grades depleted reserves - leaving thinner, lower quality seams as accessible feedstock for newer junior entrants attempting viability on tighter margins [13]. Complicating seam profitability assessments further, past miners left incomplete survey records detailing extraction specifics and remaining deposit quality [14]. So thinner, lower grade coal batches intersecting legacy infrastructure impacts pose natural viability threats before even tallying extensive licensing, skills and financing prerequisites to gain operational entry [15].

2.6 Environmental Sustainability Considerations

Nowhere do legislative environments collide more acutely with SME capabilities though than around intensified acid mine drainage threats, with small operators frequently failing safety, monitoring and closure compliance across mounting liabilities from uncontrolled heavy metal leeching [15]. Already struggling for positive cash flows, responding to spiralling acid drainage risks through comprehensive water treatment or pumping interventions exceeds the financial and technical wherewithal of most independent start-ups.

Yet regional acidification and heavy metal accumulation in critical Eastern, Central and Western catchment basins court widespread biodiversity, health and food security crises from increasing contamination concentration build up already outpacing state-owned remediation capacities even before additionally accounting for SME-attributable drainage [16]. So while necessary from an accountability lens, holding junior miners to account around worsening acid liabilities through this period of sector transition inflates closure prospects across segments where minimal profits already restrict operational longevity odds historically [17].

2.7 Theoretical Framework

To systematically identify and analyse barriers faced by SMEs in the coal mining sector, this study draws upon several theoretical frameworks:

1. Resource-Based View (RBV): This theory posits that a firm's competitive advantage stems from its unique bundle of resources and capabilities [18]. In the context of SMEs in coal mining, the RBV helps explain how limited access to critical resources (e.g., financing, equipment, expertise) can hinder their growth and competitiveness.

2. Transaction Cost Economics (TCE): TCE focuses on the costs associated with participating in a market [19]. For SMEs in coal mining, this framework helps analyze the costs of contract negotiation, monitoring, and enforcement, which can be disproportionately high for smaller firms.

3. Institutional Theory: This theory examines how institutional environments shape organizational behavior [20]. It provides a lens to understand how regulatory frameworks, industry norms, and support systems influence SME operations and strategies in the coal mining sector.

4. Dynamic Capabilities Theory: Building on the RBV, this theory emphasizes the importance of a firm's ability to adapt to changing environments [21]. For SMEs in a rapidly evolving sector like coal mining, this framework helps analyze their capacity to innovate and respond to market and regulatory changes.

These theoretical frameworks guide our analysis of the complex interplay of factors affecting SMEs in South Africa's coal mining sector, providing a structured approach to identifying barriers and evaluating support systems.

3 METHODOLOGY

A comprehensive cross-sectional survey was conducted to analyse the current status of small and medium enterprises (SMEs) with in the coal mining industry of South Africa. The study incorporated 85 SMEs operating in the coal mining industry, utilizing a well-structured questionnaire to gather data on perceived support, contractual challenges, risks, and certification requirements. The participants were SME coal mining companies selected through convenience sampling. The survey was distributed electronically to ensure accessibility and efficiency in data collection [18]. Data were collected using a questionnaire that included Likert-scale items for quantitative analysis insights. The objective of the survey was to capture a comprehensive view of SMEs' experiences in the coal mining sector, specifically focusing on: (1) Perceived levels of support from various entities. (2) Operational challenges, including reasons for failing to meet contractual obligations. (3) Financial risks and barriers. (4) Regulatory requirements and compliance issues.

Data were collected using a questionnaire that included 5-point Likert-scale items for quantitative analysis insights. The scales ranged from 1 (Strongly Disagree/Never) to 5 (Strongly Agree/Always), depending on the context of the question.

The questionnaire was validated by subject matter experts, comprised multiple scales targeting specific constructs. Scale reliability analysis, specifically Cronbach's alpha, was used to assess the internal consistency of each scale. Descriptive statistics, including means and standard deviations, provided an overview of responses. Inferential statistics, such as item-total correlations and Hotelling's T-Squared tests, were utilized to validate scales and explore fundamental dimensions. These methods were chosen to (1) Assess the reliability and validity of the measurement scales. (2) Identify potential underlying factors influencing SME experiences. (3) Explore relationships between different aspects of SME operations and challenges.

The study adhered to ethical standards and gave participants consent forms, ensuring confidentiality and the right to withdraw from the study at any point.

4 RESULTS AND DISCUSSION

This dataset presents survey results assessing the state of small and medium enterprises (SMEs) participating in South Africa's coal mining industry. 85 SME coal miners provided responses on questions covering perceived support from various entities, reasons behind failing contractual delivery quotas, typical contractual problems, key contract risks, general supply impediments, and necessary regulatory certifications for operating.

4.1 Support for Coal Miners

An 8-item scale assessed perceptions of support from various entities for small and medium coal mining enterprises. The items asked about support from the Department of Mineral Resources, Transnet, Export Merchants/Quattro, Eskom, Sasol, banks, big coal mining companies, and others as presented in Table 1.

Table 1: Perceived support for SME coal miners

Entity	Mean Support (1-5 scale)	Standard Deviation
Department of Mineral Resources	4.05	0.92
Eskom	3.93	0.88
Sasol	3.45	1.02
Banks	3.21	1.15
Big coal mining companies	3.18	1.08
Export Merchants/Quattro	2.95	1.20
Others	2.82	1.25
Transnet	2.68	1.18

The scale had good reliability with a Cronbach's alpha of 0.79. The mean levels of support reported indicate the Department of Mineral Resources (mean = 4.05 on a 5-point scale) and Eskom (mean = 3.93) provide the most support currently. Transnet (mean = 2.68) was rated lowest on average. An overall scale mean of 3.34 suggests modest levels of support from entities collectively.

The item-total correlations ranged from 0.45 to 0.57, indicating all items relate reasonably well to the overall scale. Removing items would not substantially improve alpha. The Hotelling's T-Squared test output, with $p < 0.001$, indicates significant inter-item correlations as would be expected for a reliable scale.

4.2 Reasons for Failure to Deliver Coal

A 6-item scale assessed reasons why companies fail to deliver coal on time based on causes. The reasons measured were lack of planning, breakdowns, acts of God/weather, lack of machinery, strikes/demonstrations, and employee absenteeism as illustrated in Table 2.

Table 2: Reasons for failure to deliver coal

Reason	Mean Support (1-5 scale)	Standard Deviation
Breakdowns	3.80	1.05
Lack of planning	3.72	1.12
Lack of machinery	3.66	1.08
Acts of God/weather	2.95	1.30
Strikes/demonstrations	2.88	1.35
Employee absenteeism	2.75	1.22

The scale had mediocre reliability with a Cronbach's alpha of 0.64. This indicates the reasons may represent related but distinct constructs impacting delivery. Breakdowns, lack of planning and lack of machinery received the highest mean ratings of 3.66 to 3.80 on the 5-point scale. External causes like weather and strikes were less frequently endorsed.

Looking at the item-total statistics, employee absenteeism and strikes/demonstrations related more closely to the overall scale (corrected correlations over 0.49) compared to other items. This may indicate more preventable, internal issues cause late delivery compared to external issues companies cannot control. Removing items would not increase alpha substantially. The significant Hotelling's T-Squared test confirms inter-item correlations.

4.3 Contractual Problems

A 4-item scale addressed types of contractual disagreements or problems faced as shown in Table 3.

Table 3: Contractual problems

Problem Type	Mean Support (1-5 scale)	Standard Deviation
Disputes over tonnage	3.79	1.10
Payment disputes	3.71	1.15
Legal issues	3.65	1.18
Contract duties	2.56	1.20

The scale showed good reliability with Cronbach's alpha of 0.78. The items focused on disputes over legal issues, payment, tonnage produced, and contract duties. The means ranged narrowly from 3.56 to 3.79, suggesting companies experience these problems with similar frequency on average.

Correlations between the items and overall scale were moderately strong, from 0.50 to 0.66. None of the items had low enough correlations to warrant exclusion. The Hotelling's T-Squared test was significant, supporting scale reliability.

4.4 Contract Risks

A 5-item scale measured perceived risks when engaging in coal supply contracts. Risks measured related to lack of skills/knowledge, equipment/specialization, transferring risk itself, lack of experience, and contract duration as presented in Table 4.

Table 4: Contract risk

Risk Type	Mean Support (1-5 scale)	Standard Deviation
Lack of equipment / specialization	3.82	1.05
Lack of experience	3.70	1.12
Transferring risk	3.65	1.15
Contract duration	3.58	1.20
Lack of skills/knowledge	3.51	1.18

The Cronbach's alpha of 0.72 indicates respectable scale reliability. Means spanned from 3.51 for lack of skills/knowledge to 3.82 for lack of equipment and specialization, indicating equipment issues as the most salient perceived risk.

Most inter-item correlations ranged reasonably between 0.36 and 0.59. Only contract duration related more weakly to other items. The Hotelling's T-Squared test was non-significant though, indicating marginal distinction between risks.

4.5 Penalties of Delivery Shortfalls

A 5-item scale addressed consequences companies can face for failing to deliver contracted coal. Specific consequences captured were contract termination, court cases, monetary charges, warnings, and shortfalls after the delivery date.

The scale demonstrated acceptable reliability (alpha = 0.74). Warnings (mean = 2.86) and delivery shortfalls (mean = 3.43) were the most frequently endorsed consequences out of those measured. More extreme consequences like contract termination and lawsuits occurred less often (means under 2). Item-total correlations ranged from 0.41 to 0.60, showing the interrelatedness of different consequences companies can face. With $p < 0.001$ for Hotelling's T-Squared test, the scale shows good inter-item correlations indicative of reliability.

4.6 Certification Requirements

The survey included a 5-item scale assessing requirements for various coal mining certificates and procedures. Requirements measured related obtaining water use licenses, safety and health certificates, environmental management plans, quality procedures, and ISO certifications.

The scale exhibited good overall reliability with a Cronbach's alpha of 0.76. Average possession of quality procedures (mean = 2.44) and ISO certifications (mean = 2.58) scored higher than other certificates. Water use licenses (mean = 1.76) and environmental management plans (mean = 1.89) were least common.

Item-total correlations ranged from 0.34 to 0.67, with all items relating reasonably to the overall scale. The largest gains in alpha from dropping items were minimal. The Hotelling's T-Squared test confirms significant inter-item correlations indicative of scale reliability.

4.7 Interpretation

- Perceived support for SME coal miners comes mostly from governmental entities like the Department of Mineral Resources and critical public infrastructures like Eskom. More private sector entities demonstrate lower total support. Boosting support from groups like banks, big mining corporations and industry organizations could aid SME coal miners.
- Machinery breakdowns and lack of planning are viewed as the most common reasons SME mining operators fail hitting coal delivery contracts. Better equipment maintenance and management protocols could help minimize such breakdowns. Improved planning via production forecasting, inventory assessment, logistical coordination etc. may reduce delivery issues.
- While none of the surveyed contractual problems or risks scored “often” or “always” problematic, their occasional frequency remains concerning. Disputes over tonnage, payment terms and legal issues occurring sometimes can jeopardize these small miners' thin margins. Similarly, lacking technical experience, specialized equipment and mitigating contract duration risk could imperil these SMEs. Policy and industry interventions helping mediate contract disputes, supply technical know-how, lease critical equipment and structure more favorable contract durations may assist SME miners in upholding their ends of coal agreements.

- Warnings and forced short-term delivery despite missing deadlines represent fairly common consequences SME miners face after failing to meet coal contracts. Work stoppages, financial penalties and legal actions occur less regularly. Nonetheless, habitual delivery failures frequently eliciting warnings and production headaches could slowly degrade SME miners' viability and professional reputation among coal purchasers. Developing solutions to ease typical impediments behind late coal deliveries is imperative.
- Quality control protocols and ISO certification are the most frequently cited mining/operations requirements for SME coal miners. Somewhat lower means for environmental management plans, safety documentation and water licenses suggest these are still common prerequisites for legally and effectively mining coal. Monitoring that emerging SMEs possess or obtain such standard certifications remains important for facilitating their entry into the formal coal supply chain.
- The reliability analysis provides a good starting point to assess and validate various measurement scales. But further probing the factor structure of questionnaire items using techniques like exploratory factor analysis would enhance scale validity and score interpretation.
- Merge the survey sample data with relevant external data - such as coal production figures, mining equipment costs, legal dispute records etc. Combining perceptual survey data with corresponding objective metrics allows comparing sentiment versus reality. Significant gaps may reveal areas where perceptions skew negatively from actual conditions.

5 CONCLUSION

In conclusion, this study offers a comprehensive examination of the barriers and support systems influencing small and medium enterprises in South Africa's coal mining sector. The identified challenges encompass financial, operational, and regulatory dimensions, presenting a complex landscape for SMEs to navigate. The findings underscore the urgency of tailored interventions that address the specific needs and constraints faced by SMEs, fostering a more inclusive and resilient coal mining industry.

As South Africa undergoes an energy transition, redefining the dynamics of the coal mining sector becomes imperative for balancing energy demands, economic development, and environmental sustainability. The insights derived from this study provide a foundation for policymakers, industry players, and other stakeholders to collaboratively design and implement initiatives that support the growth and sustainability of SMEs in the coal mining sector. Ultimately, a thriving SME ecosystem in this vital industry can contribute not only to economic development but also to a more equitable and sustainable energy future for South Africa.

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DYNAMIC CONTROL OF DEEP-LEVEL MINE COOLING SYSTEMS USING ARTIFICIAL INTELLIGENCE

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ABSTRACT

Deep-level mines in South Africa face rising electricity costs, with cooling systems contributing up to 28% of a mine's total energy. Existing energy-saving approaches lack adaptability. The mining industry has rarely embraced artificial intelligence (AI)-based energy efficiency strategies. This study proposes a dynamic AI-based strategy to improve energy efficiency in deep-level gold mine cooling systems. Long-short-term memory recurrent neural network (LSTM-RNN) models are integrated into dynamic control strategies for cooling components. The strategy acquires real-time data from the mine's SCADA, forecasts temperatures, and adjusts cooling component operations, potentially saving ZAR 1.5 million annually. Advantages brought to light include reduced human error and no infrastructure changes. The results serve to motivate the struggling industry to incorporate more Industry 4.0 technologies. This study contributes to mining by providing energy savings and operational improvements, as well as to AI by indicating the effective use of AI techniques in complex industrial environments.

Keywords: mining, energy saving, dynamic control, machine learning, artificial intelligence

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1 INTRODUCTION

The mining industry in South Africa plays a major role in the country's economy [1]. Moreover, 11% of the world's gold reserves are located in South Africa, as of 2016 [2]. South African gold production has steadily declined since 1990 despite the reserves and the role that mining plays in South Africa. A graphical representation of the decline over time is displayed in Figure 1.

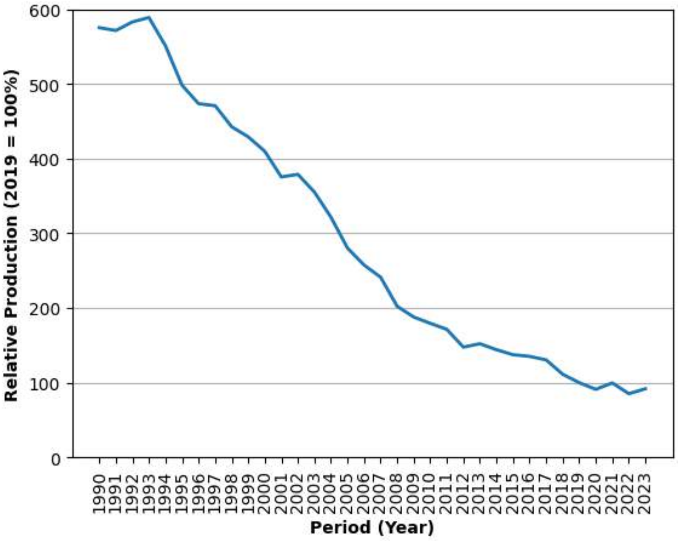


Figure 1: Gold mining historical production in South Africa [3]

The mines in South Africa are being deepened to increase their life of mine and access more gold reserves [4]. This increased depth has significantly contributed to the strain on Eskom's electricity grid [5]. Moreover, the average electricity cost in the mining industry has increased considerably each year as seen in Figure 2 [6].

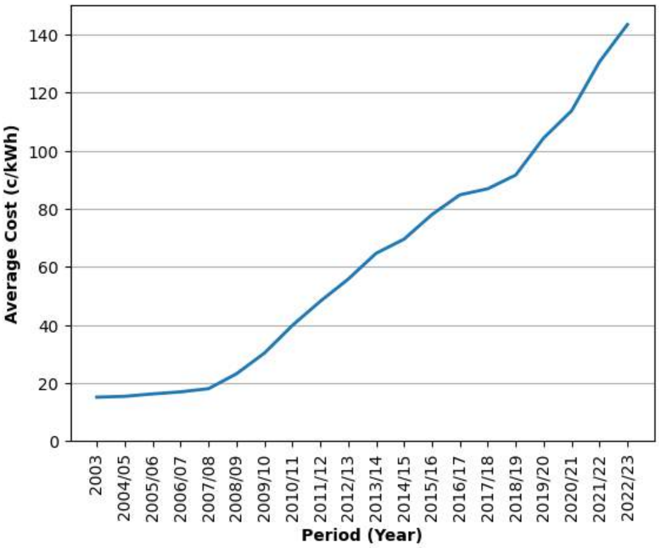


Figure 2: Electricity cost for mining in South Africa [6]

Additionally, the mining industry reduces its electricity usage during designated times to assist in maintaining a stable electricity grid thus leading to losses in production opportunities [7]. The decline in South African gold production may therefore be partially attributed to the challenges faced by deeper mines, increasing electricity costs as well as electricity supply constraints, Consequently, the implementation of energy savings initiatives can help to improve the profitability of the South African mining industry.

The main electrical energy consumers in deep-level gold mines can be observed in Figure 3 [2], [8]. Ventilation and refrigeration account for approximately 28% of the electrical energy consumption in deep-level mines [2].

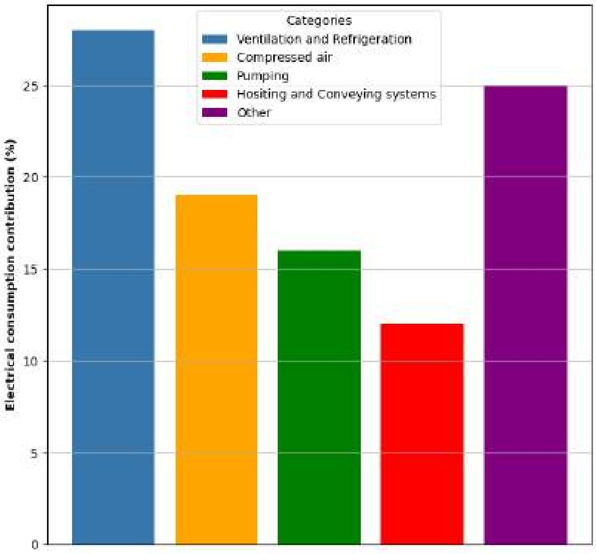


Figure 3: Typical gold mine electrical energy consumption distribution [2], [8]

Ventilation and refrigeration are typically categorised as cooling systems. Cooling systems essentially aim to reduce air temperatures in underground working areas. The air is cooled by transferring it into cold water, thus, decreasing the air temperatures in these areas [2].

South African gold mines typically reach depths of approximately 4 km and experience virgin rock temperatures (VRTs) of up to 60°C [9]. Moreover, the Mine Health Safety Act (MHSA) of South Africa prohibits working at wet bulb temperatures exceeding 32.5°C and dry bulb temperatures exceeding 37°C [10]. Therefore, cooling systems are used to mitigate the VRTs and meet the temperature regulations as set out by the MHSA of South Africa.

Typical cooling systems in deep-level mines comprise of refrigeration plants, bulk air coolers (BACs), pumps, and dams. These components are controlled to meet specific service delivery requirements, such as temperatures and dam levels [9].

In addition to meeting service delivery requirements, carrying out energy-saving strategies is crucial to address the increasing electricity costs in the mining industry. Approaches such as load shifting, peak clipping, and energy efficiency strategies are widely recognised as effective solutions for energy savings [2], [9], [11]. Table 1 indicates the use of energy savings strategies for deep-level mine cooling systems.

Table 1: Energy savings strategies for deep-level mine cooling systems [2], [9], [11]

Strategy	**Description**
Load shifting	Redistributing the system's energy requirements to different periods of the day while maintaining the same energy requirements and meeting cooling requirements. The shift is based on Eskom's Time-of-use (TOU) tariff structure
Peak clipping	It aims to decrease energy consumption during specific periods of the day. For cooling systems, this is frequently applied when mining personnel are not underground.
Energy Efficiency	Decreases the energy consumption while meeting the system's cooling requirements. Adjustments of control philosophies and the installation of new technologies like variable speed drives (VSD) are common implementations

The adjustments of control philosophies are commonly used for energy efficiency strategies. These are done by implementing set point control and dynamic control methods.

Set point control uses the step response method, which delivers an output to a system in response to an instantaneous event [9]. For instance, a guide vane angle is adjusted based on a predetermined angle set for a specific time of the day. This is commonly used for compressor control. Dynamic control typically considers various inputs to achieve a specific goal [12]. The response to this method is adjusted between the baseline and current operations [13]. Artificial Intelligence (AI) has shown promise in dynamic control applications [2], [14], [15].

AI is a field that encompasses numerous subjects including computer science, engineering, mathematics, and statistics [16]. However, it is often referred to as a "buzzword" and lacks a precise definition. AI is commonly defined as a resource that enhances daily human activities by various scientific committees [17].

The use of AI has become increasingly widespread across various industries for tasks that usually can operate without human intervention [18], [19]. AI applications include [16], [20], [21]:

- Automation,
- Robotics,
- Decision-making using forecasting and optimisation techniques.
- Image processing

However, the mining industry is not among the leading industries in adopting AI in its systems and processes [16]. The current nature of the data present in mining *illuminates* the potential to apply AI in the industry, specifically for decision-making [22]. Machine learning and deep learning are AI techniques commonly used for decision-making [20].

Most of the data generated in mining is time-dependent, also known as time series data. This data serves as the basis for time series forecasting. Time series forecasting aims to predict future values using time series input data [23]. This technique derives insights by examining the correlations between inputs with similar timestamps [24]. Due to the advancement of technologies and the growth of data over recent years, machine learning and deep learning techniques have increased in popularity for time series forecasting [22].

Table 2: Machine learning and deep learning techniques for time series forecasting

Model	**Description**
Linear regression	Identifies a linear relationship between independent and dependent variables [14], [19].
Auto-regression (AR)	Determines the future value of a variable based on its previous variable in the form of a linear formula [25].
Moving average (MA)	Linear formula based on previous average values to determine the future value of the variable [26].
Auto-regressive moving average (ARMA)	Combination of the AR and MA models.
Auto-regressive integrated moving average (ARIMA)	Modification of the ARMA, by incorporating the "integrated" section, which allows the model to predict non-stationary data [27].
Seasonal auto-regressive integrated moving average (SARIMA)	Enhances the ARIMA model by including seasonal parameters [27].

Recurrent Neural Networks (RNN)	Neural network model that uses sequential data like time series data to predict future values [28].
Gated Recurrent Unit (GRU)	Modification of the RNN, which incorporates gates to address long sequence inputs [22] [25].
Long Short-term Memory (LSTM)	Modification of the RNN, which incorporates a memory cell (gates and states) to address long sequence inputs [25].

1.1 Summary of literature

Air temperature is the primary parameter for deep-level mine cooling systems [2]. Moreover, it is a sequential measurement that varies over time, thus being categorised as time series data [29]. Therefore, it is a suitable parameter for time series forecasting.

Classical or numerical air temperature forecasting employs atmospheric models based on the existing ambient conditions [23]. This has been applied in unforeseen events like tornados, prediction of soil temperature, and energy consumption [30].

Additionally, air temperature has been an integral parameter in developing control strategies for Heating, Ventilation, and Air Conditioning (HVAC) systems in residential and office buildings [31]. Recent literature has observed that deep learning techniques are feasible for air temperature forecasting in HVAC control systems [31], [32] .

The findings of these studies indicate that LSTM-RNNs are the most common approach for air temperature forecasting. Moreover, the studies suggest that neural networks outperform traditional forecasting methods like SARIMA when handling multiple input and output parameters.

Badenhorst [33] noted that deep-level mine cooling systems are like office and residential HVAC systems, where the main parameter for their control strategies is temperature. Thus, against this backdrop, the LSTM-RNN model is the most suitable for deep-level mine cooling system control which focuses on air temperature forecasting.

LSTM-RNN models can identify patterns from input variables over a long sequence [25]. As mentioned in Table 2, the LSTM model incorporates a memory cell. The memory cell is divided into two segments. The first segment contains an input gate, a forget gate, and an output gate. Usually, the multilayer perceptron (MLP) serves as the output gate. The second segment contains a cell state and a hidden state.

MLP is the most common and simplest form of an Artificial Neural Network (ANN) [28]. ANNs are seen as representations of complex mathematical equations [34]. Its structure is based on neurons, like those in the human brain [14], [35]. The neurons are interconnected and communicate with each other, forming a network enabling it to derive insights from the communication channel [36]. Figure 4 illustrates the basic architecture of an ANN feed-forward network.

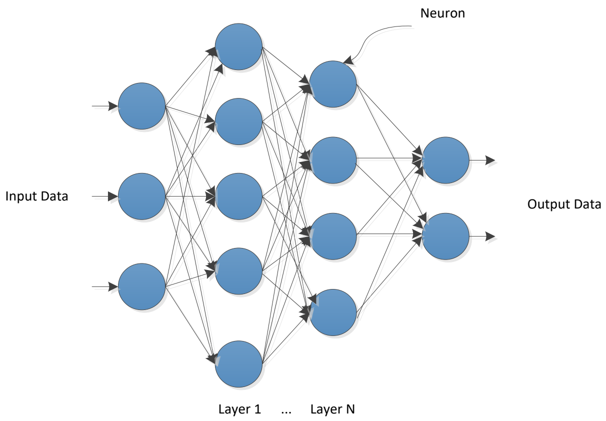


Figure 4: ANN architecture (adapted from [36])

MLP is a feed-forward network [32], [37]. A feed-forward network is an ANN where information flows in one direction.

The gates of the LSTM determine which data is important for the model. The states are used for collecting data for the next time step [22]. These segments are integral for gathering insights from the data for accurate forecasting.

The input, forget, and output gates are described mathematically in Equations *(1)*, *(2)*, and *(3)*. The hidden, cell, and new state are given by Equations *(4)* and *(5)*. The structure of the LSTM memory cell is illustrated in Figure 5.

$$i_t = \sigma\left(W_i h_{(t-1)} + W_i h_t\right) \tag{1}$$

$$f_t = \sigma\left(W_f h_{(t-1)} + W_f h_t\right) \tag{2}$$

$$o_t = \sigma\left(W_o h_{(t-1)} + W_o h_t\right) \tag{3}$$

$$C = tanh\left(W_c h_{(t-1)} + W_c h_t\right) \tag{4}$$

$$c_t = (i_t C) + \left(f_t c_{(t-1)}\right) \tag{5}$$

Here:

- i_t is the input gate
- σ is the sigmoid function
- W_i, W_f, W_o, and W_c are the parameter matrices for each of the gates and states
- h_t is the new state or output vector
- f_t is the forget gate
- o_t is the output gate
- C is the hidden cell state
- c_t is the cell state

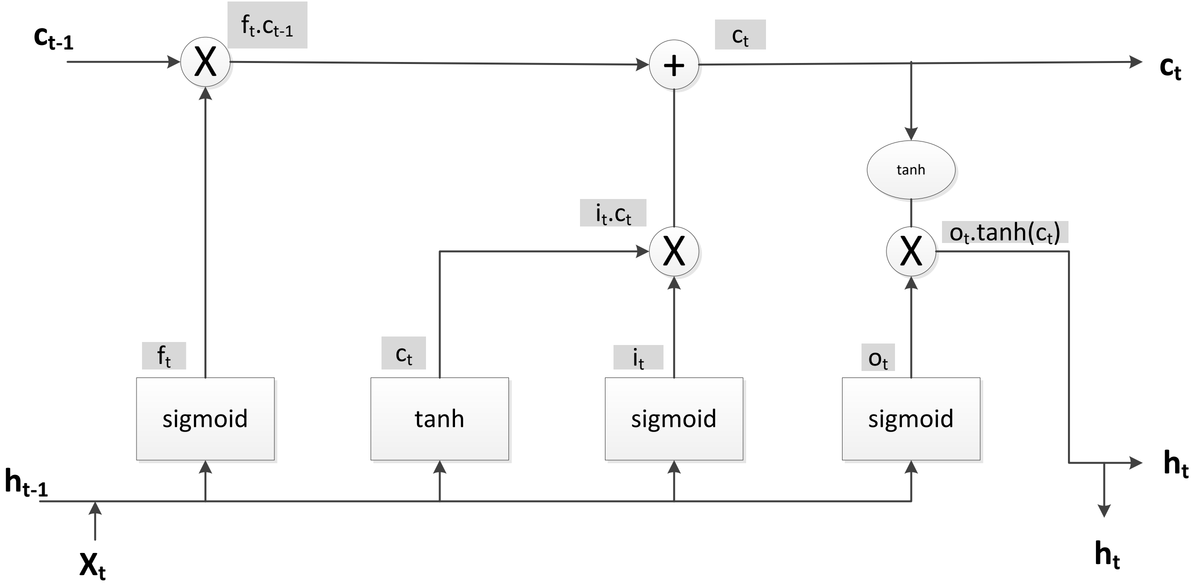


Figure 5: LSTM cell structure (adapted from [22])

Here:

- X_t is the input vector or variable

Existing literature indicates that traditional control strategies have been implemented successfully for deep-level mine cooling systems [9], [11], [33]. However, some of the studies required the installation of additional infrastructure for their control strategies [9]. Moreover, some of the implemented strategies lack adaptability [11], [33]. Cooling systems depend on dynamic conditions, like underground air temperatures. AI-inspired forecasting methods have shown the ability to forecast these conditions [31], [32].

1.2 Study objectives

This paper is based on the research conducted for the M.Eng dissertation completed at the North-West University in 2023 by Furumele [38]. The study aims to develop a dynamic control strategy for deep-level mine cooling systems using AI-inspired temperature forecasting. A case study research methodology is employed to evaluate the strategy on a deep-level gold mine cooling system. Key parameters related to the cooling system are identified and used to develop and evaluate a temperature forecasting model, which forms the basis for the dynamic control solution on the cooling system.

Furthermore, the study aims to contribute to mining research by implementing a control strategy that achieves energy savings in the mining environment and to the field of AI by applying AI techniques in complex industrial settings.

2 DYNAMIC CONTROL STRATEGY DEVELOPMENT

This study focuses on developing a dynamic control strategy for a section of a deep-level gold mine cooling system in South Africa. Additional information regarding the dynamic control strategy methodology can be observed in Furumele [38]. The overview of the methodology is illustrated in Figure 6

Figure 6: Methodology development overview

The mine, extending to a depth of 3 700 m and containing 15 working levels, uses a surface cooling system to reduce water temperature before it is transported underground. Due to the high VRTs at the mine's depths, additional cooling from smaller systems such as BACs and cooling cars is used to ensure reduced air temperatures in the working areas.

The surface cooling system is illustrated in Figure 7. The system contains three fridge plants (FPs) two ammonia plants (APs), and an optional cooling plant, which includes BAC ammonia plants (BAC APs). Hot water is pumped from underground to the pre-cooling dam, then it passes through the pre-cooling towers before being sent to the FPs for initial cooling of the hot water.

The water then moves to the intermediate dam and the APs for additional cooling. The BAC APs draw water from the intermediate dam send the water to the BAC and return it to the intermediate dam. Additionally, the APs and the BAC APs send cold water to the chill dam. Subsequently, the water from the chill dam is sent underground. This study will focus on the BAC APs and the BAC.

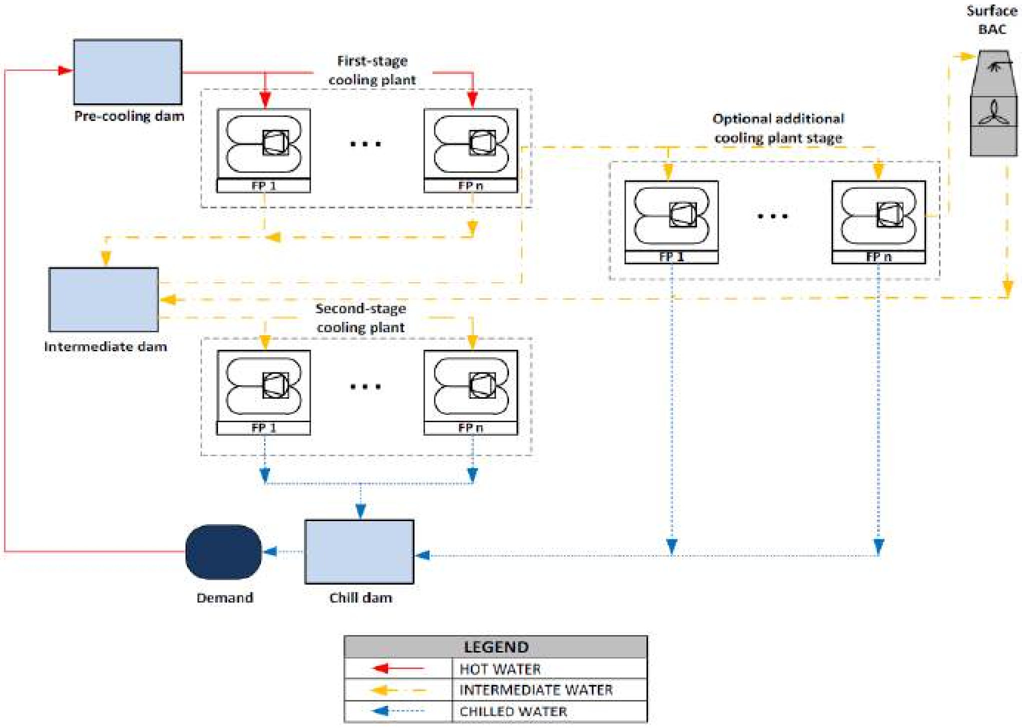


Figure 7: Multi-stage cooling system with the option for additional cooling [11]

2.1 System parameter identification

The study is limited to the BAC APs, the BAC, and a specific working area to avoid scope creep and reduce model complexity. Key parameters, including the surface and underground temperatures, BAC AP power consumption, BAC AP and BAC fan running statuses, and additional cooling auxiliaries were determined from the SCADA system. These parameters, primarily, the temperatures, form the basis of the dynamic control solution and can be adjusted during the temperature forecasting model development.

2.2 LSTM-RNN model development

The LSTM-RNN model is developed to forecast surface and underground air temperatures. The model is developed in Python using the Keras, Pandas, NumPy, and Scikit-Learn libraries. Various models are developed to forecast towards different horizons, such as forecasting one day (48 timesteps) in advance. The following models are developed:

- Model A: trained to forecast 48 timesteps (30-minute intervals) in advance.
- Model B: trained to forecast 24 timesteps (30-minute intervals) in advance.
- Model C: trained to forecast 4 timesteps (30-minute intervals) in advance, yielding a mean absolute percentage error (MAPE) of 10% on the test set.
- Model D: trained to forecast 2 timesteps (30-minute intervals) in advance, yielding a mean absolute percentage error (MAPE) of 5% on the test set.
- Model E: trained to forecast 1 timestep (30 minutes) in advance.

Figure 8 details the steps required to develop and evaluate the model [38]:

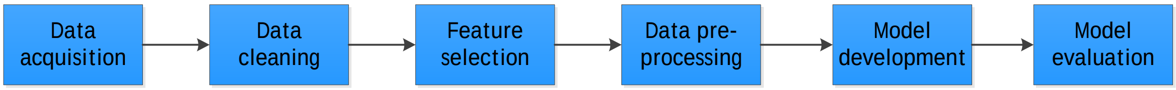


Figure 8: LSTM-RNN model development steps [38]

2.2.1 Step 1: Data acquisition

Data from the mine's historian database is extracted in 30-minute intervals using SQL queries. Each SQL query selects the "*TagName*", "*DateTime*", and "*Value*" from the database. Each parameter is represented as a tag ("*TagName*" and "*Value*") and extracted by specifying the date interval ("*DateTime*"). The data is aggregated in 30-minute intervals. This query is repeated for each parameter that is relevant to mine's cooling system and saved in a CSV file for further analysis and modelling.

2.2.2 Step 2: Data cleaning

The data that is extracted from the previous step is in its raw format and requires transformation for the subsequent steps of the model development. The data cleaning process includes the removal of outliers and the handling of missing data. The outliers were detected by examining the parameter's normal operating ranges. After examination, the identified outliers are removed from the dataset.

The missing data is handled using K-nearest neighbours (KNN) imputation. KNN imputation uses the "*K*" closest data points (neighbours) to determine what the missing data would be. The five closest data points are used to identify the missing values and can be adjusted if model improvement is required.

2.2.3 Step 3: Feature selection

Feature selection identifies the most relevant parameters that are suitable for forecasting the temperatures. Additional parameters can be incorporated if the model's performance is inadequate. The following parameters are determined as inputs for the model development:

- Surface ambient wet bulb air temperature (°C)
- Surface ambient dry bulb air temperature (°C)
- Hour of the day
- Day of the month
- Month of the year
- 7 Level air wet bulb temperature (°C)
- 7 Level air dry bulb temperature (°C)

2.2.4 Step 4: Data pre-processing

Further transformations of the data need to be implemented to ensure that the data is suitable for the LSTM-RNN model. Sliding window implementation, data partitioning, and data scaling are the techniques that will need to be implemented.

The sliding window represents the number of previous time values to forecast the next output value. For instance, model A uses 48 previous timesteps to forecast the value 48 timesteps ahead. The window "slides" to the next position to forecast the next output values.

Data partitioning divides the dataset into training, validation, and test sets. Model training uses the training set and the model's performance is evaluated using the validation set. After training, the model's performance is further evaluated using the test set. The dataset is divided such that 80% of the dataset is the training set, 5% is the validation set, and 15% is the test set.

The data is now scaled to improve the performance of the model during training, especially if the parameters' values differ drastically. The min-max scaling method is commonly used as a scaling method for neural network models and can be observed in Equation (6) [36].

$$x_{i_{scaled}} = \frac{x_i - x_{min}}{x_{max} - x_{min}} \tag{6}$$

2.2.5 Step 5: Model development

The model can now be developed after all the data has been transformed from its raw format to the model's desired format. The following hyperparameters are determined for all the models:

- Hidden layer activation function: LSTM (hidden layer)
- Output layer activation function: Linear
- Number of neurons: 7 (input layer), 32 (hidden layer), and 4 (output layer)
- Number of epochs: 300
- Callback function: Model checkpoint (saves the best performance to avoid overfitting)
- Batch size: 32
- Learning rate: 0.0001

The model is trained based on these hyperparameters using the training set and then verified using the validation set. After training both sets are evaluated using the coefficient of variation for the root mean square error (CV(RMSE)), the root mean square error (RMSE), and MAPE described in Equations:

$$CV(RMSE)\% = \sqrt{\frac{\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}{\bar{y}}} \times 100 \tag{7}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}{N}} \tag{8}$$

$$MAPE = \frac{\sum_{i=1}^{N}|y_i - \hat{y}_i / y_i|}{N} \times 100 \tag{9}$$

Here:

- N is the number of parameters.
- y_i is the actual value.
- $\hat{y}_i$ is the predicted value.
- $\bar{y}$ is the mean value of the actual values.

2.2.6 *Step 6: Model evaluation*

After model training, the models are evaluated based on their ability to forecast surface and underground temperatures to determine if they are suitable for a dynamic control strategy. According to ASHRAE Guideline 14, an acceptable CV(RMSE) value for model performance below 5% for half-hourly data is acceptable [39]. A maximum value of 10% for the MAPE is considered acceptable for the models [14], [34], [11]. The RMSE value will indicate whether the models are overfitting [14].

2.3 Dynamic control strategy

The model is ready to be implemented into the dynamic control strategy after the model has undergone training and evaluation. The model makes forecasts based on real-time data. This data will need to undergo the same data transformations that were done during the model training phase.

The control strategy will be used to pinpoint periods of the day when the surface BAC APs and fans may not be required to be operational. The basic flow diagram can be observed in Figure 9. The strategies that are determined will be based on the temperature forecasting models that were developed. The models that are insufficient in terms of performance will be disregarded. Thus, decreasing the number of solutions.

Figure 9: Dynamic control solution overview [38].

The following specifications form the basis of the control strategy [38]:

- Specification 1: Data gathering.
- Specification 2: Temperature forecasting.
- Specification 3: System operations suggestion.

The real-time data is extracted in half-hourly periods and undergoes the same transformations that were done during model development. Once the data is in the correct format, the temperatures are forecasted and evaluated against temperature targets.

The target for the surface air wet-bulb temperature is **7°C**, which is based on a previous study that implemented a seasonal control strategy on the surface cooling system. The 7 level air wet bulb temperature target is **32°C**, which is based on the MHSA of South Africa's underground temperature requirements. Against this backdrop, the operation suggestion is determined based on these target temperatures.

3 RESULTS AND DISCUSSION

3.1 Model development results

As discussed in Section 2.2, Five models were developed with varying forecasting horizons. The model performance after training can be seen in Figure 10.

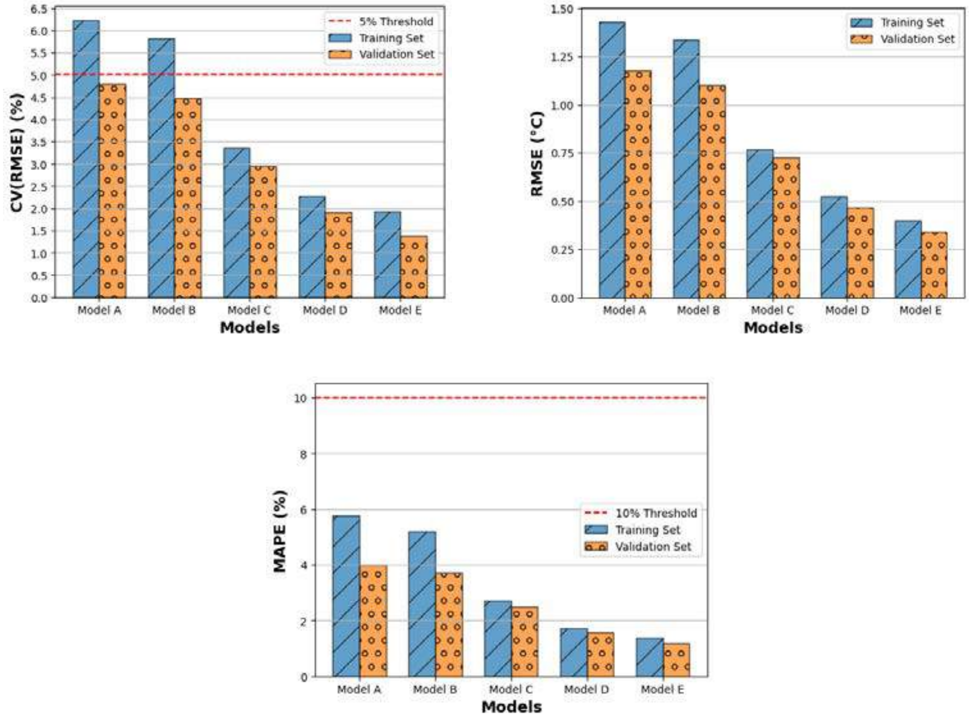


Figure 10: CV (RMSE), RMSE, and MAPE values for the training and validation sets [38].

Based on Figure 10, the validation sets exhibit lower values than the training sets for all the above metrics. Thus, this suggests that the models can predict well on unseen data. Moreover, the metrics show that the model improves for smaller forecasting horizons.

The true performance needs to be evaluated using the test set which is not involved during the model training phase. The model performance based on the test set indicates whether the models can predict temperatures on new and unseen data. The CV(RMSE) and MAPE values can observed in Figure 11. The results show the same trend observed in Figure 10, where values improve as the forecasting horizons decrease. The model is less likely to include irregular data points as inputs for predictions for smaller horizons. Thus, improving the model performance.

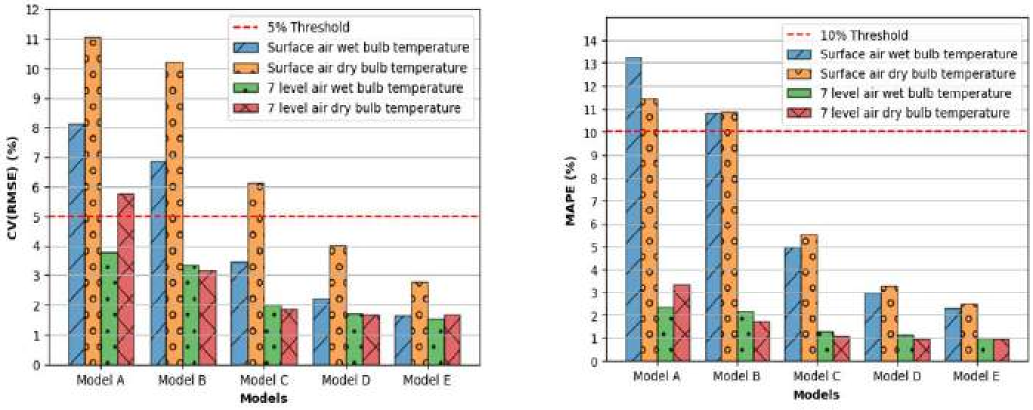


Figure 11: CV(RMSE) and MAPE values for the test set [38].

Models D and E attained CV(RMSE) values below the 5% threshold for all forecasted temperatures. Additionally, Models C, D, and E achieved MAPE values below the 10% threshold for all forecasted temperatures. Although Model C achieved a value above the 5% threshold for the surface air dry bulb temperature (6.12%). Model C is still considered an accurate model since the wet bulb temperatures are crucial for the dynamic control strategy instead of the dry bulb temperatures. Consequently, Models C, D, and E are deemed accurate for temperature forecasting.

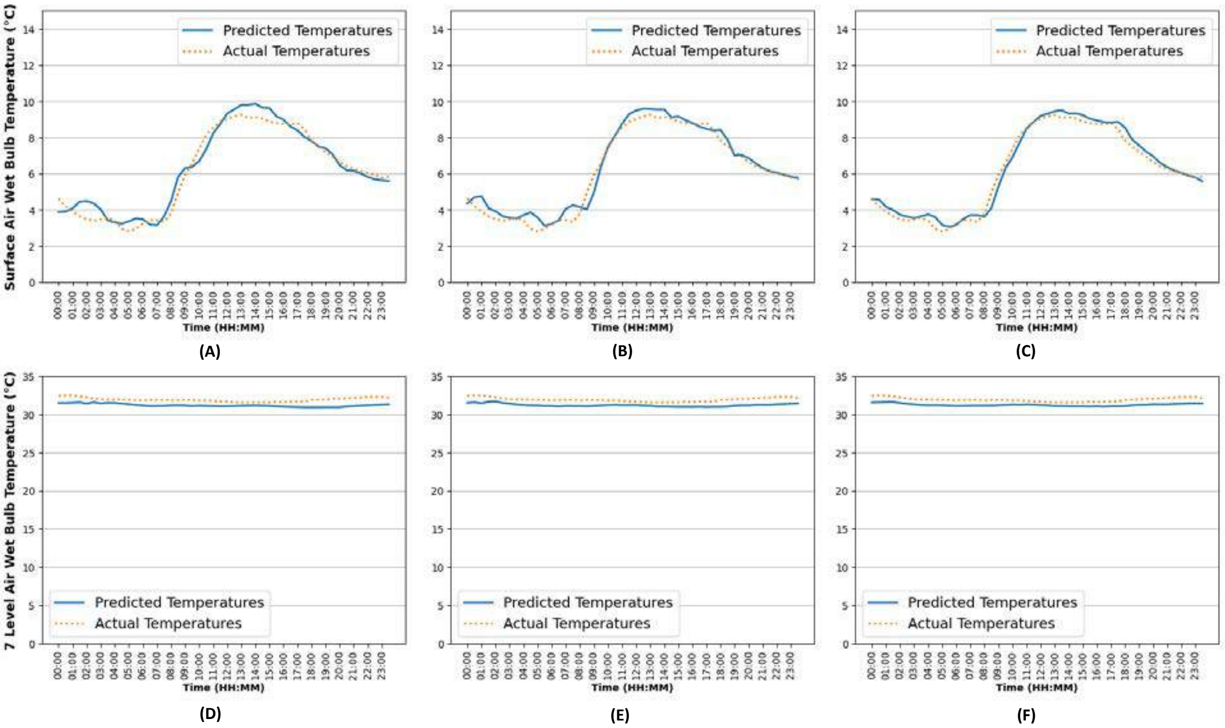
3.2 Dynamic control solution

The dynamic control solution was developed based on specifications detailed in Section 2.3 and Figure 9. Models C (two-hour forecast), D (one-hour forecast), and E (30-minute forecast) were used to develop the strategies.

Real-time data was extracted to be used for the chosen models. The amount of data (periods) extracted depended on what was required to forecast the temperatures.

For instance, Model D requires data from the previous hour and the present time to forecast the next two timesteps (30-minute intervals).

The extracted data was transformed using the same procedure used during model training. However, data partitioning is excluded from the transformations. Figure 12 shows the real-time wet bulb temperature forecasts.



(A) (B) (C)

(D) (E) (F)

Figure 12: Real-time forecast of the surface and 7 level air wet bulb temperatures using model C [(A) and (D)], model D [(B) and (E)], and model E [(C) and (F)] [38].

From the observations, the forecasting accuracy improves later in the day since it becomes less dependent on the previous day's data. Moreover, there is less variation in the underground temperatures compared to the surface temperatures, due to the additional cooling auxiliaries underground. Table 3 details the MAPE values for the real-time temperature forecasts.

Table 3: MAPE (%) values for real-time temperature forecasts [38].

Parameter	Model C	Model D	Model E
Surface air wet bulb temperature	7.72	6.57	4.9
Surface air dry bulb temperature	6.36	4.02	3.41
7 level air wet bulb temperature	2.32	2.27	2.14
7 level air dry bulb temperature	2.25	2.28	2.37

The MAPE values are below the 10% threshold for all the temperatures, thus indicating that the models are accurate. These models form the basis of the dynamic control solutions. Temperature targets of 7°C for the surface air wet bulb temperature and 32°C for the 7 level air wet bulb temperatures are used to determine whether BAC APs and fans need to operate based on the temperature forecasts.

The dynamic control solution was implemented for a day in the summer months and the winter months (June, July, and August). The real-time forecasted temperatures on a day in the summer months are detailed in Figure 13.

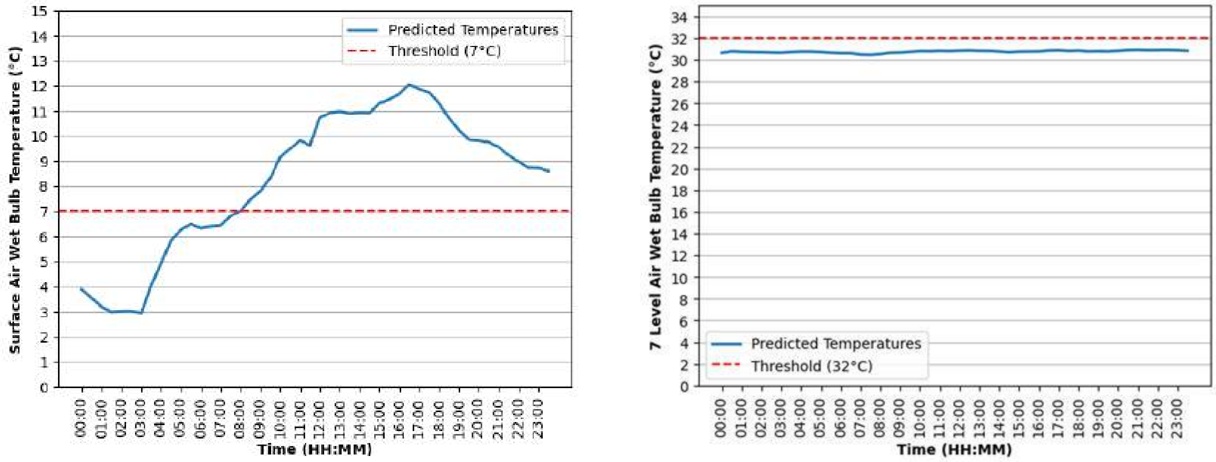


Figure 13: Forecasted summer surface and 7 level air wet bulb temperatures using model E [38].

MAPE values of 3.75% and 1.42% were achieved for the summer months. The surface temperatures were below the 7°C threshold between 00:00 and 08:00 and were below the 32°C threshold for the 7 level temperatures for the whole day. Therefore, the temperatures suggest that the BAC APs and fans can be switched off between 00:00 and 08:00.

However, this is under the assumption that the additional cooling auxiliaries remain constant throughout the day. The real-time forecasted temperatures on a day in the winter months are detailed in Figure 14.

MAPE values of 6.82% and 2.31% were achieved during the winter months. The BAC APs and fans can be switched off all day since the surface temperatures are slightly above the 7°C threshold (peak = 7.11°C) and below the 32°C threshold.

Model C achieved MAPE values of 13.81% and 2.80% and Model D achieved MAPE values of 8.26% and 2.68%, respectively. These values are for the surface and 7 level air wet bulb temperatures. Model D was the most suitable for the dynamic control solution. Model C is most likely to yield inaccurate forecasts. Although Model E is the best-performing model, Model D gives the mine sufficient lead time to prepare to change the operating status of BAC APs and fans.

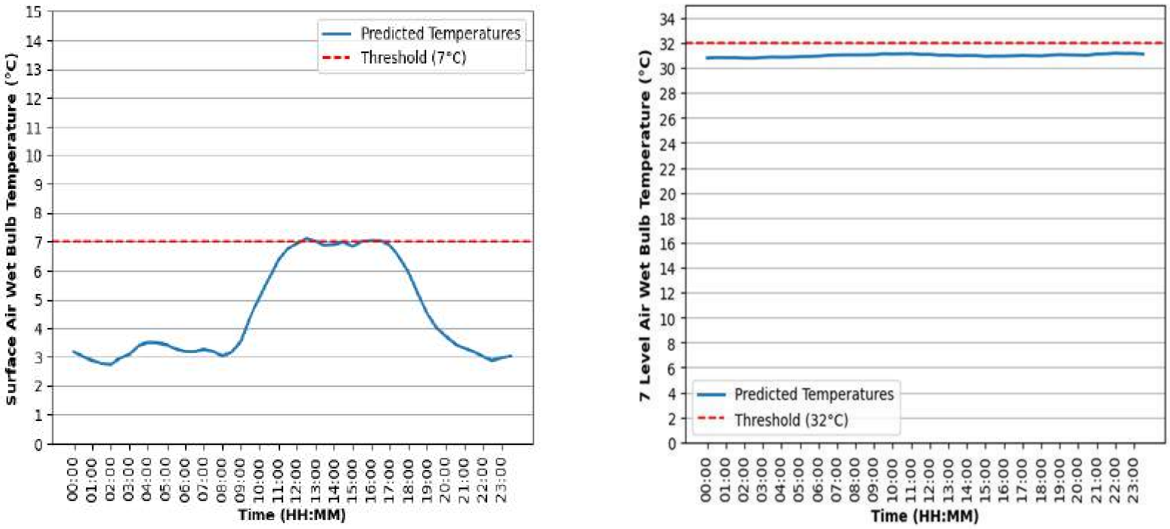


Figure 14: Forecasted winter surface and 7 level air wet bulb temperatures using model E [38].

Electricity cost savings were calculated to assess whether the dynamic control strategy leads to a reduction in electricity usage. A potential electricity cost savings of ZAR 1.5 million per annum are projected with a reduction in electricity of 20 MWh in 2023. The cost savings were calculated using 2022/2023 Eskom tariffs. Most of the savings were observed during the transitional months between the seasons (May and September).

4 CONCLUSION

Existing deep-level mine cooling system strategies lack adaptability based on dynamic conditions. AI *illuminates* the potential to address dynamic control strategies. This study developed a dynamic control strategy for a deep-level mine cooling system, specifically the BAC APs and fans. An LSTM-RNN temperature forecasting model formed the basis of the control strategy. The model was used to forecast temperatures across various horizons and was used to identify suitable operating conditions for the BAC APs and fans.

4.1 Limitations and Recommendations

The models that were developed were able to forecast temperatures accurately. However, they did tend to struggle for longer forecasting horizons (more than 2 hours). It is important to consider applying other forecasting techniques such as GRU and CNN techniques, which could yield better results for the longer horizons. However, the chosen model will improve with additional data.

Moreover, the strategy should be implemented as an automated real-time solution with a model that contains smaller forecasting horizons (30 minutes or less) for BAC APs and fans. Additionally, the solution can be integrated into a holistic control strategy for the entire cooling system.

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COST-TO-SERVE AND PROFITABILITY ANALYSIS OF PRODUCTS AND CUSTOMERS IN A SUPPLY CHAIN

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ABSTRACT

Conducting a cost-to-serve analysis of products and customers is pivotal for any organisation since it directly impacts profitability. Understanding the relationships between customers and products and how their profitability contributes to supply chain competitiveness and sustainable growth is often a strategic imperative. Therefore, this paper is concerned with analysing and optimising the cost-to-serve in end-to-end supply chains to understand profitability across different products and customers. The primary objective of this paper for end-to-end supply chains is to unpack a proposed cost-to-serve and profitability analysis structure with easy-to-follow components and linkages. By applying this cost-to-serve and profitability analysis structure, businesses can gain a better understanding of their true costs and profitability related to specific product portfolios and customer segments and make more informed strategic decisions to optimise cost-to-serve and maximise overall profitability.

Keywords: Cost-to-serve, Profitability analysis, Supply chain cost

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1 INTRODUCTION

Understanding the relationships between customers and products and their profitability is important for supply chain competitiveness and sustainable growth. Conducting a cost-to-serve (CTS) and profitability analysis of products and customers is pivotal for any organisation since it directly impacts business profitability.

Traditional cost accounting methods are sometimes unsuitable for customer and product cost analysis when output and cost contribution allocation are not correlated, as is often the case in logistics and supply chain management [1]. To circumvent these shortcomings, Activity-Based Costing (ABC) provides an alternative approach to costing and profitability analysis in logistics which has revolutionised how costs are allocated to products and customers in businesses [2].

In summary, ABC is used to identify cost activities (such as production, warehousing, etc.) Then cost drivers are identified for all cost activities (such as the number of units produced, the number of units stored, etc.). Costs are then allocated to cost objects (such as customer accounts, products, etc.) based on these objects' consumption of cost drivers [2]. ABC is an effective and granular approach to costing in businesses, but in some instances, this level of granularity in costing analysis is not feasible or even required for higher-level end-to-end supply chain analysis and decision-making in businesses.

Hence, this paper introduces a project that aims to analyse and optimise the cost-to-serve in a supply chain to understand profitability across different products and customers at a higher level of granularity than most ABC applications. To this end, this paper presents an easy-to-follow, higher-level, supply chain cost analysis approach that can be used by organisations to gain an understanding of its profitability dynamics and position themselves to make informed strategic decisions to optimise cost-to-serve and maximise overall profitability.

The remainder of this paper is structured as follows: The next section explores the essence and possible benefits of supply chain cost and profitability analysis. In Section 3, the proposed CTS and profitability analysis approach is introduced. This approach is unpacked with examples and general recommendations in Section 4. Finally, the project is concluded in Section 5.

2 LITERATURE REVIEW

Customer and product costing and profitability analysis are important to supply chain decisions and management. In the context of a supply chain, customer or product profitability analysis refers to the process of allocating costs and revenues to different customer accounts or product lines to calculate the true profitability of those customers or products [2]. Different products and customers require different types and levels of activities, implying that customers and products have different relationships to supply chain costs, leading to different levels of profitability [2].

2.1 Overview of supply chain Cost-to-Serve and profitability analysis

Traditional costing methodologies (grounded in management accounting practices) generally focus on measuring the cost of products and services provided to customers and deducting these costs from customers' revenue without considering the actual cost of serving different customers or customer segments [3, 4]. These approaches generally assume that the cost of serving all customers is the same, regardless of customer ordering behaviour. As a result, these approaches do not always focus on understanding how customer service and customer ordering behaviour influence the cost to serve and the profitability of different customers or customer segments, and how this can affect the business' costs and profitability.

To address this shortcoming, a CTS and profitability analysis approach adopts a different perspective. This approach focuses on determining the actual costs related to customer service activities in the supply chain and allocating those costs to customers to allow businesses to understand the cost of serving and the true profitability of individual customers [3, 4]. Businesses need to understand the true CTS and profitability of their customer accounts and product lines since an improved understanding of a customer's or product's true profitability (considering its individual CTS) can help organisations manage and improve their overall profitability [4, 5].

2.2 Benefits of using Cost-to-Serve and profitability analysis in supply chains

There are many possible direct and indirect benefits of using CTS for product and customer profitability analysis and management in supply chains. First, knowing what it costs businesses to serve their customers enables them to identify unprofitable customers and possible areas where cost can be reduced in the supply chain, or if pricing decisions must be revisited or re-negotiated, to improve customer profitability. This is confirmed by Stentoft and Rajkumar [6] who analysed the benefits of a supply chain CTS analysis and found that one of the most significant benefits is improved customer profitability. They find that a structured CTS and profitability analysis can help businesses to protect existing highly profitable customers, because of more accurate knowledge of their actual profitability contributions to the business.

Secondly, in line with the findings of Stentoft and Rajkumar [6], understanding the true end-to-end cost of delivering a product or serving a customer, can provide a basis for pricing and discount decisions and negotiations. Van Raaij et al. [5] note that discount decisions are often made based on sales volume, but previous CTS and customer profitability studies found that sometimes the larger customers are less profitable or even unprofitable. This highlights the importance of using actual cost and profitability indicators to inform pricing and discount decisions for improved profitability.

Finally, understanding the true end-to-end cost of products, allows businesses to identify possible areas for further analysis and improvement, such for example, reducing the number of movements of products within or between facilities owned by the company. This can lead to significant cost reductions and improved profitability.

To this end, O'Byrne [7] used a structured CTS approach to determine actual supply chain cost in a consumer product business in Thailand. This analysis highlighted cost reduction opportunities during distribution, amounting to distribution cost savings of approximately 20% per year. Another study of a food company in the Netherlands, Belgium, and Luxembourg focused on using CTS to enable supply chain cost reduction [8]. In this study, using a structured CTS approach to quantify cost and identify cost reduction opportunities resulted in possible customer CTS reductions of more than 40%.

The literature illustrates some of the cost reductions that can be directly attributed to CTS and profitability analyses in supply chains. However, many of the benefits that can be realised by businesses, will ultimately be due to improved visibility of true costs and, consequently, more informed and aligned decision-making.

2.3 Supply chain Cost-to-Serve and profitability structures in the literature

Different types of supply chain cost structures are found in the literature. In a study focused on the outbound supply chain, Gevers [8] identified four key cost areas in a supply chain CTS project: order processing, warehousing, transportation, and customer service. Even though this approach results in an outbound supply chain CTS calculation (which is the part of the supply chain mostly impacted by customer ordering behaviour and requirements), it is often necessary to consider inbound, operations, and other associated processes to enable decision-makers to get a view of the end-to-end supply chain cost of products and services.

One such structure is presented by Pettersson and Segerstedt [9], who divide supply chain costs into five main areas: Manufacturing cost, Administration cost, Warehouse cost, Distribution cost, Capital cost, and Installation cost. In this structure, manufacturing costs include direct material and labour costs as well as production overheads. Administration costs include all costs related to management and administration in the business, such as order processing, etc. Warehousing cost includes inventory and storage costs, and Distribution cost covers all the costs associated with inbound and outbound transportation and management. Capital cost relates to company investments and Installation costs are included for companies who install products at customer sites.

Total supply chain cost (SCC) is then calculated as a sum of these five cost categories and a Supply chain cost volume ratio (SCCR) is then calculated using equation 1 [9, 10].

$$SCCR = \frac{Sales - SCC}{Sales} \tag{1}$$

In addition the studies by Gevers [8] and Pettersson and Segerstedt [9] many other studies in the literature focus on conducting CTS and profitability analysis in supply chains [11,12,13]. However, most of these studies focus on modelling the cost of one or two key processes in the supply chain (such as transportation and warehousing, the outbound supply chain process, etc.) at a very low level of granularity. These approaches, even though useful and accurate, may not be the most desirable approach for a higher level of granularity end-to-end supply chain CTS view that is often needed by decision-makers.

3 RESEARCH APPROACH

To address the need identified in the literature, the primary objective of this project is to unpack a proposed CTS structure that can be used for cost analysis in supply chains at a higher level of granularity than ABC, whilst focusing on understanding product and customer profitability. To this end, the key elements or phases included in the proposed supply chain CTS structure are summarised in Figure 1.

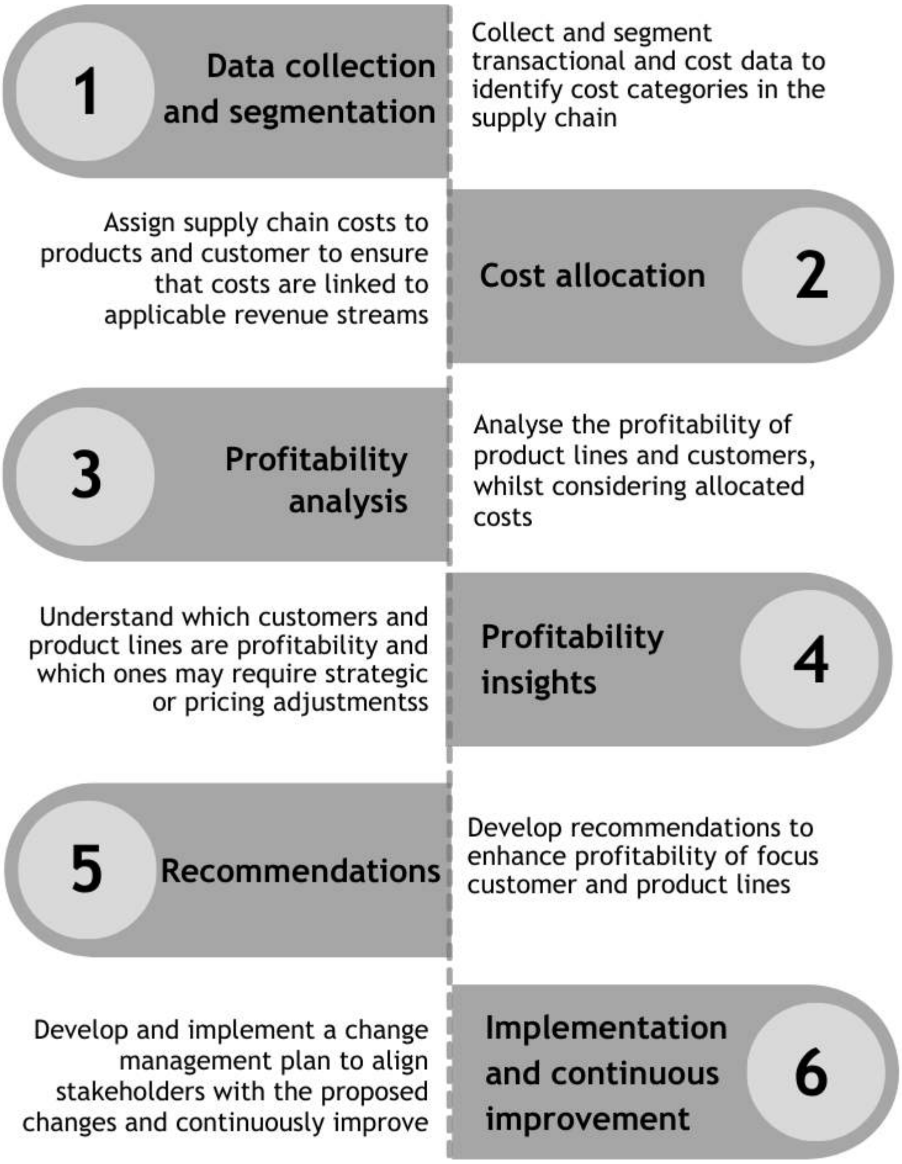

Figure 1: Cost-to-serve and profitability analysis approach

The first step of the proposed CTS and profitability approach (*Data collection and segmentation*) focuses on collecting and segmenting customer transactions, product lines, and supply chain cost data to identify cost categories in the supply chain. For example: input material cost, outbound transportation cost, etc.

These cost categories are then allocated to applicable products and customers (during the *Cost allocation* step) to ensure applicable costs are linked to revenue streams. For example: if one customer requires delivery of an ordered product, and another customer picks up the ordered product from the factory gate, outbound transportation costs are linked to the first customer, but not to the second. However since both customers order the same product, the input material cost is allocated to both customers.

Once this is done for all revenue streams, the profitability of products and customers is calculated and analysed in the *Profitability analysis* step, whilst considering the allocated cost categories and applicable revenue generated by each. During the *Profitability insights* step, the resulting profitability values are then used to segment products and customers to understand which contributes the most to profitability and which may require strategic or pricing adjustments.

The fifth element (*Recommendations*) focuses on developing recommendations to enhance the profitability of focus customers and product lines identified during the profitability analysis and insights phases. Appropriate implementation and change management plans must also be developed and implemented (during the *Implementation and continuous improvement* step) to ensure all stakeholders are aligned with the proposed changes.

4 RESEARCH RESULTS

The research approach was used to conduct supply chain CTS and profitability analysis in actual supply chains. During this process, the approach was continuously updated and refined to ensure that it provides an easy-to-follow process for decision-makers to obtain a higher-level understanding of product and customer costs in supply chains. The resulting refined approach with more detailed steps is therefore presented in this section.

4.1 Data collection and segmentation

The first element focuses on collecting and segmenting customer transactions, product lines, and supply chain cost data to identify cost categories in the supply chain. For this, access to detailed financial transactions in the considered company's ERP system is required. The transactions are then grouped and allocated to different cost categories. The high-level supply chain cost categories identified through actual supply chain CTS examples from the chemicals, mining, and agriculture sectors in South Africa are summarised in Figure 2.

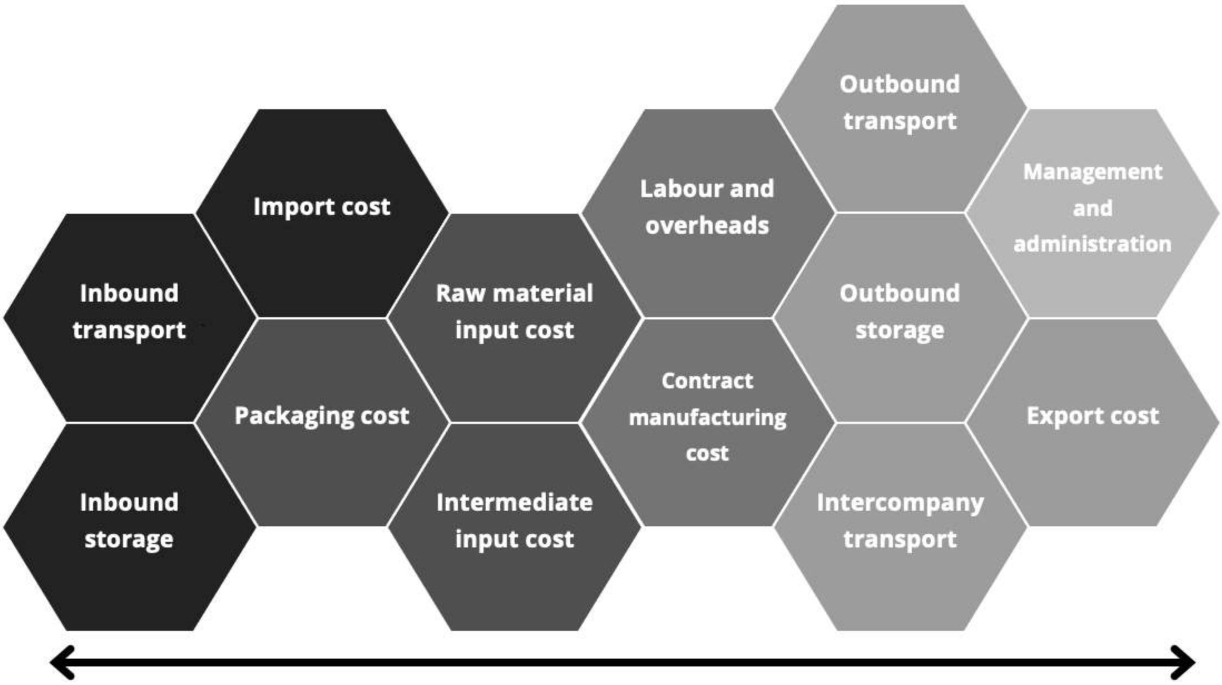

Figure 2: High-level supply chain cost categories

The main cost categories identified focus on inbound, production, outbound, and management and administration costs and many of these categories may apply to both forward and reverse flows in the supply chain. Additional cost categories can be added, if needed, depending on the specific cost drivers in a supply chain, but the categories depicted in Figure 2 are the main ones the researchers used in their higher-level supply chain CTS and profitability analysis applications. These cost categories align with some cost categories used in the literature [8,9], however, the list of cost categories is expanded to include all cost categories from an end-to-end supply chain view.

4.2 Cost allocation

After identifying the cost categories in the supply chain, different cost categories must be allocated to different product lines and customers. Some cost categories may apply to all customers and products, for example: the direct cost of raw material used during production will be allocated to all customers ordering that product and to the product cost itself. Other cost categories may only apply to some customers or products, for example: packaging cost will only apply to packaged products, but not necessarily bulk products), or outbound transportation cost may only apply to customers requiring delivery of their orders (instead of collecting orders from the factory gate).

There are various supply chain-specific complexities and nuances that must be considered when identifying cost categories. For example, transportation cost: There are cost categories for *inbound transport cost* of raw materials, packaging, and in some instances inbound transportation of sub-assemblies or intermediate products but there is also an *outbound transport cost* category for finished goods being delivered to customers. However, it was found that often goods are also moved between different facilities or nodes in the supply chain before sale. These transportation costs should also be accounted for in the CTS structure, even though they are not directly linked to meeting demand. Therefore, an *Intercompany transport* category is added to compensate for these movements.

After completing the cost allocations, it is important to find a way to visualise the results for easy interpretation. A Sankey diagram is an effective way to visualise the contribution of cost categories to the total supply chain cost of a specific product line or customer [14]. This can enable decision-makers to see which factors contribute to the total cost end-to-end supply chain cost of products and customers at a lower level of granularity, making it easier to identify specific focus areas for further investigation and cost reduction. An example of such an end-to-end supply chain cost allocation calculation for a product (produced from two types of raw materials and two intermediate products as input) is provided in Figure 3 (developed by authors).

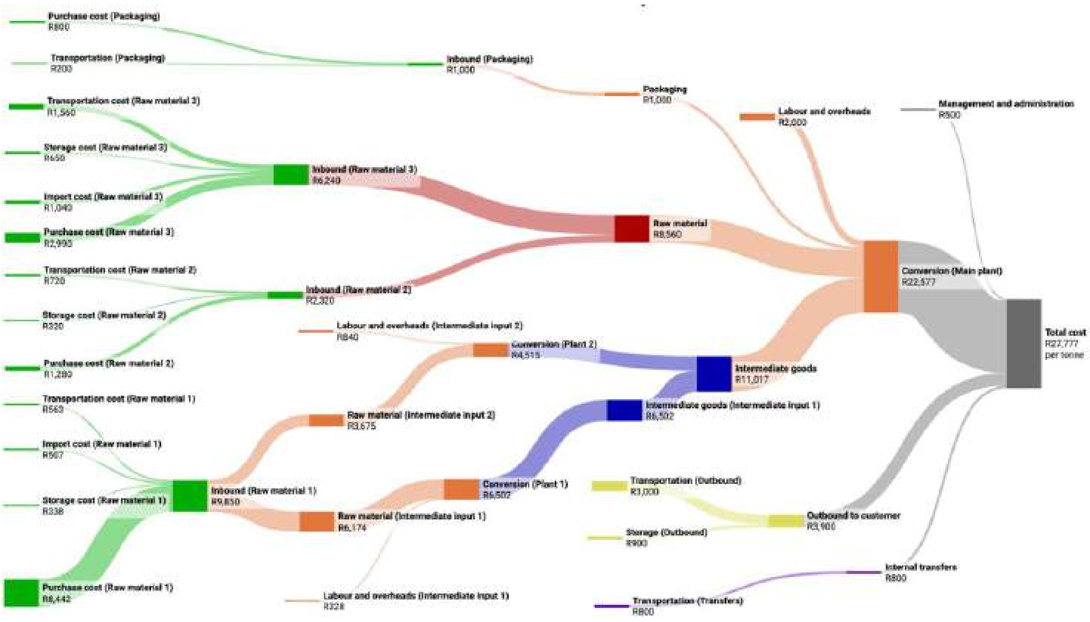

Figure 3: Product supply chain cost allocation example

In this diagram, all the individual cost categories and the contribution to the cost of a particular product can be seen. In this example, the final product cost amounts to R27 777 per tonne. This cost is the sum of all the smaller cost contributions of different processes and inputs needed to produce and deliver the final product at the customer location. All the costs shown in Figure 3 are scaled to the cost per tonne of the final product, using the Bill-of-Material (BOM) of intermediate products as well as the final product.

To illustrate this, consider *Raw material 1*. This material is bought from an international supplier; hence it incurs both a purchase cost and an import cost. In addition, the raw material is transported to and stored in one or more warehouses before being used as input into two manufacturing processes that produce *Intermediate input 1* and *Intermediate input 2*. These two intermediate inputs are then used as intermediate goods inputs into the main production process of the finished product. The cost of these intermediate inputs allocated to the final product is scaled depending on the quantity of each in the final product as indicated in the BOM. In addition, the inbound cost of *Raw material 1* is also scaled based on the different BOMs, and a portion allocated to the final finished product. To ensure that all costs are accounted for in these calculations and the Sankey diagram, it is important to ensure that the inflow and outflow of costs of each element are balanced, for example: the costs flowing into *Inbound (Raw material 1)* must be the same as the cost flowing out of this element.

The Sankey diagram depicted in Figure 3 can also be used from a “per customer” perspective and allows decision-makers to see the different cost elements in addition to the total cost of a product from the first input to final delivery at customers. This can enable decision-makers to identify possible focus areas for improvement in different product lines or customers.

4.3 Profitability analysis

After allocating costs to different products and customers, the next step focuses on analysing the profitability of product lines and customers, whilst considering the calculated cost and revenue generated by these products and customers. To calculate product profitability the formula provided in equation 2 is used, where the total cost to serve of the product (as calculated in Section 4.2) is depicted by C, the sales price of a product (in R/tonne) is depicted by S, sales recoveries for that product (for example recovered transport cost) depicted by R (in R/tonne), and sales discounts (in R/tonne) by D, then the product profitability rating (depicted by P) can be calculated as shown in equation 2. This calculation is like calculations found in the literature [9, 10], however, in this structure cost recoveries and discounts per order are included as separate components and not as part of the net sales price.

$$P = 100\frac{C}{S+R-D} \qquad (2)$$

The formula provided in equation 2 can also be used in a similar way to calculate the profitability percentage of a customer. In essence, the lower the value of P, the more profitable a product. Ideally, the value of P should be less than 100% for products and customers, which implies that products and customers are profitable (i.e. CTS of a product or customer is less than income for that product or from that customer).

This profitability calculation is then used to determine the profitability of all products or customers and final results are summarised on profitability graphs (as depicted in Figure 4 and Figure 5) to provide high-level views of product or customer group profitability to decision-makers.

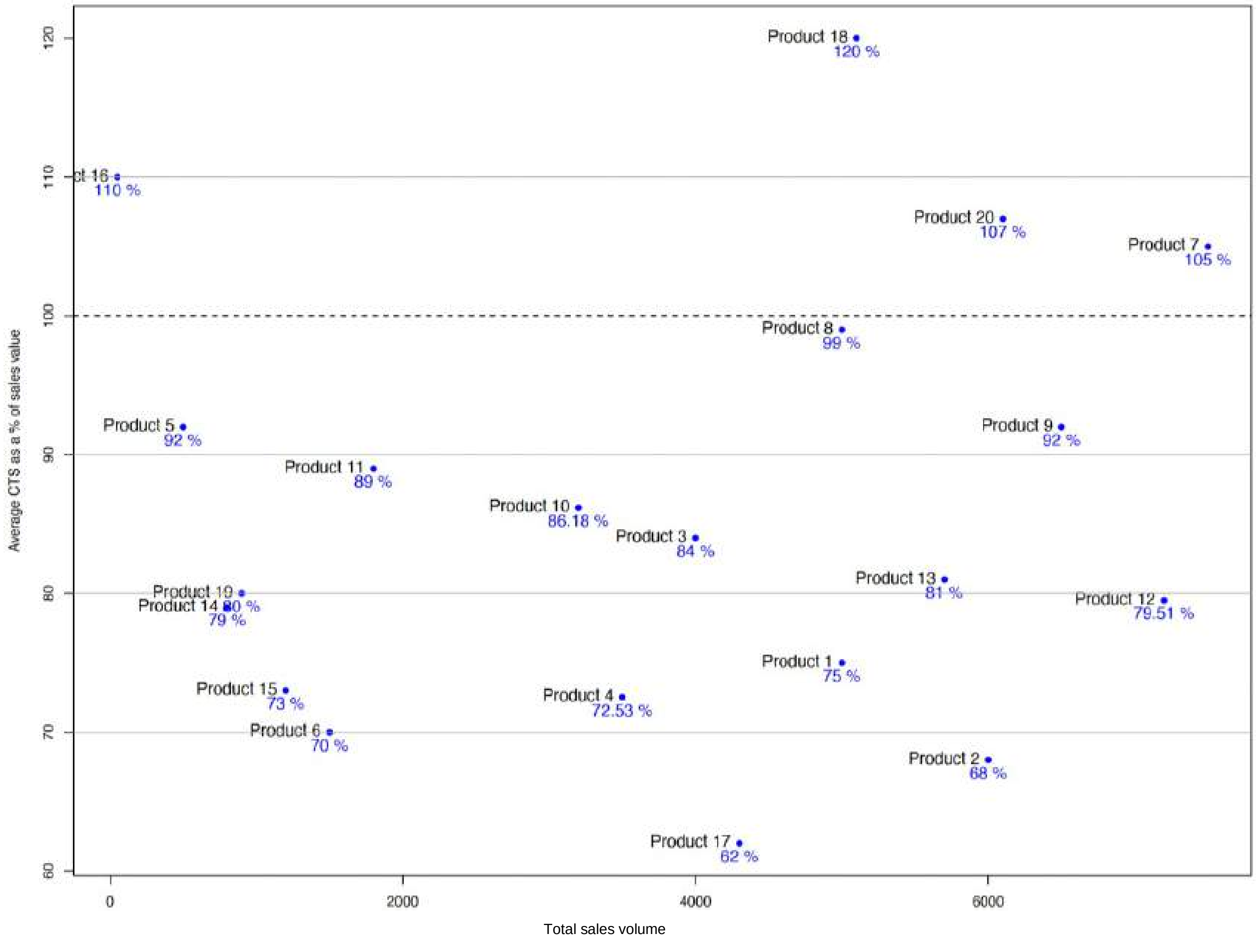

Figure 4: Product-level profitability analysis example

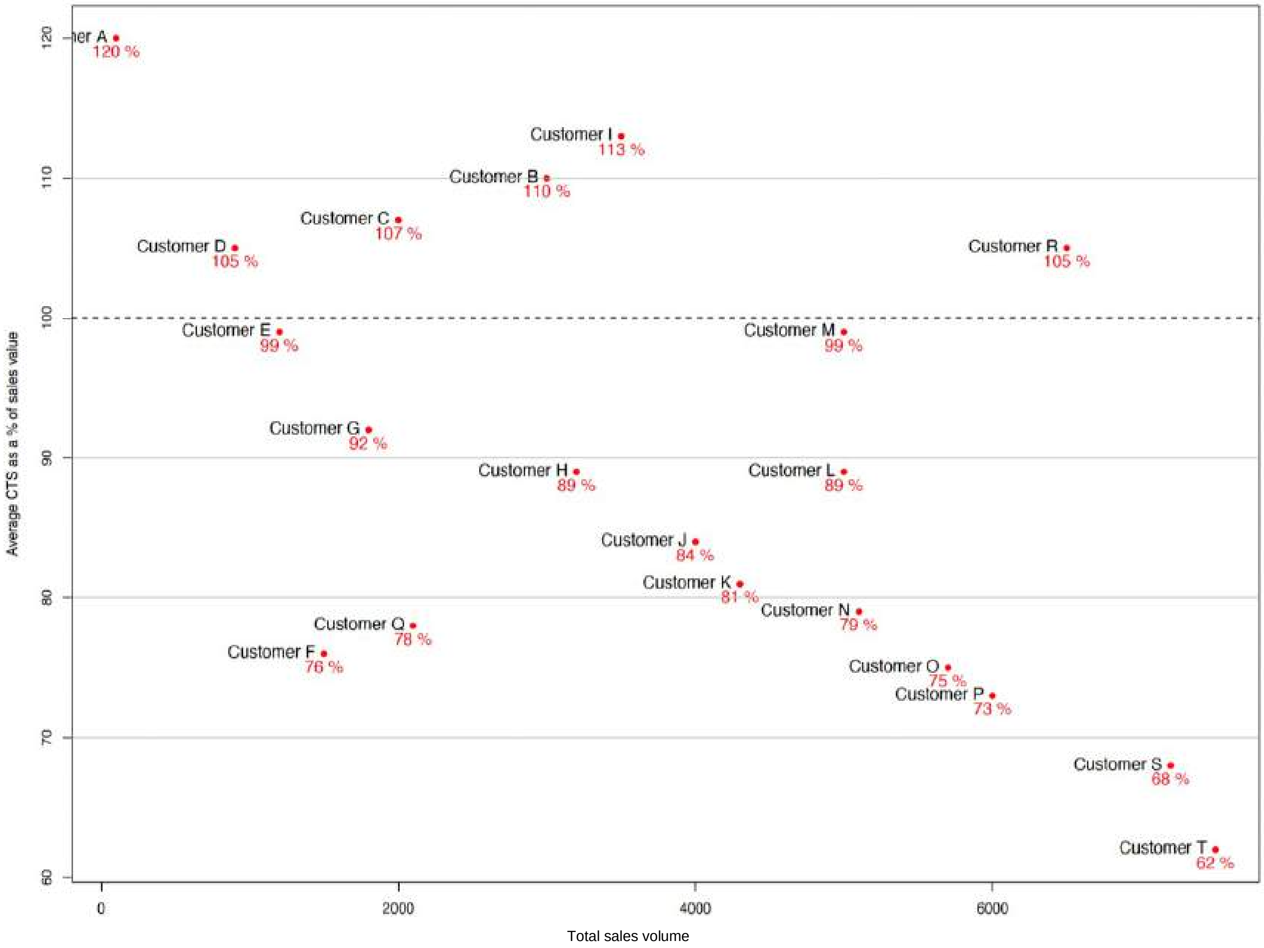

Figure 5: Customer-level profitability analysis example

These “snapshots” of profitability presented in Figures 4 and 5 allow decision-makers to analyse overall profitability and identify possible focus customers or products for profitability improvement during the next phase.

4.4 Profitability insights

The cost and profitability calculations and graphs from Sections 4.2 and 4.3 are used during the *Profitability insights* phase to glean some insights about product and customer profitability, and possible focus areas for improvement. Customers can be segmented to identify which customers to focus on and what order management and customer service approaches to investigate to enhance overall profitability.

For example, in line with the customer segmentation matrix presented by Langley et al. [1], consider the four different customer segments based on their CTS and annual sales volume shown in Figure 6.

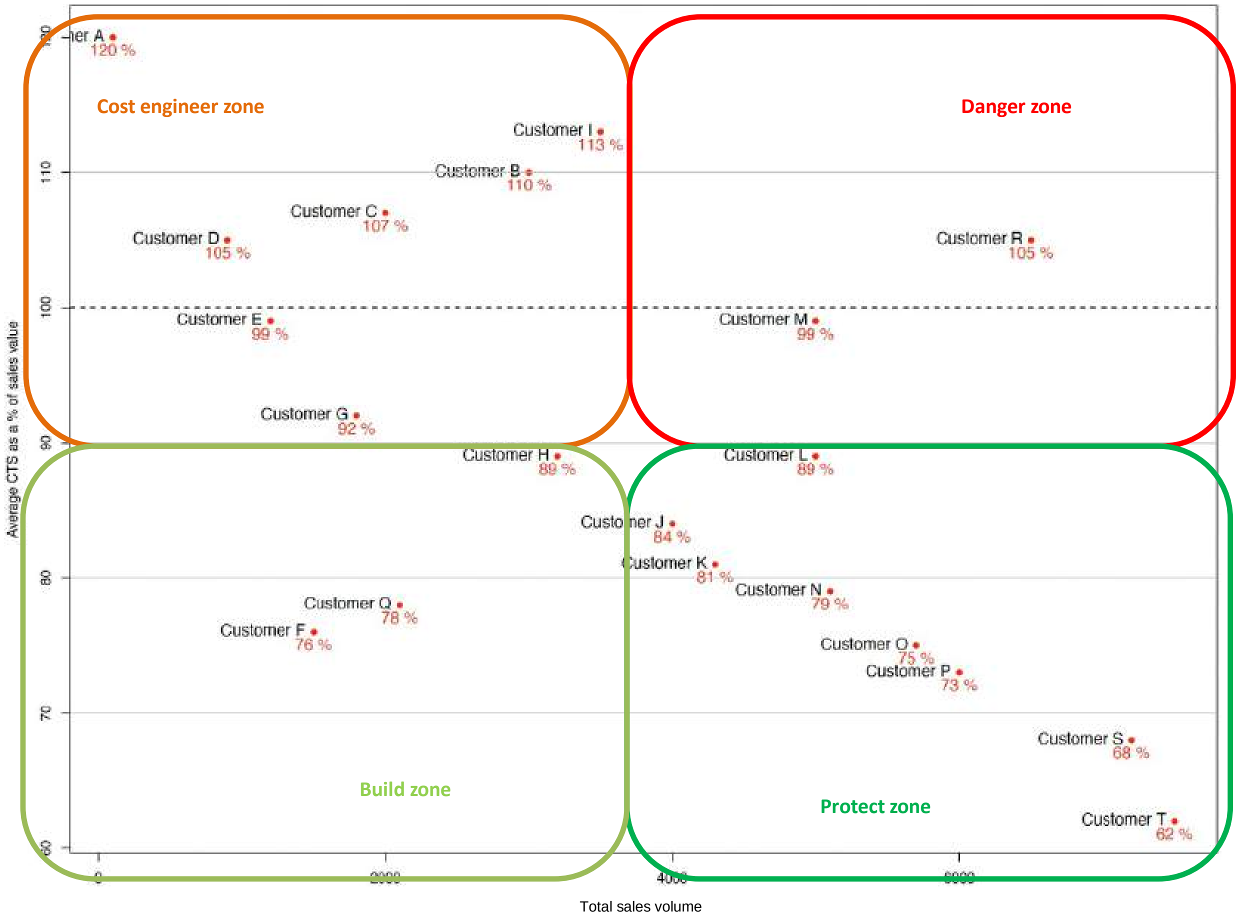

Figure 6: Customer-level profitability insights example

Customers in the *Protect* and *Build zones* are highly profitable customers. Due to the higher sales volume of customers in the Protect zone, these customers should be protected and their cost to serve and sales value (and value) maintained. Whereas the CTS of customers in the Build zone must be maintained whilst exploring opportunities to build their sales volume or even their net sales value. The less profitable (or unprofitable) customers are included in the *Cost engineer* and *Danger zones*. They have a higher CTS and the higher the sales volume of these customers, the higher the risk. Customers in the *Cost engineer zone* are not very profitable, but because of lower order volumes, their impact on overall company profitability may be less pronounced than those in the *Danger zone*. Therefore it is recommended that customers in the *Danger zone*, are focused on first to see how their CTS can be reduced whilst maintaining their sales volumes.

This same approach can be adopted for product profitability segmentation and focus area identification. Analysis teams can then delve into more detail for unprofitable products or customers, identify opportunities for improvement, and develop appropriate recommendations to achieve these improvements during the next phase, all whilst considering strategic or tactical reasons for specific circumstances such as product portfolio buying which may require the inclusion of less profitable product lines.

4.5 Recommendations

During the recommendation phase, focus areas for improvement are unpacked and investigated, and possible ways to improve profitability or reduce cost are identified and formulated.

One of the recurring insights the researchers found during their past supply chain CTS applications is the importance of having and maintaining visibility of the true end-to-end product and customer cost in a supply chain. Often a single point where the end-to-end view of actual product costs in the business is lacking. This results in the true customer or product cost (and profitability) of a product or customer not being available or accessible in the data used for decision-making. Therefore, providing visibility of the actual end-to-end product and customer cost and profitability at key points in supply chains can lead to more informed (and often improved) decision-making.

Another insight or recommendation from past supply chain CTS applications is the importance of understanding what factors are contributing to the cost of a product or the cost of serving a customer. Understanding how these factors impact the profitability of products and customers can enable more informed decision-making, lead to more efficient supply chain operations, and reduce overall costs. For example, understanding the cost of non-value-adding movements and transfer of goods between facilities in a supply chain can enable decision makers to, for example, re-evaluate inventory and stock allocation policies to reduce the need for these intercompany transportation activities. , for example, understanding the implication of the Make vs. Buy decision on overall product cost (and profitability) can provide a foundation for discussions and more informed Make vs. Buy decisions.

4.6 Implementation and continuous improvement

The last step in the process is to develop and implement a comprehensive implementation and change management plan to recommend improvement initiatives to ensure that all stakeholders are aligned with the proposed changes. Re-evaluating CTS and profitability frequently to determine the impact of interventions on overall CTS and supply chain profitability and identify new focus areas to reduce cost and improve profitability. This step is crucial to ensure that the potential benefits of a costing and profitability project can be realised. Also, although the process is based on historical data, a more frequent and dynamic approach could be investigated to provide better decision-making.

One way in which continuous improvement can be enabled is through benchmarking supply chain CTS and profitability performance [15, 16]. Firstly, internal benchmarking can be used to compare CTS values calculated for different product lines and customer accounts against other (similar) product lines or customer accounts for the same period, or against the CTS values of previous years for the same product line or customer account. Competitive benchmarking can be used to compare the supply chain CTS of similar products with competing companies in the same industry locally or internationally. Lastly, industry benchmarking can be used to compare CTS and profitability values, CTS practices, as well as cost drivers of products and customers with businesses in other industries to facilitate the identification of key areas for improved supply chain profitability.

5 CONCLUSION

Customer and product profitability are important contributors to supply chain profitability and competitiveness. It is, therefore, crucial for decision-makers to understand the contribution of customer accounts and product lines to overall business profitability. Conducting a CTS and profitability analysis is an effective way to understand these relationships.

Many studies in the literature focus on conducting some form of CTS analysis of selected supply chain processes (especially logistics operations), but very few studies are concerned with calculating the true end-to-end supply chain cost of serving customers. This paper, therefore, focuses on presenting and unpacking an easy-to-follow end-to-end supply chain CTS and profitability analysis approach that can be used to analyse CTS and profitability across different customer accounts and product lines in supply chains.

Some of the insights obtained from the application of this approach in actual CTS and profitability analyses are that visibility of profitability insights is often lacking in supply chains and that there is rarely one point where decision-makers can get a true end-to-end view of actual costs (and more importantly profitability) in supply chains. The implication of this is that unprofitable customers and products are not always visible. Therefore, providing end-to-end visibility of the true cost is often the most impactful insight from a profitability analysis.

From an Operational Excellence perspective, this CTS approach provides a holistic and systemic view of an organisation’s end-to-end supply chain. This visibility can enable alignment and engagement across various departments, fostering a shared understanding of cost drivers and performance metrics. By identifying the true cost of serving different customers, products, and channels, CTS analyses can empower organisations to make informed decisions to improve profitability. This systemic view can act as a continuous improvement lever, allowing teams to collaboratively identify inefficiencies, implement targeted improvements, and track progress over time, leading to sustained operational excellence.

By using the proposed approach to conduct an end-to-end CTS and profitability analysis of products or customers, businesses can gain an understanding of their profitability dynamics and position themselves to make informed strategic decisions that optimise CTS and maximise their overall profitability. The approach presented in this paper can therefore serve as a guideline for businesses that want to unlock profitability potential within their supply chains while delivering continued value to customers.

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A FRAMEWORK FOR INDUSTRIAL CLUSTER-DRIVEN ADOPTION OF INDUSTRY 4.0 TECHNOLOGIES

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ABSTRACT

Today's policymakers face a significant challenge in successfully integrating Industry 4.0 technologies across various sectors. With Industry 4.0 set to play a crucial role in the future, the need for a robust implementation framework is evident. This article focuses on an appropriate pattern for deploying Industry 4.0 technologies with the assistance of industrial clusters. The methodology adopted in this paper involves identifying the advantages and challenges of implementing Industry 4.0 and reviewing existing adoption frameworks at different levels. Through this comprehensive analysis, we aim to find new solutions facilitated by industrial clusters. Moreover, by focusing on the potential of industrial clusters, we will explore a pattern and framework for smart industrial clusters to act as catalysts, propelling industrial regions toward greater economic, environmental, and social development through the adoption of Industry 4.0 technologies. This research supports policymakers and researchers in driving innovation and sustainable growth within Industry 4.0.

Keywords: Industry 4.0, Industrial Clusters, Implementation framework

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1 INTRODUCTION

In an era marked by rapid technological advancements and the rise of Industry 4.0, the need for innovative strategies to navigate this transformative landscape has never been more pressing. As traditional industries struggle with the challenges of digitalization and automation, offering a collaborative framework for embracing the opportunities presented by Industry 4.0 is necessary. By investigating the strengths and resources of interconnected businesses within geographic proximity, industrial clusters hold the key to accelerating the adoption of Industry 4.0.

The impact of Industry 4.0 on transforming businesses goes beyond the use of modern technological tools and has, in fact, fundamentally altered the nature of business operations. [1]. Industry 4.0 brings about significant improvements in economic and work efficiency, flexibility, and technological innovation, leading to cost reduction [2, 3]. It fosters interconnectivity, virtualization, and collaboration, paving the way for smart, sustainable cities [4, 5]. Moreover, it enhances productivity through decentralization and real-time capabilities [6, 7, 8], offering benefits such as blockchain-enabled transparency, vertical and horizontal integration, smart factories, and product personalization [9, 10]. These advancements drive economic development and long-term sustainability [11, 12]. However, the adoption of Industry 4.0 faces challenges such as talent scarcity, financial constraints, data security concerns, and resistance to change, among others [2, 13]. Addressing these challenges requires appropriate policies and strategies at various levels to effectively navigate complexities and embrace the opportunities of the fourth industrial revolution [14, 15, 16].

To understand Industry 4.0 implementation frameworks, we first explore its defining features to enhance technological advancements, processes, and collaboration. These features include interconnectivity, interoperability, virtualization, and automation, supported by digitization and optimization to streamline production processes and enable real-time adjustments [4, 17]. Models like those by Stock [18] emphasize both macro and micro perspectives, advocating for optimized value chains and Smart City integration. At the macro level, they highlight enhancing horizontal integration and optimizing value chains across various sectors. They also outline critical factors on the micro level, emphasizing equipment integration, skill development, organizational structure, and process optimization. Additionally, frameworks for manufacturing firms and smart factories prioritize technology integration and process optimization throughout the product life cycle [5, 18].

Another comprehensive framework for manufacturing firms and smart factories includes two crucial components: Industry 4.0 Technologies and Manufacturing Processes [19]. Models by Frank [21] focus on firm-level strategies that help companies adapt system architectures, integrate business processes, optimize supply chains, analyze performance data, enhance service orientation, digitalize operations, upskill the workforce, employ lean production, maintain strategies, and develop new business models [20, 21]

Despite their strengths, existing Industry 4.0 models often fall short in prioritizing environmental and social sustainability, fostering innovation and entrepreneurship, establishing robust communication and trust networks, ensuring data security governance, and securing regulatory and government backing. For instance, models like the Smart City framework focus on specific aspects like renewable energy but overlook broader environmental and social equity issues. Similarly, De Chiara's Ecosystem of Industry 4.0 emphasizes economic development but lacks comprehensive strategies for continuous innovation and entrepreneurship.

Given these limitations, this article aims to present a conceptual framework for integrating industrial clusters within the context of Industry 4.0 technologies. By defining industrial clusters and examining their components and benefits, we can explore how these clusters can drive collaboration, innovation, and sustainable growth. This framework seeks to address the gaps in existing models and provide a more comprehensive approach to Industry 4.0 adoption, benefiting policymakers and researchers in the pursuit of regional sustainable development.

2 FOURTH INDUSTRIAL REVOLUTION (INDUSTRY 4.0)

The concept of the 'fourth industrial revolution' emerges as a pivotal theme for the upcoming decades, embodying the seamless interaction between machines and humans through a plethora of innovations. These innovations span artificial intelligence, robotics, advanced materials, energy technologies, new computing paradigms, biotechnologies, geoengineering, neurotechnology, and space technologies across three fundamental dimensions: physical, biological, and digital, profoundly reshaping our social, environmental, and economic landscapes [22]. Since its inception in 2011, numerous studies have sought to define its features, labeling it as Industry 4.0, smart manufacturing, smart industry, and other terms [23].

Industry 4.0 heralds a transformative era in industrial evolution, characterized by the integration of cutting-edge digital technologies that collectively foster vertical and horizontal connectivity across organizations, manufacturing, supply chains, and systemic processes [24]. This revolution harnesses an array of technologies and foundational pillars such as the Internet of Things (IoT), cyber-physical systems (CPS), cloud computing (CC), 3D printing, additive manufacturing (AM), big data analytics (BDA), robotics, simulation, augmented reality, and cybersecurity to enhance operational efficiency and flexibility [19, 25]. The primary goal of Industry 4.0 is to propel enhancements across the entire value chain through digital transformation, stressing efficiency and environmental sustainability by addressing demands for expedited delivery, enhanced automation, superior quality, and personalized products facilitated by these technologies [26].

This revolution permeates modern information and communication technologies across all spheres of life, including cities, industries, manufacturing, and logistics, facilitating the transition from conventional to digital business models [20]. For instance, smart cities, pivotal in this revolution, utilize information and communication technologies to collect and analyze data, thus implementing innovations that bolster sustainability [6]. Noteworthy is that, while Industry 4.0 seemingly favors machines over humans and Industry 5.0 integrates human values with technology for sustainability, this article advocates for merging Industry 4.0 with human well-being, thus emphasizing sustainable development. The concept of smart specialization strategies, introduced by the OECD in 2013, amalgamates modern industrial and innovation policies, centering on transparency, progress tracking, and adaptable practices [24]. In the context of Industry 4.0, national competitiveness entails achieving heightened productivity, sustainable growth, and an elevated standard of living, while remaining receptive to international markets. Indeed, a new industrial wave is swiftly and prominently establishing itself across all societal strata.

Furthermore, the oversight in thoroughly investigating the adoption of new technologies at the regional level has been detrimental, particularly concerning the potential of industrial clusters as highly efficient solution in realizing the objectives of the fourth industrial revolution. These clusters, congregating complementary industries and fostering collaboration and innovation, inherently possess the capacity to propel advancements in technology adoption and integration. Neglecting their role in shaping regional technological policies could hinder progress and curtail the full realization of the transformative potential of Industry 4.0 within local economies [19].

2.1. Benefits and Challenges of Industry 4.0 Adoption

Industry 4.0 presents numerous benefits and challenges as countries worldwide integrate its technological advancements. Economically, it enhances efficiency, productivity, and flexibility while fostering innovation and sustainability. Work efficiency and productivity are maximized through reduced downtime, automation, and enhanced monitoring capabilities, creating opportunities for new jobs and entrepreneurship. Flexibility and customization enable adaptability and personalized experiences, though implementation complexity and increased production costs may arise [2]. Technological innovation and integration drive greater intelligence and innovation. Interconnectivity ensures seamless communication and data exchange, though data security and privacy concerns persist. Virtualization and digitalization transform traditional processes, enhancing responsiveness and decision-making, but robust cyber security measures are essential [10]. Collaboration fosters transparency and teamwork, yet organizational silos and data security remain challenges. Decentralization promotes agility, though coordination and synchronization are needed. Sustainability efforts maximize competitive advantages but must balance economic efficiency. Optimization strategies improve efficiency and operational excellence, though stakeholder resistance may arise. Service orientation prioritizes customer-centricity, yet consistency across channels is essential. Blockchain enhances transparency and efficiency but faces scalability and regulatory challenges. Smart applications drive efficiency and intelligence across sectors but require continuous innovation and data security considerations [1,9].

2.2. Challenges of Implementation I4.0

Successfully implementing Industry 4.0 demands addressing a multitude of challenges. These include securing skilled human resources amidst talent shortages and digital skill gaps, overcoming financial constraints associated with high initial investments and ongoing maintenance costs, and addressing infrastructure deficiencies like inadequate technological infrastructure and limited data storage capacity [17, 28]. Furthermore, ensuring cyber security and privacy, fostering leadership support, and nurturing a digital culture within organizations are crucial for successful integration. Collaboration barriers, employment disruptions, regulatory uncertainties, and environmental impacts further complicate the landscape. Overcoming these multifaceted challenges requires holistic strategies and careful consideration of societal and environmental implications [14, 21].

2.3. Elements and Frameworks for Implementation Industry 4.0

To review the framework for implementing Industry 4.0 and identify influencing factors, we will examine Industry 4.0 features, explore adoption factors at micro and macro levels, and focus on the smart firm’s model. Industry 4.0 is characterized by several key features that enhance technological, process, human-machine integration, communication, and collaborative innovation. Key technological elements include interconnectivity via the Internet, interoperability with Enterprise Resource Planning (ERP) systems, virtualization using Customer Relationship Management (CRM) and accounting systems, and information transparency through Big Data. These are supplemented by digitization and optimization to streamline and customize production processes, along with automation that preserves human decision-making in critical areas. Advanced interfaces enable effective human-machine interaction, adding value to services and allowing real-time process adjustments for optimal performance [4, 17].

Stock [18] also defined factors on the micro level, This model revolves around several critical factors. Firstly, in terms of **Equipment**, the emphasis is on integrating cutting-edge technologies such as robots, sensors, and cyber-physical systems (CPS) into manufacturing processes to enhance automation and efficiency. Secondly, the **Human** aspect entails the development of new skills among employees, implementation of real-time monitoring systems, and the management of short-term job roles to adapt to changing demands. **Organizationally**, the model advocates for a shift towards decentralized structures to foster agility and responsiveness. **Process**-wise, it involves the implementation of advanced techniques like 3D printing and additive manufacturing to revolutionize production methods. Finally, the focus on **Product** centers around ensuring closed-loop life cycles, enabling customization, and facilitating real-time adjustments in production to meet evolving market needs [29].

The Smart City model aims to enhance urban environments by integrating advanced technologies across various sectors. Key elements include a smart economy driving innovation, smart management enhancing governance through data-driven decisions, smart finance for financial accessibility and security, and smart infrastructure for sustainable city operations. It promotes smart citizens through digital literacy, a smart environment for ecological sustainability, and utilizes technologies like IoT, AI, and blockchain to improve urban living. Overall, this approach supports economic development, enhances public services, and promotes sustainability, making cities more livable and resilient [5].

A framework for smart factories includes Industry 4.0 Technologies and Manufacturing Processes. I4.0 Technologies integrate advanced tools like Cyber-Physical Systems (CPS), Internet of Things (IoT), Big Data, AI, Robotics, and Blockchain, creating adaptable manufacturing environments. Manufacturing Processes optimize production, supply chain, and life-cycle management for efficient manufacturing systems [19].

The framework by Frank [21] offers a tailored approach for individual firms to thrive in Industry 4.0. Divided into Front-End Tech and Base Tech, it emphasizes Smart Manufacturing, Smart Product, and Smart Supply Chain. Smart Manufacturing optimizes production with vertical integration, virtualization, automation, traceability, flexibility, and energy management. Smart Product enhances connectivity, monitoring, control, optimization, and autonomy. Smart Supply Chain utilizes digital platforms for efficient collaboration with suppliers, customers, and other entities. This framework aids companies in adapting system architectures, integrating business processes, optimizing value chains, integrating supply chains, analyzing performance, enhancing service orientation, digitizing operations, upskilling the workforce, implementing lean production, devising maintenance strategies, and developing new business models, thereby enhancing their competitiveness in Industry 4.0 [21].

The main shortcomings observed across the mentioned models entail a failure to prioritize environmental and social sustainability, a lack of thorough strategies for innovation and entrepreneurship, inadequate direction concerning communication and trust networks, shortcomings in data security governance, and deficiencies in regulatory standards and government backing. Overall, these models highlight the necessity for a more comprehensive approach to Industry 4.0 implementation.

Such an approach should prioritize environmental and social sustainability, foster innovation and knowledge transfer, and address communication and network issues, security concerns, and regulatory government support.

3 INDUSTRIAL CLUSTERS

For over two decades, industrial clusters have played a crucial role in fostering economic growth in both developed and developing countries for policymakers due to the significant advantages associated with them. Regarding the application of industrial clusters, various definitions have been employed in the literature. Alfred Marshall [30], a prominent economist of the late 19th and early 20th centuries, profoundly influenced the field of economics through his innovative perspectives on industrial organization. Among Marshall's significant contributions was his investigation into the concept of "localized industry," which bears resemblance to modern understandings of industrial clusters. Marshall's insights highlighted the importance of geographic concentration in industries, foreshadowing the critical role that agglomerations now play in stimulating economic growth [30]. Michael Porter pioneered the notion of industrial clusters, emphasizing the importance of agglomerations of related industries in driving economic growth, competitiveness and improving the overall performance of enterprises inside these clusters. Porter’s model has been extended by the Organization for

Economic Co-operation and Development (OECD), the UN, and many governments around the world [31, 32, 33].

Industrial clusters refer to geographic concentrations of interconnected networks of businesses, suppliers, and supporting institutions in a particular industry, sector, or value chain, aiming to enhance competitiveness, cooperation, innovation, and sustainable regional industrial development [34, 35].

The actors within industrial clusters encompass a diverse range of entities, collaborating within the cluster to foster an environment conducive to economic growth, innovation, and competitiveness. These actors include [36, 37, 38]:

- **Main Firms:** This category includes both leading firms and SMEs (Small and Medium-sized Enterprises) that drive innovation and production within the cluster.
- **Suppliers:** These are entities that provide essential materials, machinery, and other inputs necessary for the manufacturing processes.
- **Government and Policies:** Government bodies and policy-making institutions that create the regulatory framework, provide subsidies, and support infrastructure development.
- **Research Institutes:** Universities, R&D centers, and other research organizations that contribute to technological advancements and innovation.
- **Institutes:** This includes both profit and non-profit organizations that offer various services, support, and resources to firms within the cluster.
- **Market:** The market actors consist of local and non-local consumers and businesses that create demand for the cluster's products and services.

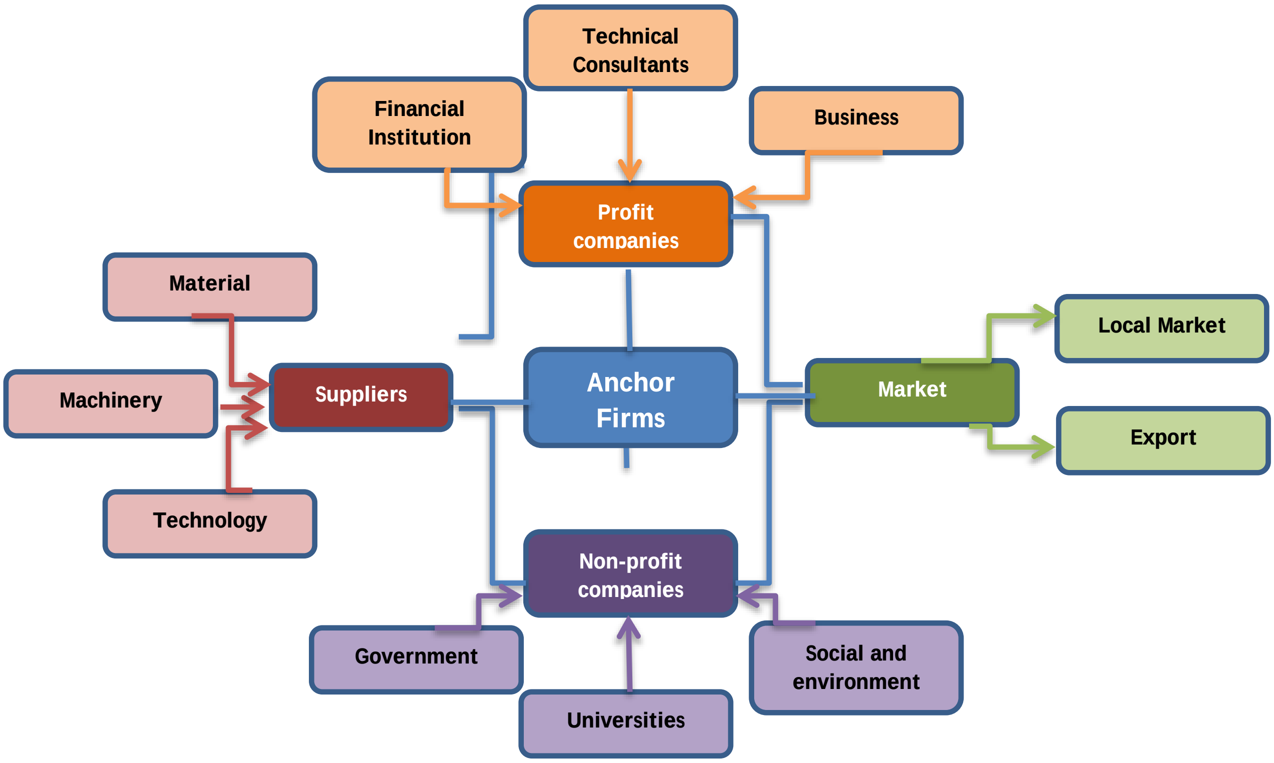

Figure 1: Industrial Cluster Actors [36, 37, 38]

In general, evaluating the contribution of industrial clusters to regional development can be divided into numerous groups based on various criteria. Researchers classify industrial clusters using various approaches tailored to specific requirements and objectives. These classification models help analyze the structure, dynamics, and characteristics of clusters based on factors such as industry sectors, geographical locations, technological capabilities, network connections, value chains, and innovation ecosystems. This diversity in classification provides insights into the strengths and challenges of clusters, aiding policy decisions, strategic planning, and economic development at different levels, as shown in Table 1. [39, 40].

By summarizing several research studies, the key elements for supporting the development of industrial clusters, outlined in Table 1, [17, 22, 41].

Table1: Key elements for supporting industrial cluster development

1	Networking (Supply chain and Value chain)
2	Innovative and knowledge management
3	Market and Economic factors
4	Geographical Concerns (Traditional, virtual)
5	Product nature (Life cycle, Complexity level)
6	Access to Resources (Materials, Technology, Human, Financial, Data)
7	Anchor Firms structure (Size, Location, Business model)
8	Infrastructure (Physical, Digital)
9	Suppliers and supportive institutes
10	Government and supportive policies (Training, Laws, International rules)
11	Social and environmental conditions

According to Table 1, Industrial clusters offer significant benefits for Industry 4.0 implementation by addressing key challenges through enhanced communication and networks, joint environmental and social initiatives to sustainability development, and robust innovation and knowledge transfer mechanisms. Clusters facilitate improved connectivity, collaboration, and real-time data sharing, which are essential for efficient supply chain integration. They promote green technologies and corporate social responsibility, helping to tackle environmental and social issues cost-effectively. Moreover, clusters support continuous R&D, attract skilled talent, and provide targeted training programs, fostering innovation. Additionally, they benefit from government support through favorable policies and infrastructure investment, ensuring a conducive environment for Industry 4.0 adoption [42, 43]. Over time, the significance of clusters has expanded beyond geographical proximity to encompass an innovative and knowledge transfer culture. Geographic location alone no longer defines clusters; innovation factors now play a vital role in new industrial clusters [29, 44].

4 DEVELOPING SMART INDUSTRIAL CLUSTER FRAMEWORK

Based on the research findings, it becomes evident that by using the advantages of industrial clusters, they can be employed to tackle the challenges presented by Industry 4.0. By integrating these two elements, we not only establish an appropriate framework for the adoption of new technologies but also enhance the smartness of industrial clusters. This will lead to increased efficiency in industrial clusters through the incorporation of essential elements such as flexibility, decentralization, digitization, virtualization, technological innovation, optimization, service-oriented approaches, and customization [10, 45].

The scope of studies on integrating industrial clusters with new technologies is limited due to the multidimensional nature of these clusters, involving stakeholders, networks, and diverse objectives. Therefore, presenting a single model for implementing new technologies at the entire cluster level is complex. Achieving such a framework requires drawing upon the mentioned models from various sectors. One of these models could be the establishment of a smart city framework. In the context of smart cities, it is crucial to take into account a range of smart components, including a smart economy, smart infrastructure, smart environment, smart technology, smart governance, and smart services [5, 46]. When implementing the Industry 4.0 ecosystem, however, four essential domains must be considered: the technology ecosystem, the people ecosystem, and the operations ecosystem, with some elements comprising users, devices, networks, technology, and the environment [22, 47]. These factors are examined in three layers: the physical layer, the analytical system layer, and the cyber layer [27]. This framework can also be divided into three sections: Industry 4.0 infrastructure, Big Data, and Industry 4.0 applications [4]. To address the complexities and multidimensional nature of industrial clusters and their integration with Industry 4.0 technologies, this article explores key models that facilitate the adoption of new technologies in table 2. These models help enhance connectivity, optimize processes, and improve flexibility within industrial ecosystems, offering insights into technology adoption stages and advancements for successful Industry 4.0 integration.

Table2: Frameworks and Key Factors for Implementing Industry 4.0

Ref	**Topic**	**Framework (Factors)**		
18, 46	Perspective of Industry 4.0	Macro level (Horizontal Integration/Value Chain)	Micro level (Life cycle/ Vertical Integration)	
		1.Smart Logistic 2. Smart Factory 3. Smart Costumer 4. Smart Grid 5. Smart Home 6. Renewable Energy 7. Mining 8. Cloud	1.Equipment (Robots, Sensors, CPS) 2. Human (New Skill, monitoring, short-term job) 3. Organization (Decentralization) 4. Process (3D, AM) 5. Product (Closed loop life cycle, customization, real time)	
48	Industry 4.0 Variables	1.Interconnectivity (Internet) 2. Interoperability (ERP) 3.Virtualization (CRM, Accounting) 4.Collaboration 5. Information Transparency(Big Data) 6.Technologies (Website, 3D, Robots)	Smart Factory Layers	1.physical layer 2.Transferring data Layer 3.Support Layer
19	Factors to implement Industry 4.0	1.Smart Factory 2. Research and Innovation	3. Digitalization 4.Training system	5. Human-centered society 6.Government support
20	Supply Chain digitalization framework	1.Physical SC -Supplier -Factory -Wholesaler -Retail	2.Analytical System Supply Chain -Forecasting -Optimization -Simulation -Real time	3.Cyber (Big data) -Material data (ERP) -Manufacturing data (3D, Robots, VR, AR, Sensors) -Logistic Data (Tracking and Transformation) -Sales Data (Blockchain)
49	Digital Industry 4.0 Ecosystem	1.Infrastructure 2. human resource 3. manufacturing	4.Management 5. Marketing and sales 6. Technology development 7. Procurement service	
49	Factors to assess levels of the Industry 4.0 digital ecosystem	1. Customer Solutions ecosystem (platforms, market, financial, product, CRM)	2. The Operations ecosystem (Digital procurement, smart research, product life cycle, after sale service, smart manufacturing, logistic)	3. The Technology ecosystem (people ,technology, Innovation)
6	Indicators to assess smart city	1.Economic and management 2.Quality of Life	3.Environment 4.Innovation	
6	Smart city elements	1. Smart economy 2. Smart management 3. Smart finance	4. Smart infrastructure 5. Smart citizens 6. Smart environment 7. Smart technologies	
50	strategic guidelines for 4IR	1. Research and innovation 2. Work, education and training 3.Infrastructure modernization 4. Business environment 5.Reference architecture, standards and norms	6. Green manufacturing: 7. Legal framework 8. Security of networked systems 9.Internationalization 10 Industry showcasing	

Ref	Topic	Framework (Factors)		
4	Framework I4.0 in manufacturing firm	1.I4 Technologies CPS, IoT, Big Data, Cloud, AI, Virtualization ,Robots, Additive Manufacturing ,Block chain, Simulation	2. Manufacturing Process 2.1.production Operation System Internal Logistic, Scheduling, Energy, Quality, Maintenance management 2.2.Supply Chain Management (SC Configuration, Integrated Sc planning 2.3.Life-Cycle Management (New Product Development)	
21	Framework of Industry 4.0 Implementation	1.Front-End Tech 1.1.Smart Manufacturing (Vertical integration, Virtualization, Automation, Traceability, Flexibility, Energy management) 1.2. Smart Product (Product's connectivity Product's monitoring Product's control Product's optimization Product's autonomy)	1.3.Smart Supply Chain (Digital platforms with suppliers Digital platforms with customers Digital platforms with other company Units) 1.4.Smart Working (Remote monitoring, Remote operation, Augmented reality for maintenance Virtual reality for workers training , Collaborative robots)	2.Base Tech (IoT, Big Data, Analytic, Cloud)

Furthermore, one of the most effective Industry 4.0 theoretical frameworks highlights two key dimensions: base technologies and front-end technologies. This framework emphasizes the increasing complexity and implementation of Industry 4.0 technologies across smart supply chains, smart manufacturing, smart workspaces, and smart products. It maps the progression from the initial integration stage (basic systems and technologies) to the automation and virtualization stage (advanced AI, IoT, and robotics), and ultimately to the flexibilization stage (autonomous and real-time adaptive systems) of adoption [51].These stages, their respective focuses, and the types of technologies can be summarized in Table 3.

Table 3: Industry 4.0 Adoption Stages and Technologies

Stages	Technologies	Focus
Stage 1: Initial Integration	Embedded Sensors, Basic IoT, Basic ERP Systems, Basic Energy Management Systems, Basic Cloud Platforms, E-learning Platforms, Basic Market Data Collection Tools, Initial Sustainability Programs, Firewalls, Basic Encryption	Establishing connectivity, basic data collection, and initial automation
Stage 2: Automation & Virtualization	Advanced Analytics, Predictive Analytics, Collaborative Research Platforms, Advanced Communication Networks, Efficient Data Processing and Storage, Adoption of Sustainable Manufacturing Technologies, Advanced Network Security Solutions	Enhancing automation capabilities and data analytics
Stage 3: Flexibilization	AI and Machine Learning for Autonomous Systems, AR/VR Integration, Real-time Data Analysis with Advanced AI, Autonomous Logistics Systems, Advanced Training with AR/VR, AI-driven Workforce Management, Proactive and Autonomous Cyber-security Systems	Achieving autonomy, flexibility, and agility in processes through advanced technologies

Then by using the models introduced in the article, we propose a new framework (table 4) for the adoption of Industry 4.0 technologies within industrial clusters, aiming to transition towards smart industrial clusters.

Table 4: Integrated Framework for Implementing Industry 4.0 in Industrial Clusters

Factors & Layers	Stage 1. Initial Integration	Stage 2. Automation and Virtualization	Stage3. Flexibilization
Smart Product	• Passive Smart Products: Embedded Sensors • Monitoring and Remote Capabilities: Basic IoT	• - Active Smart Products (Optimization Capabilities): Basic AI • Remote Operation: IoT with Remote Control	• Autonomous Smart Products: AI and Machine Learning • Augmented and Virtual Reality: AR/VR Integration
Smart Factory	• ERP: Basic ERP systems • MES: Manufacturing Execution Systems • SCADA: Supervisory Control and Data Acquisition • Sensors and Actuators: Basic IoT Sensors • Energy Management: Basic Systems • Traceability: Barcode/RFID for tracking	• Automated Nonconformities Management: Basic AI • AI for Quality: Machine Learning Algorithms • Industrial Robots: Basic Automation • M2M Communication: Machine to Machine Communication • AI for Production: Advanced Analytics	• Autonomous Production Systems: AI-Driven Systems • Real-Time Data Analysis: Advanced AI • Flexible Lines and Robots: Advanced Robotics with AI Optimization and additive manufacturing
Smart Supply Chain & logistics	• Digital Platforms with Other Companies' Units: Basic Cloud Platforms • Cloud: Cloud Computing Services	• Digital Platforms with Suppliers: Enhanced IoT Integration • IoT: IoT Sensors and Devices • Blockchain: Basic Blockchain for Traceability • Smart Warehousing: IoT for Inventory Management • Basic Tracking Systems: RFID, GPS	• - Big Data: Advanced Data Analytics • Analytics: Predictive Analytics • Blockchain: Full Integration for Supply Chain Transparency • Autonomous Logistics Systems: Autonomous Vehicles, Drones • Use of Drones for Delivery and Logistics: Advanced UAV Systems
Smart Working	• Basic Digital Training Tools: E-learning Platforms	• Advanced Training with AR/VR: AR/VR Devices	• AI-Driven Workforce Management: AI Systems for HR

Factors & Layers	**Stage 1. Initial Integration**		**Stage 2. Automation and Virtualization**	**Stage3. Flexibilization**
	• Basic Monitoring and Collaborative Robots: Basic IoT, Basic Robotics		• Collaborative Robots: Enhanced Robotics for Collaboration	• Advanced Collaboration Tools: Integrated Platforms
Smart Market & Costumer Engagement	• Basic Market Data Collection and Analysis: CRM Systems, Basic Analytics Tools		• Customer Insights through Big Data: Advanced Analytics Platforms • Enhanced Digital Marketing Platforms: AI Tool	• Predictive Market Analysis with AI: Advanced Predictive Algorithms • Advanced CRM Systems: AI-Driven CRM Systems • Personalized Customer Interaction Platforms: AI-Enhanced CRM
Smart Research & Innovation	• Basic Research Initiatives: Initial Funding Programs • Establishment of Innovation Hubs: Basic infrastructure		• Collaborative Research Platforms: Digital Collaboration Tools • Increased Funding for Innovation: Government Grants	• Advanced Research Networks: AI and Big Data Integration • Innovation Hubs with Real-Time Data Exchange: IoT and Cloud
Smart Government Support	• Policy Frameworks: Basic Regulatory Support • Initial Incentives for Adoption: Financial Incentives		• Expanded Incentive Programs: Grants and Subsidies • Support for R&D Initiatives: Research Funding	• Fully Integrated Smart Governance System: Digital Governance Platforms • Real-Time Policy Adjustments: AI Tool
Smart Infrastructure	Physical	• Basic IoT Sensors and Connectivity: Initial IoT Setup • Advanced Communication Networks: High-Speed Internet	• - Advanced Communication Networks: 5G • Enhanced IoT Infrastructure: Comprehensive IoT Systems	• Fully Scalable and Integrated Smart Infrastructure: Advanced IoT and Cloud Platforms
	Data and Analytical	• Data Collection Systems: Basic Databases • Efficient Data Processing and Storage: Cloud Solutions	• Efficient Data Processing and Storage: Big Data Platforms • Initial Data Governance Frameworks: Compliance Tools	• Advanced Data Analytics: Predictive Analytics • Comprehensive Data Governance and Privacy Management: AI for Data Management
Smart Environmental and Energy Management	• Implementation of Basic Green Practices: Initial Sustainability Programs • Basic Energy Monitoring Systems: Initial IoT Sensors		• Adoption of Sustainable Manufacturing Technologies: Green Tech Integration • Environmental Monitoring Systems: Basic Sensors • Optimized Energy Usage through Advanced Monitoring: Smart Meters • Implementation of Energy-Efficient Technologies: Green Tech	• Full Integration of Circular Economy Practices: Advanced Sustainability Programs • Real-Time Environmental Impact Analysis: IoT and Big Data • Integration with Smart Grids: IoT and AI • Renewable Energy Sources: Advanced Integration with Green Energy
Smart Security and Networks	• Basic Cyber security Measures: Firewalls, Basic Encryption		• Advanced Network Security Solutions: AI-Based Security Tools	• Proactive and Autonomous Cyber security Systems: AI-Driven Security, Advanced Threat Detection

Factors & Layers	**Stage 1. Initial Integration**	**Stage 2. Automation and Virtualization**	**Stage3. Flexibilization**
		• Implementation of Security Protocols: Enhanced Encryption	

5 CONCLUSION

In this study, an effort has been made to utilize industrial clusters as effective solution to develop strategies for transitioning from the traditional industrial era to the Fourth Industrial Revolution. By exploring the potential of industrial clusters, our research introduces a conceptual framework to enhance these clusters. The main goal of this framework is to identify essential criteria for developing smart industrial clusters, focusing on various Industry 4.0 technologies. We outline ten layers, including smart product integration, factory optimization, supply chain efficiency, workforce, innovation, customer engagement, policy support, infrastructure enhancement, environmental sustainability, and network security, each influenced by different new technologies. By structuring this framework with an emphasis on economic, social, and environmental aspects, we anticipate achieving greater innovation, competitiveness, market share, and sustainable development within smart industrial clusters. Implementing this framework will require thorough studies tailored to each cluster's nature and level of industrial development. So far, we have presented a conceptual framework and key elements derived from existing literature. While industrial clusters can be effective in adopting Industry 4.0 technologies and policies, our study is limited by insufficient research on their role in technology transition and a lack of practical studies with access to executive data. Consequently, the proposed framework remains conceptual. Future research should focus on implementing this framework across various industrial clusters, analyzing each new technology's role, and making necessary adjustments accordingly.

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ENERGY INNOVATION OPPORTUNITIES IN HIGH ENERGY CONSUMING SECTORS IN SOUTH AFRICA

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ABSTRACT

This paper provides a perspective on energy innovations in high-energy consuming sectors in South Africa. Despite South Africa’s high energy consumption, innovation adoption is sub-optimal. We investigated the research question: How are energy innovations implemented within high-energy consuming sectors in South Africa? Following an appropriate research methodology focused on a scoping literature review, we thematically synthesized 35 studies from diverse databases. The study revealed some significant findings under five thematic areas: Technological Innovations, Innovation Management Strategies, Socio-Cultural and Gender Considerations, Policy Influence, and Application of Energy Innovations. The synthesis accentuates the role of 4IR technologies, Complex Adaptive Systems (CAS), and gender-responsive approaches in fostering sustainable energy practices. The results of this study contribute to the existing literature by providing a structured review and novel insights into South Africa’s energy landscape that may assist in the formulation of strategic and informed energy policies.

Keywords: Energy Innovation, High-Energy Consuming Sectors, Sustainable Energy Policies

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1 INTRODUCTION

As the world approaches the cusp of the Fourth Industrial Revolution (4IR), there is an unparalleled emphasis on productivity and economic growth, resulting in a surge in energy consumption. This evolving landscape requires forward-thinking and optimised energy resources management, particularly within high-energy-consuming sectors such as manufacturing, mining, and utilities [1]. High-energy-consuming sectors refer to industries that consume significant amounts of energy, including electrical energy, coal, gas, and liquid fuels.

South Africa, one of Africa's most industrialised nations, faces an intricate energy challenge. Dominated by an aging coal-based infrastructure with high carbon emissions and inefficiency, the country's energy landscape poses significant challenges to industrial growth [2]. Frequent electricity load-shedding further compounds these problems, with substantial impacts on the industrial sector, which accounts for nearly 40% of the nation's total energy consumption [3].

In this context, energy innovation emerges as a pivotal strategy, encompassing the application of novel technologies, policy reform, capacity building, and user engagement to transform energy production, distribution, and consumption [4]. Advanced technologies such as Artificial Intelligence (AI), Internet of Things (IoT), Big Data, and Machine Learning (ML) open new avenues for energy management within the industrial sector, though they bring challenges, including technological hurdles, financial constraints, and regulatory bottlenecks [5].

Despite these barriers, energy innovation is vital for enhancing energy efficiency, sustainability, and resilience within South Africa's industrial sector amid global energy transitions. This scoping review aims to provide an in-depth examination of the current literature on energy innovation opportunities within South Africa's high-energy-consuming sectors, considering principles of industrial management and systems engineering [6]. By exploring existing literature, this review will augment understanding, identify knowledge gaps, and lay the groundwork for future research, guiding stakeholders in harnessing energy innovation for sustainability and efficiency [7].

2 STUDY CONTEXT

The South African energy sector, with particular emphasis on high-energy-consuming industries such as mining, manufacturing, and utilities, presents an intricate landscape fraught with various challenges. A significant challenge is the frequent instances of load-shedding, mainly as a consequence of dependence on coal-powered plants and outdated infrastructure [8]. This scenario underlines the urgent need for broad-ranging research and innovation aimed at optimizing energy consumption within these industries, a matter that extends beyond simply incorporating alternative energy sources.

2.1 Growing scholarly interest in energy innovation

The number of hits for "energy innovation" has increased significantly in the past 15 years, from 29,700 in 2009 to 3,621,600 in 2023. This growth shown in Figure 1 reflects a growing interest in the research area of energy innovation. The significant spike in 2016 can be attributed to increased global focus on sustainable development goals and the Paris Agreement, which heightened interest and research in energy innovation.

The Fourth Industrial Revolution (4IR) has brought to the fore complex tools like Cognitive Computing, Networked Devices, Big Data Analysis, and Intelligent Algorithm Processing [9]. The right application of these technologies could unlock considerable opportunities for improving energy management. Yet, there exists a significant gap in the literature and in practice concerning the efficient integration of these technologies within South Africa's high-energy-consuming sectors.

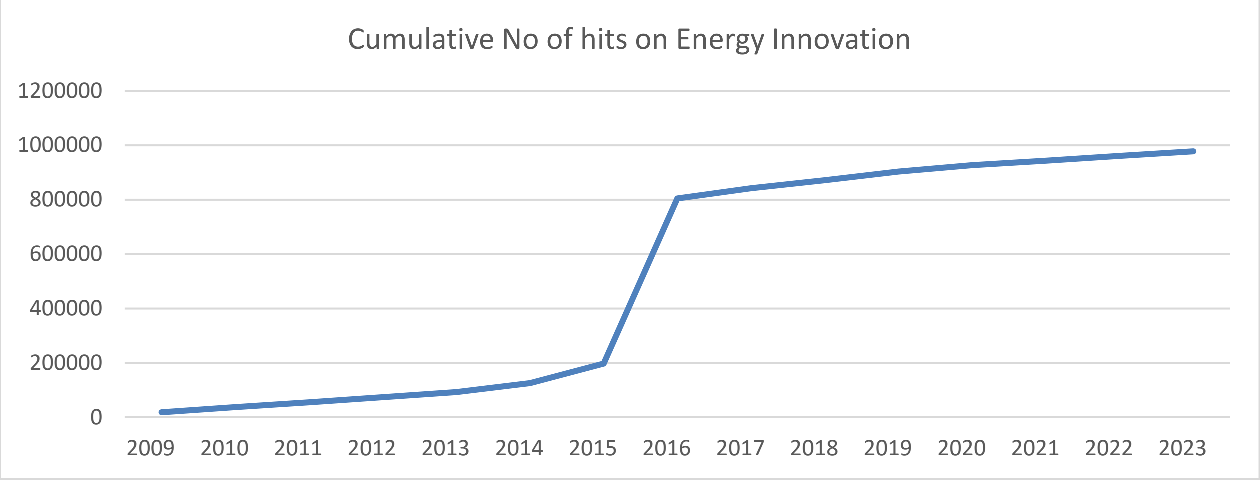

Figure 1: Cumulative Number of Google Scholar Hits for "Energy Innovation"(2009-2023)

Engineering and systems sciences champion a holistic approach to managing complex systems throughout their life cycles [10]. This perspective, in the context of South Africa's energy crisis, can provide valuable insights for formulating sustainable energy management strategies, optimizing the infrastructure life cycle, and implementing smart-grid technologies. However, this necessitates extensive research to map the landscape and pinpoint potential areas for innovation.

Issues such as equipment theft at power stations, allegations of incompetencies, and political interference complicate South Africa's energy landscape. While these matters predominantly fall outside the engineering domain, it is crucial to investigate how engineering innovations can help mitigate these problems, possibly through theft detection technologies, Artificial Intelligence and Machine Learning applications for efficiency enhancement, and smart technologies for infrastructure monitoring. South Africa's energy policy exerts a significant influence over the energy landscape [11]. Therefore, understanding how this policy can better encourage and foster innovative initiatives is a crucial area of study. Applying engineering management principles to inform policy decisions based on technical feasibility studies, cost-benefit analyses, and impact assessments is a topic that merits further exploration.

Through this scoping review, our goal is to develop a more detailed understanding of the study context, identify key knowledge gaps, and chart potential research avenues for energy innovation within South Africa's high-energy-consuming sectors. This approach will ensure that we maintain a balanced and objective perspective, acknowledging the complexities of the situation without prematurely proposing solutions.

3 MATERIALS AND METHODS

This review followed a six-stage process for conducting scoping reviews: (1) establishing the research questions; (2) locating pertinent studies; (3) shortlisting articles; (4) extracting information; (5) summarizing, analysing, and presenting the findings; and a possible sixth stage, which entails consultations. PRISMA-Scar guidelines were employed to ensure quality in reporting the findings [12].

3.1 Defining research questions

The primary research question (RQ) was, "How can energy innovation improve the resilience and efficiency of high energy-consuming sectors in South Africa amidst electricity load-shedding?" To deepen our exploration of this core issue, we developed two sub-questions (RQ1 and RQ2). The initial sub-question (RQ1) examined how these sectors are responding and adapting, with a particular emphasis on energy innovations:

- What forms of technology and innovations have been employed in these sectors to mitigate the impact of load-shedding?

The second (RQ2) focused on the purposes of these energy innovations:

- What are the main objectives of these energy innovations, and how do they contribute to mitigating the impacts of load-shedding?

3.2 Identification of studies

Research sources were selected from databases that focus on engineering sciences and technology, including online repositories like the Institute of Electrical and Electronics Engineers' digital library, Elsevier's comprehensive full-text scientific database, Springer's international publishing platform, and the widespread academic search engine Google Scholar. We utilized keywords such as "energy innovation," "high-energy consuming sectors," "South Africa," "load shedding," "renewable energy," "energy efficiency," and "4IR technologies."

Time Period Limitation (2022-2023): The focus on the 2022-2023 period aligns with the exploratory nature of this study, which aims to capture the most recent developments in energy innovation. This targeted approach allows for the identification of current trends and gaps, setting the foundation for more detailed future research that will encompass a broader time frame.

Keywords and Inclusion/Exclusion Criteria:

- **Keywords:** The search included keywords such as "energy innovation," "high-energy-consuming sectors," "South Africa," "load shedding," "renewable energy," and "sustainability." These were selected to capture studies relevant to the study's objectives.
- **Inclusion/Exclusion Criteria:** The inclusion criteria focused on peer-reviewed studies directly related to the keywords, particularly within the South African context. Studies outside the 2013-2023 timeframe, non-peer-reviewed sources, and those not addressing the specified thematic areas were excluded.

Sector Inclusion: The study focused on sectors like mining, manufacturing, and utilities due to their high energy demands. While some sectors are spared from load shedding through Eskom's load curtailment program, the emphasis was on how these sectors are leveraging innovations to ensure responsible and sustainable energy use, independent of load shedding status.

Role of Load Shedding in Inclusion/Exclusion: Load shedding was considered a critical energy challenge, but it was not the primary criterion for inclusion. The study's broader focus was on how energy innovations address energy constraints and enhance sustainability across high-energy-consuming sectors. This approach allowed for the inclusion of studies relevant to energy innovation beyond the scope of load shedding.

3.3 Selection and handling of studies

In handling the selection of studies, duplicate entries were effectively organized using a reference management tool. The selection procedure consisted of two phases: an initial screening of abstracts followed by a comprehensive assessment of the complete texts, guided by pre-established inclusion and exclusion parameters. The screening task was shared between two separate researchers who agreed on 97% of the selection, thereby making the involvement of a third researcher unnecessary.

3.4 Data extraction and charting

Data was extracted into Excel spreadsheets designed in line with RQ1 and RQ2, enabling the synthesis of significant themes and assigning codes to aid in subsequent analysis where applicable.

3.5 Study analysis, summarising, and reporting of results

Our review utilized the three-phase approach recommended for scoping reviews, including data analysis, result presentation, and interpretation of the findings. Specifically, we utilized a six-stage process for thematic content examination and synthesis that comprised data familiarization, initial code assignment, theme exploration, theme review, theme finalization, and report creation. The cumulative outcomes were presented in accordance with the PRISMA-Scar guidelines, culminating in a comprehensive report featuring a tabulated thematic synthesis intended to address the initial research questions [12].

3.6 Consultations

We incorporated consultations in our study, consistent with the scoping review methodology, to gain additional insights and perspectives relevant to the research scope. Preliminary results were discussed with experts in energy management, policy making, and 4IR.

4 STUDY RESULTS

4.1 Overview of included results

Our primary database exploration produced a total of 172 records (IEEE Xplore: 18, Science Direct: 21, SpringerLink: 33, Google Scholar: 100). The detailed findings and thematic synthesis of these records are presented in Table 2. Following the removal of 15 duplicate entries, 157 articles remained for title and abstract screening. Post-screening, 106 articles were excluded, leaving 51 for full-text evaluation. Upon further scrutiny, 13 of these 51 articles did not meet the inclusion requirements and were thus excluded.

The reference lists of the remaining 38 full-text studies were examined to discover additional relevant studies. Two more records were identified through the manual scanning of reference lists, and six more were found during a hand search on the internet. The final synthesis, therefore, included a total of 46 records.

Of these 46 records, 40 were journal articles, shedding light on various aspects of energy innovation and their employment within South Africa's sectors that use large quantities of energy. Six remaining documents were sourced from grey literature. These included a book exploring the evolution of South Africa's energy landscape via pioneering technologies, two reports examining the usage of renewable energy and energy-conservation technologies in industrial sectors, a working paper emphasizing the need for innovation in energy efficiency, and two book chapters discussing the impact of energy innovation in the backdrop of South African industries.

Further details regarding the study selection process can be found in the PRISMA flow diagram shown in Figure 1.

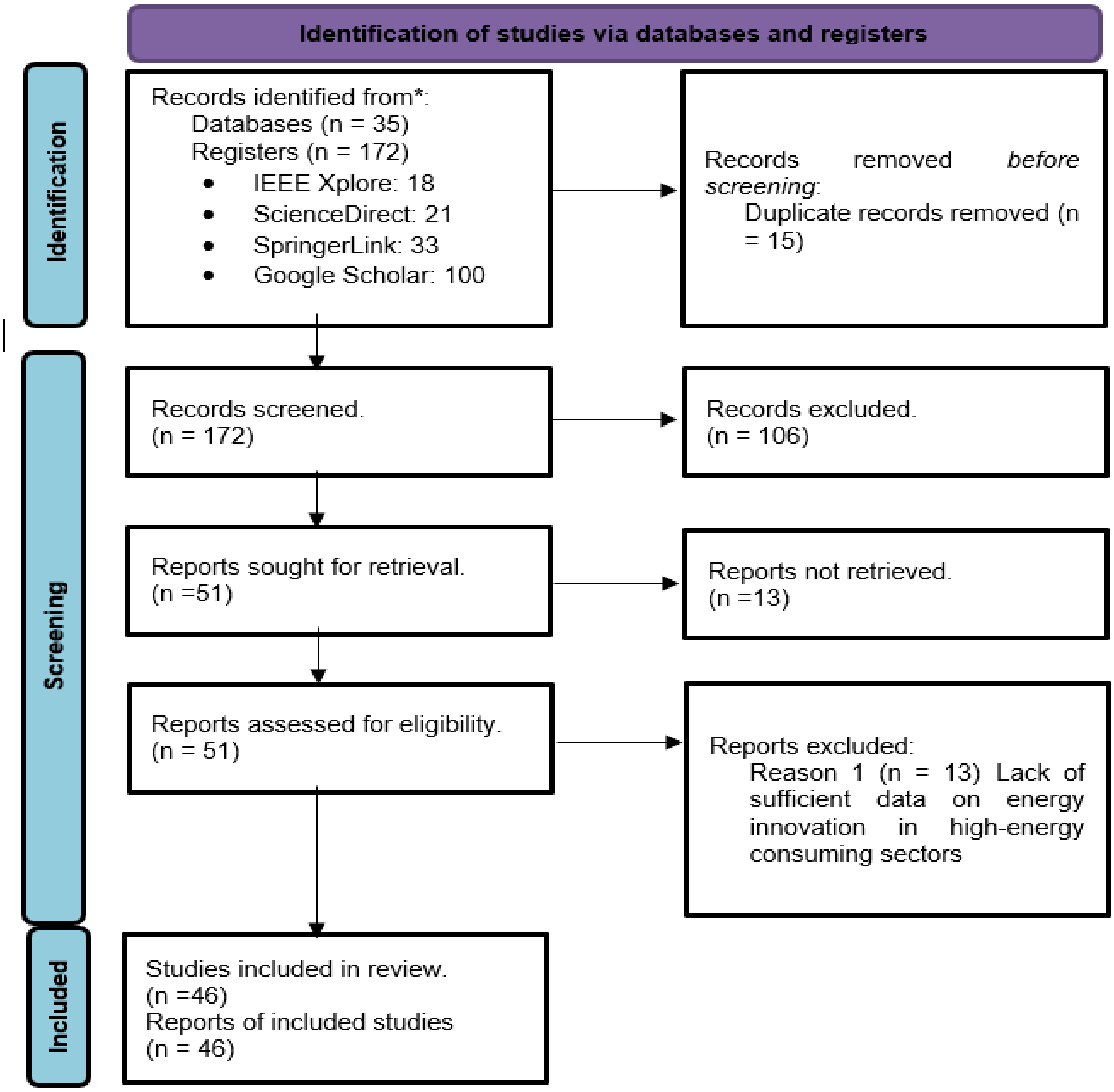

Figure 2: Prisma Flow Diagram

4.2 Thematic synthesis to respond to research questions

This section synthesizes the thematic classes and key domains identified in the scoping review to directly address the research questions guiding this study. The 19 thematic classes and 5 key domains provide an integrative framework for analysing the role and impact of energy innovations within South Africa's high-energy-consuming sectors.

4.2.1 Technological innovations: enhancing energy efficiency and system reliability

Research Question 1 (RQ1): *What are the varieties of energy innovations within South Africa's high-energy-consuming sectors?*

In response to RQ1, technological innovations emerged as a central theme, encompassing advancements in renewable energy technologies (e.g., photovoltaic solar energy, wind turbine technologies, bioenergy solutions) and energy efficiency technologies (e.g., energy management systems, advanced insulation, high-efficiency HVAC systems). These innovations are critical in enhancing energy efficiency and improving system reliability across various industries. For example, the implementation of smart grids and AI-based energy management systems has enabled real-time energy monitoring and predictive maintenance, which are essential for reducing carbon emissions and optimizing energy usage. This alignment of technology with operational goals illustrates how South Africa’s high-energy-consuming sectors are adapting to the evolving energy landscape.

4.2.2 Innovation management strategies: driving industrial transformation

Research Question 2 (RQ2): *How are these energy innovations implemented, and what are their impacts on high-energy-consuming sectors in South Africa?*

To address RQ2, the study highlights the role of innovation management strategies in driving industrial transformation and energy efficiency. Complex Adaptive Systems (CAS) and the integration of Social, Economic, and Environmental (ISEE) parameters are central to managing the dynamic interactions within industrial energy systems. These strategies not only optimize processes and automate operations but also enhance overall productivity while ensuring sustainable energy practices. CAS, for instance, provides a framework for industries to adapt to energy challenges dynamically, fostering resilience and long-term sustainability.

4.2.3 Socio-cultural and gender considerations: informing policy and innovation

The inclusion of socio-cultural and gender considerations within the broader energy innovation discourse is crucial for creating inclusive and equitable energy solutions. By addressing gender disparities and integrating social sciences into energy policy, South Africa can develop more effective, socially responsive energy strategies that support a just transition to greener energy sources. This approach ensures that the benefits of energy innovations are distributed equitably across all segments of society, including marginalized groups, thereby reinforcing the socio-cultural dimensions of sustainability.

4.2.4 Influence of policy and R&D intensity: shaping energy diversification and security

Government policies and R&D intensity play a pivotal role in driving energy diversification and shaping the future of South Africa's energy landscape. Policies that promote renewable energy integration, support regulatory changes, and incentivize R&D in energy technologies are essential for reducing the country's reliance on fossil fuels and enhancing energy security. These policies not only accelerate the adoption of innovative energy technologies but also create a favourable environment for sustained energy innovation, positioning South Africa as a leader in the global energy transition.

4.2.5 Application of energy innovation: transforming industrial and commercial sectors

The practical application of energy innovations in industrial and commercial settings underscores the transformative potential of these technologies. Deploying energy-efficient designs, real-time monitoring systems, and other innovative technologies has enabled these sectors to significantly reduce energy consumption, improve operational effectiveness, and contribute to national sustainability goals. These applications demonstrate how energy innovations are not just theoretical concepts but are actively reshaping the energy dynamics within South Africa's high-energy-consuming sectors.

5 DISCUSSION

This section discusses the synthesized findings from the systematic literature review, providing valuable insights into the current state of energy innovation in high-energy-consuming sectors in South Africa. These findings directly address the research questions guiding this study and illustrate the diverse approaches and innovations implemented across various sectors, as summarized in Table 2.

Table 1: Thematic synthesis of reviewed literature

Key Themes	**References**
Technological Innovations Artificial Intelligence (AI) and Machine Learning (ML) Fourth Industrial Revolution (4IR) Technologies Renewable Energy (RE) Technology Innovations	[5, 13, 18, 19, 20, 27, 28, 41]
Innovation Management Strategies Complex Adaptive Systems (CAS) Integration of Social, Economic, and Environmental (ISEE) Parameters The Role of Systems Engineering in Renewable Energy	[4, 5, 6, 20, 21, 22, 29, 30]
Socio-Cultural and Gender Considerations in Energy Innovation Gender in Energy Innovation Role of Social Sciences	[6, 7, 8, 9, 23, 24, 31, 32]
Influence of Policy and R&D Intensity Government Policies and R&D Intensity New Energy Paradigm for South Africa	[2, 12, 17, 24, 25, 26, 35, 36]
Application of energy innovation Commercial Properties	[8, 25, 32, 37, 39, 40]

5.1 Prevalent energy innovations in high-energy consuming sectors

Research Question 1 (RQ1): *What are the varieties of energy innovations within South Africa's high-energy-consuming sectors?*

The thematic synthesis, highlighted in Table 1, reveals a broad spectrum of energy innovations deployed across high-energy-consuming sectors in South Africa. Renewable energy technologies, including solar photovoltaics, wind turbines, and bioenergy, are particularly prominent [5, 13]. These technologies not only reduce dependency on fossil fuels but also contribute significantly to the reduction of carbon emissions, aligning with global sustainability goals [18, 19]. The widespread adoption of energy efficiency technologies, such as advanced insulation and energy management systems, is also notable. These innovations play a critical role in curbing energy consumption, thereby enabling more cost-effective operations and lowering environmental impacts [20, 27].

5.2 The Role of Digital Technologies in Energy Innovation

Research Question 2 (RQ2): *How are these energy innovations implemented, and what are their impacts on high-energy-consuming sectors in South Africa?*

Digital technologies are increasingly central to energy innovation, as demonstrated by the growing adoption of AI-based energy management systems and big data analytics for energy analysis [28, 41]. These technologies enhance predictive maintenance, improve demand response, and optimize energy use, leading to substantial cost savings and environmental benefits. The integration of such technologies highlights a shift towards more intelligent and responsive energy management practices, which are essential for enhancing the efficiency and resilience of high-energy-consuming sectors.

5.3 Adoption and Impact of Energy Innovations

The adoption of energy innovations varies across sectors, influenced by sector-specific challenges, financial constraints, and the regulatory environment [29]. Understanding these varying adoption rates is crucial for developing effective policies and strategies that promote broader uptake of energy innovations. Despite these challenges, the positive impact of these innovations on energy efficiency and carbon emissions reduction is evident. The implementation of renewable energy technologies, energy efficiency measures, and digital innovations has significantly contributed to advancing energy sustainability in high-energy-consuming sectors [30].

5.4 Future Directions for Energy Innovation in South Africa

South Africa's evolving energy landscape presents both opportunities and challenges for energy innovations. The country's abundant renewable energy resources and commitment to reducing carbon emissions create a conducive environment for the growth of energy innovations [31]. However, challenges such as infrastructural limitations, financial barriers, and policy uncertainties may impede widespread technology adoption [32]. Addressing these challenges requires a collaborative effort from stakeholders, including policymakers, industry players, and researchers. By leveraging these opportunities and overcoming obstacles, South Africa can harness the full potential of energy innovations to achieve sustainable development goals.

6 IMPLICATIONS FOR FUTURE RESEARCH

The findings of this review underscore several key areas for future research, vital for enhancing energy innovation in South Africa’s high-energy-consuming sectors. Firstly, the legal frameworks and licensing for emerging technologies remain ambiguous, necessitating further investigation and clarification [33]. Secondly, there is a critical need to focus on quality assurance and skills development to ensure the effective deployment of these technologies across various sectors [34]. Additionally, understanding the technical aspects, such as standards for interoperability, infrastructure requirements, and platforms, is essential for integrating new technologies like AI, IoT, and Big Data into existing systems [35]. Lastly, research is required to explore the financial dynamics associated with these innovations, including cost-effectiveness, funding opportunities, and incentives for adoption [36]. Tailoring these research efforts to specific sectors can significantly enhance the formulation of robust energy strategies [37].

7 RESEARCH LIMITATION

This study acknowledges certain limitations that may have influenced the results. Firstly, due to the exploratory nature of our research questions, the study could only provide a broad examination of various aspects of energy innovation [12]. This calls for more detailed studies focusing on specific areas within energy innovation. Secondly, we limited our review to papers published in English, which could have introduced a language bias and potentially excluded relevant studies conducted in other languages. Additionally, the study period was confined to the years 2022 to 2023. This time constraint might have excluded important innovations and studies published outside this period. Moreover, the absence of explicit quality assessments of the included studies is an inherent limitation of scoping reviews, which could have affected the reliability of our findings [12]. Despite these limitations, we believe this study offers structured insights into the evolving landscape of energy innovation in high-energy-consuming sectors in South Africa, providing valuable guidance for future research.

8 CONCLUSION

This study aimed to answer two critical research questions concerning the role and impact of energy innovation in South Africa's high-energy-consuming sectors. **Research Question 1 (RQ1)** sought to identify the varieties of energy innovations in these sectors, while **Research Question 2 (RQ2)** focused on understanding how these innovations are implemented and their impacts.

The review identified a diverse array of energy innovations, ranging from renewable energy technologies to advanced energy efficiency measures. These innovations are pivotal in enhancing sustainability, efficiency, and productivity within these sectors. As summarized in Table 2, the thematic areas explored in this study highlight the significant potential of energy innovations in transforming South Africa's high-energy-consuming sectors. The uptake of these innovations is critical in addressing current and future energy challenges, offering solutions that reduce carbon emissions and enhance energy security.

However, the integration of these innovations is not without challenges. Policy constraints, financial considerations, and infrastructural barriers present significant obstacles to widespread adoption. This calls for strategic planning, robust research, and interdisciplinary collaborations among policymakers, stakeholders, and academia to develop an environment conducive to energy innovation.

Moreover, the implications for the field of engineering sciences are profound. Energy innovation challenges existing theories and practices, necessitating a multidisciplinary approach that incorporates elements from environmental science, economics, policy studies, and engineering. As South Africa continues to grapple with energy crises and climate change, it is essential for the engineering community to remain adaptive and responsive to these evolving challenges.

In conclusion, while the potential of energy innovation in transforming South Africa’s high-energy-consuming sectors is substantial, realizing this potential requires a concerted effort to navigate the associated complexities. The road ahead is challenging, but the prospects for a sustainable energy future are promising, contingent upon our commitment to innovation, research, and continual learning. Future research must build upon these findings, exploring more specific aspects of energy innovation to further our understanding and contribute to the continual evolution of knowledge in engineering sciences.

Table 2: Summarized thematic synthesis of the reviewed literature

Citation	Purpose	Method	Findings	Relevance
[1]	Investigate 4IR technologies in the energy sector	Survey analysis	Most companies recognize the importance of 4IR technologies. China placed more importance than South Africa and Germany	Offers a comparative lens for the adoption of 4IR technologies in South Africa’s energy sector
[2]	Examine the potential of AI and ML in the SA energy sector	Literature review	AI and ML have the potential to improve energy operations but face challenges in SA.	Highlights opportunities and challenges of AI and ML in trans-forming South Africa’s energy sector

[3]	Examine the significance of ISEE parameters in managing alternative energy tech	Qualitative and quantitative analyses	Suggests a holistic management model with ISEE parameters for alternative energy tech	Highlights the applicability of ISEE parameters in managing alternative energy tech within South Africa.
[4]	Conceptualize "qualified determinism" for managing CAS in emergent tech	Literature analysis	CAS can exhibit different characteristics when viewed differently, introduces "qualified determinism”	Provides insights for managing complex adaptive systems within the context of emergent technologies in South Africa’s energy sector.
[5]	Argue for the role of social sciences in managing climate change	Literature discussion	Social sciences should influence consumer choices and ensure adaptable governance for energy innovation	Provides insights for managing complex adaptive systems within the context of emergent technologies in South Africa’s energy sector
[6]	Importance of considering gender in energy innovation in the Global South	Literature review	Unique gender inequality dimensions within informal settlements.	Underlines the need for a socio-technical approach to energy innovation, including policymaking in South Africa illustrates the necessity to consider gender in energy innovation policies and strategies in South Africa.
[7]	Analyse the role of R&D intensity and government policy in EII innovation	Cross-sectional research design	Positive relationship between R&D intensity and innovation performance in EII	Highlights the critical role of R&D intensity and government policy in energizing South Africa’s energy innovation landscape
[8]	Understand the role of innovative technologies in reducing energy consumption in SA commercial properties	Mixed-method approach	Deployment of innovative technologies can reduce the energy consumption of commercial buildings	Offers insights on applying innovative technologies in commercial properties for energy conservation in South Africa
[9]	Propose a new energy paradigm for SA	Policy analysis and industry best practices	Existing energy providers cannot meet the country’s power needs in their current form	Provides a policy-based perspective on transitioning towards a green energy paradigm in South Africa
[10]	Develop a strategic managreement framework for the commercialization of multi-tech renewable energy systems	Strategic management framework	Significant barriers to the successful application of the framework in the current SA context	Offers practical measures for accelerating energy transitions in South Africa
[11]	Examine the role of energy innovation in addressing GHG emissions	FMOLS and DOLS estimators	Energy innovation plays a significant role in mitigating GHGs emissions	Supports the need for increased investment in energy research and development in South Africa to reduce GHG emissions
[12]	Discuss the dependence on coal-powered plants and outdated infrastructure in South Africa	Policy analysis	Frequent instances of load shedding due to reliance on coal-powered plants and outdated infrastructure	Highlights the need for infrastructure upgrades and alternative energy sources in South Africa

[13]	Discuss the potential of 4IR technologies in energy management.	Literature review	The potential of 4IR technologies to improve energy management	Illustrates the potential of 4IR technologies in energy management in high-energy-consuming sectors.
[14]	Explain the holistic approach in managing complex systems.	Literature discussion	A holistic approach can provide valuable insights for formulating sustainable energy management strategies.	Demonstrates the relevance of a holistic approach to energy management in South Africa
[15]	Discuss the complications in South Africa's energy landscape.	Case study	Issues such as equipment theft and political interference complicating the energy landscape	Underlines the need for innovative solutions to tackle non-technical issues in the energy sector
[16]	Examine the influence of South Africa's energy policy	Review	Energy policy has a significant influence over the country's socio-economic development	Offers insights into the relationship between energy policy and economic development in South Africa
[17]	Explore opportunities for biomass energy in South Africa	Survey	Opportunities for biomass energy in South Africa are promising but underutilized	Suggests potential for growth in biomass energy sector in South Africa
[18]	Discuss strategies for integrating renewable energy into South Africa's national grid	Review	Challenges and solutions for integrating renewable energy into the national grid	Highlights technical and policy considerations for renewable energy integration in South Africa
[19]	Evaluate renewable energy policies in South Africa	Review	Policies and regulations can enhance renewable energy adoption.	Emphasizes the role of policies and regulations in renewable energy adoption in South Africa
[20]	Analyse the success and failure of renewable energy policies in South Africa	Review	Factors contributing to the success and failure of renewable energy policies	Offers a balanced perspective on the effectiveness of renewable energy policies in South Africa

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MAINTENANCE PLANNING EFFECT ON PLANT'S HEALTH

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ABSTRACT

Plant availability remains a vital lever for the production manager to exceed the demands of the ever-changing customers' demands and one of the pillars to achieve this is through a healthy plant. Although the industrial advancements have made it easier for the maintenance manager to plan and achieve this target, minimization of uncertainty in planning remains elusive. The critical literature review research methodology was adopted in this study and guided by the maintenance planning framework. Relationship between planning and its success has been outlined, this highlighted the importance of strict adherence to the front-end planning policy for execution. Various planning tools that were used in the industry have been highlighted. Hypothetical planning tool was developed and fictitiously scored using the readiness assessment approach to illustrate its vitality in the maintenance value chain. This planning tool will be tested in the system dynamics maintenance model to be developed in the future.

Keywords: maintenance, planning, health, tools, readiness.

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1 INTRODUCTION

McConkey [1] postulates that effective planning demand leadership to take into account the factor of uncertainty. This phenomenon makes life unbearable as no-one can predict the future or knows what to expect at any point in time in the future. Humankind from time immemorial had numerous endeavours to eliminate the known unknowns and unknown unknowns from their formula of life without success. Foundation of planning hinges on this uncertainty. The planner attempts to minimise the negative impact of the known unknowns and unknown unknowns from the formula by putting the plans in place before project execution. Kerzner [2] argues that the four elementary motives for maintenance project planning are to remove or minimize uncertainty, improve maintenance project efficiency, gain a better picture about the maintenance goals and give the foundation for maintenance performance. In order to deal with this uncertainty, McConkey [1] recommends that managers must score and rank all of the alternative plans and select the best alternative (Plan A). The second best alternative must be retained as contingency (Plan B) in case plan A fails.

1.1 Introduction to maintenance planning

According to Kerzner [2] planning is customarily defined as strategic, tactical, or operational. A strategic planning horizon is normally for five years or more, tactical planning horizon is one month to 60 months, and operational planning horizon in the context of power plant maintenance is between now and 52 weeks. The off-line maintenance is generally planning horizon is about 24 months while the on-line maintenance has a planning horizon of one week to 52 weeks. Below in Table 1 is a list of planning definitions obtained from literature:

Table 1: Planning definitions

Author (s)	Planning definitions
EPRI [3]	Planning is a process of *determining resources required on future maintenance work*. This includes estimating labour, materials and tools on future jobs. Scheduling is a process of *setting the start time and duration for future maintenance work* that allows an orderly progression of allocating labour, material and tools so that the work *fits into the plant production schedule*.
Smith [4]	Planning as the process used to develop a *course of action*.
Kerzner [2]	Planning in a project environment may be described as establishing a *predetermined course of action* within a *forecasted environment*.
Gulati and Smith [5]	Process of *determining the resources and methods* needed to perform maintenance work efficiently and effectively. They further distinguish *Planning* from *Scheduling* by stating that planning defines *what and how* whereas scheduling defines *who and when*.
Friedman and Scholnick [6]	Planning is defined as *formulating in advance an organised method* for action.
Duffuaa and Raouf [7]	Planning is the process by which the elements required to perform a task are *determined in advance* of the job's start time. Scheduling deals with assigning the jobs to be accomplished at a specific time.

The recurring theme in these definitions is making provisions for the future by taking action in today and these provisions are determined by using a certain forward looking techniques (subjective or objective). Porter [8] argues that in order for the organisation to have competitive advantage in the process of determining the resources [5] needed in advance [7] for the course of action [5], the first step is to achieve the *operational effectiveness* in all of the supporting and primary activities. Thereafter identify *opportunities* in its supporting and primary activities so that one can develop the competitive strategy. One of the sub-elements of primary activities is *planning*. In this activity the maintenance manager is challenged on the daily basis to enhance planning so that maintenance times can be reduced, costs minimised, quality of work improved and ultimately exceed the customer's expectation through quality products/services.

2 OBJECTIVES

The researcher's goal was to enhance the coal-fired power plant's dust and ash plant's health, and it was determined that additional knowledge from the planning researchers would be necessary. One of the most important components needed to maximize plant uptime and surpass customers' expectations is *planning*. Thus, through a general systematic review of the literature, the study's goal was to identify characteristics that contribute to the effective plant maintenance planning and develop a tool that can used by the maintenance managers to enhance their maintenance planning. The findings of this study will be used in the future to build the dust and ash plant maintenance model using the system dynamics tool.

3 METHODOLOGY

Through a thorough study of the 38 studies, a critical review research approach was used in this analysis to determine the factors that contribute to successful maintenance planning in the power plants. The study is based on the work conducted by various researchers dating from 1981 to 2021 and met the criteria (see figure 1). A general systematic literature review methodology was adopted, Sciencedirect and Google scholar databases were indexed on the 1st January 2023 to extract relevant journals, conference papers, reports, theses and books that were applicable for maintenance planning.

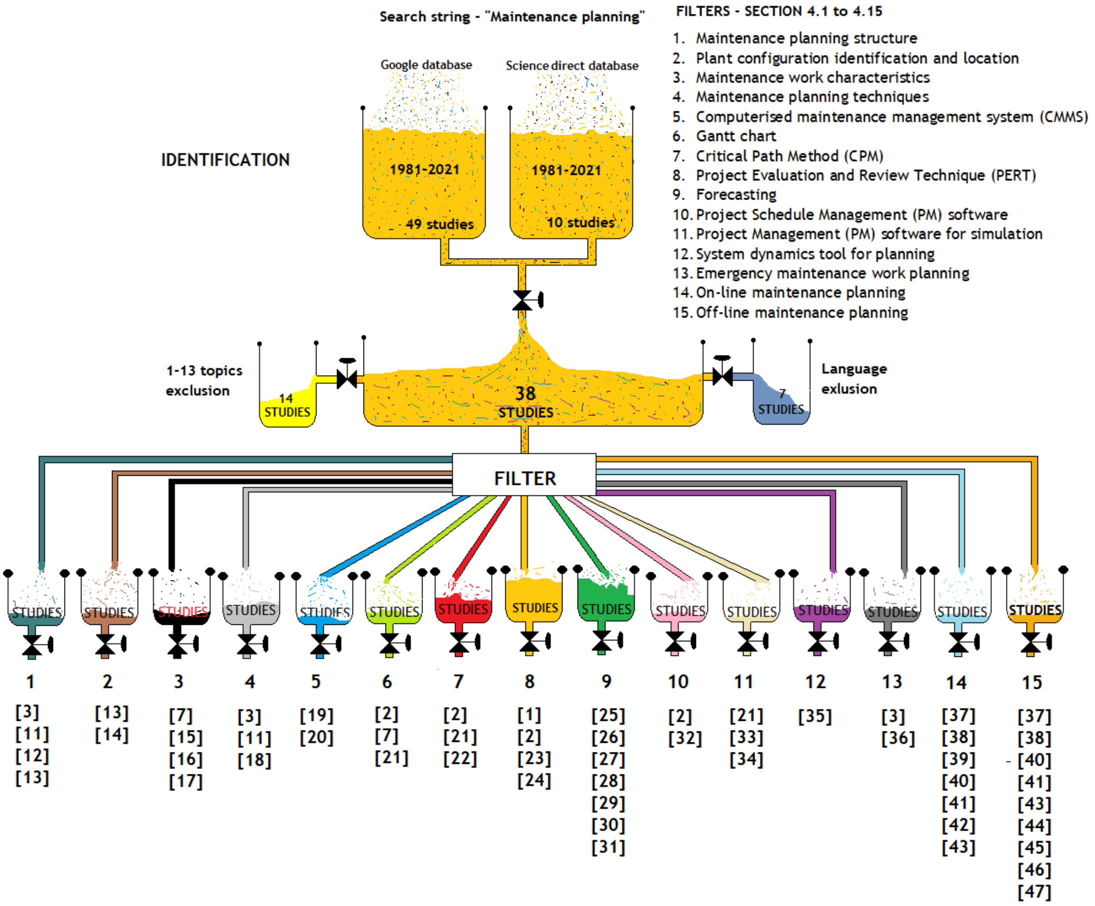
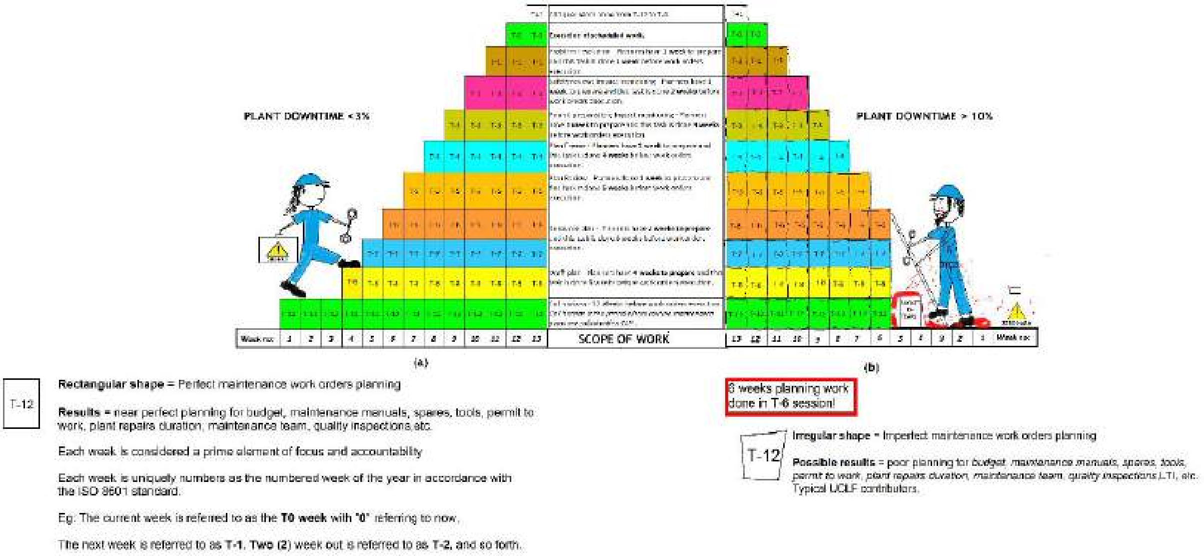


Figure 1: General systematic literature review flow diagram.

The maintenance planning life cycle served as the foundation for the development of the adopted research framework. In order to determine the examples in which failures or successes had been documented in the literature, their underlying reasons, which key performance indicators were employed or not, and their link with planning during the operational phase, a comprehensive literature review was carried out on all systems that were used to plan maintenance work. The dynamic relationship between planning life cycle and execution was studied and illustrated by introducing a hypothetical scorecard model (Figure 2a and 3a), which was subjectively graded (Figure 2b and 3b) for each planning phase through focus group sessions.



Rectangular shape = Perfect maintenance work orders planning

Results = near perfect planning for budget, maintenance manuals, spares, tools, permit to work, plant repairs duration, maintenance team, quality inspections etc.

Each week is considered a prime element of focus and accountability

Each week is uniquely numbers as the numbered week of the year in accordance with the ISO 9001 standard.

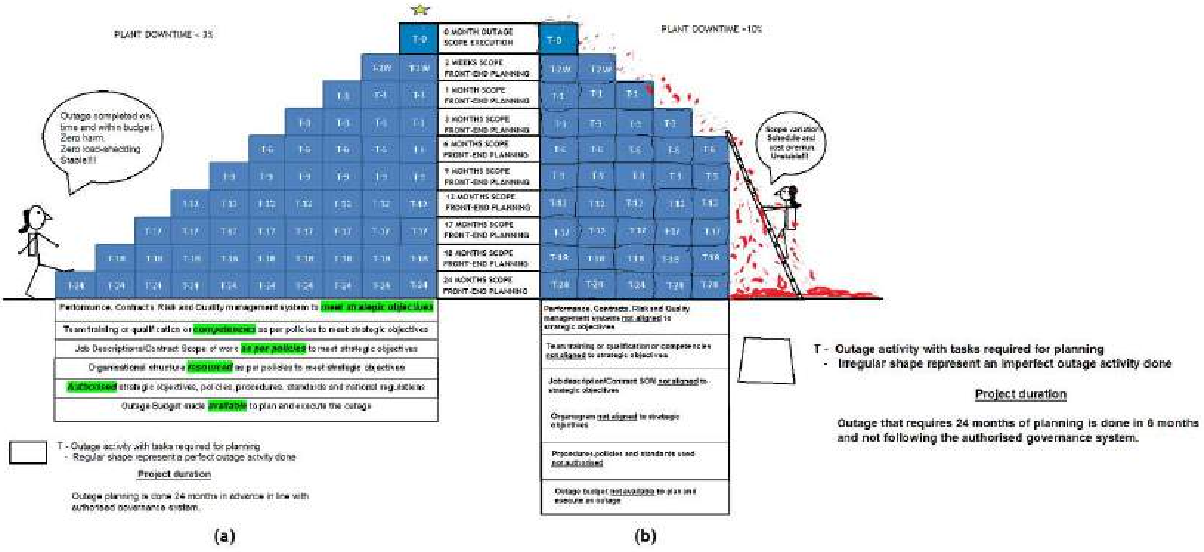
Eg: The current week is referred to as the **T0 week** with **"0"** referring to now.

The next week is referred to as **T-1**. **Two (2)** week out is referred to as **T-2**, and so forth.

Irregular shape = Imperfect maintenance work orders planning

Possible results = poor planning for *budget, maintenance manuals, spares, tools, permit to work, plant repairs duration, maintenance team, quality inspections*,LTI, etc. Typical UCLF contributors.

Figure 2: On-line maintenance planning with 14-weeks planning horizon - (a) Perfect planning (left) and (b) Poor planning (right) with fictitious scores for illustration purposes.



Performance, Contracts, Risk and Quality management system to meet strategic objectives

Team training or qualification or competencies as per policies to meet strategic objectives

Job Descriptions/Contract Scope of work as per policies to meet strategic objectives

Organisational structure resourced as per policies to meet strategic objectives

Authorised strategic objectives, policies, procedures, standards and national regulations

Outage Budget made available to plan and execute the outage

T - Outage activity with tasks required for planning
- Regular shape represent a perfect outage activity done

Project duration

Outage planning is done 24 months in advance in line with authorised governance system.

Performance, Contracts, Risk and Quality management systems not aligned to strategic objectives

Team training or qualification or competencies not aligned to strategic objectives

Job description/Contract SOW not aligned to strategic objectives

Organogram not aligned to strategic objectives

Procedures,policies and standards used not authorised

Outage budget not available to plan and execute an outage

T - Outage activity with tasks required for planning
- Irregular shape represent an imperfect outage activity done

Project duration

Outage that requires 24 months of planning is done in 6 months and not following the authorised governance system.

Figure 3: Off-line (Outage) planning with 24-months planning horizon - (a) Perfect planning (left) and (b) Poor planning (right) with fictitious scores for illustration purposes.

4 MAINTENANCE PLANNING IN THE PLANT

Power plant is composed of mechanical, electrical, civil, operating technology, control and instrumentation systems that are systemically connected to generate power. All of these items or systems require regular maintenance intervention owing to statutory reasons or strategic plant maintenance objectives and at times they randomly fail prematurely. These disruptions of the power plant demands sound management in order to exceed the customer's expectations without contravening the statutory requirements. In order for the maintenance manager to achieve these stringent functional targets, planning becomes imperative. Smith [9] argues that maintenance planning has a direct relationship with plant availability and according to [4] about one third of the operating costs were maintenance costs (US$ 1.2 trillion) while [10] found that a third of the total extraction costs in North American open pit mines were maintenance related.

4.1 Maintenance planning structure

Palmer [12] postulates that managers need to place maintenance planners out the control of team supervisors to prevent the planners from being assigned field work as technicians. This is also supported by [3] as planner is reporting to the Supervisor Planning and scheduling. Kelly [11] concurred as the planner office was headed by the maintenance support supervisor. Figure 4 below serve to illustrate the planner position that not recommended by the Palmer, Kerzner and Kelly.

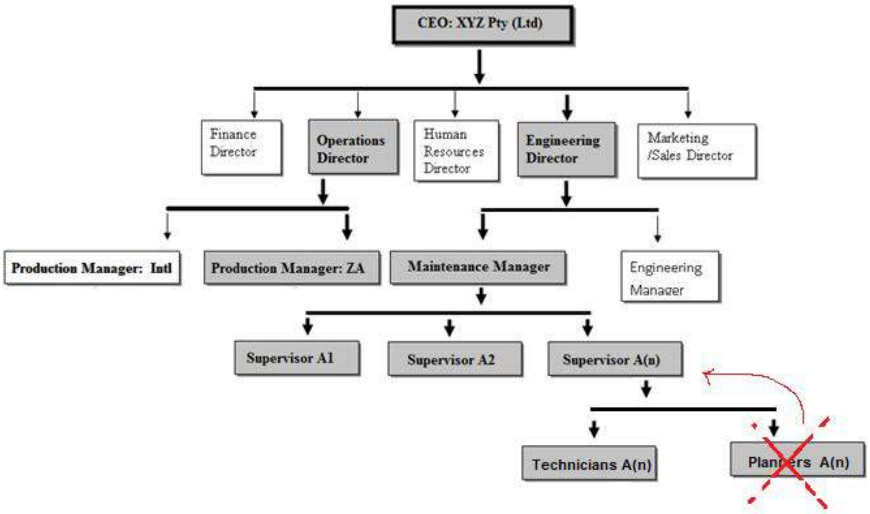


Figure 4: Organisational Structure - Planner not to report to Maintenance Supervisor [13]

4.2 Plant configuration identification and location

The modern industrial plants are functional of high technical sophistication, the satisfactory operation of these plants depend on the fully co-ordinated interplay of supply, auxiliary and safety systems that are based on modern configuration management principles. Alpha-numeric system is a subset of the configuration management system that is commonly used in the power plants in either Anlagenkennzeichnungssystem (AKZ) or Kraftwerk-Kennzeichensystem (KKS system). Elísson [13] conducted a research at the geothermal power plant found that components were not fully integrated using KKS with computerised maintenance management system and this prohibited the company from being able to track the mean time between failure (MBTF) of the plant components. Ahmed [14] argues KKS is a plant classification system that enhances the productivity of personnel through excellent work, prevention of mistakes and minimisation of unproductive search efforts when plant has failed and it needs repairs. A key advantage of this system is the capturing of the component history which is used when planning future activities and determining the type of intervention required. IEEE 807:2011 defines "KKS as systems and their related components by function or process, point of installation, or location code". Process designations will identify the specific plant system and the function of each component. KKS designations consist of a series of breakdown level, or BDL, codes arranged in a hierarchical order. An example of a process related identification code is: FW1-MED00-CT001-QB001.

4.3 Maintenance work characteristics

Maintenance work emanates from the adopted plant maintenance strategy that can be further divided into the following: *Planned maintenance, Breakdown maintenance, Condition monitoring, Predictive maintenance, etc*. Maintenance tasks stemming from these strategies are further prioritised according to the criticality with respect to production capacity, production equipment, workers' safety, the environment, etc. These are also categorised in terms of off-line and on-line maintenance strategies. Saaty [15] argues that the most imaginative task in making a maintenance decision is to choose the factors like safety or production or environment or cost which are important for plant decision.

Planning of maintenance work requires the planner to classify between emergent, urgent, normal and scheduled tasks so that works that are of higher priority can be given the necessary attention accordingly. In order to tackle this challenge, work is categorised in line with a classification system similar to [7] as shown in the table below. Maintenance work priority decision is made by the planner once it has been directed to the planning office using the matrix in Table 2.

Table 2: Maintenance work priorities. Source: [7].

Priority	Priority name	Description	Nature of work
1	Emergency	Action required immediately	Defect item has negative impact on Safety or Legal or Environment or Production or Consequential cost
2	Urgent	Action required within 24 hours	Defect item has negative impact on Safety or Legal or Environment or Production or Consequential cost
3	Normal	Action required with 48 hours	Defect item is likely to have impact on production within a week. This is composed of offline maintenance work.
4	Scheduled	As per maintenance schedule	Planned maintenance as per adopted plant maintenance strategy. Work is prearranged. This is composed of off-line & on-line maintenance work.
5	Postponable	Action required when resources are available or at shutdown period	Defect item that do not have immediate negative impact on Safety or Legal or Environment or Production or Consequential cost. This is composed of off-line and off-line maintenance work during the opportunity maintenance.

Márquez [16] criticizes the use of qualitative criticality analysis as it based on the planner's opinion, feelings, experience about the plant and intuition. This is subjective and it could cause the stakeholders pain with the inspector of the machinery if work is incorrectly ranked and the organisation encounter catastrophe. The use of the *quantitative criticality analysis* is highly recommended as it is bias free and consistent. This method was successfully applied at the Petrochemical plant by [16] making use of the Analytic Hierarchy Processes (AHP) as developed by [15] and results have demonstrated that criticality analysis can be done objectively together with the plant maintenance strategy. Gopalakrishnan [17] postulates that criticality analysis tool must be based on dynamic or real-time plant data analysis in order to enable a more accurate and dynamical approach to identify critical plant items and optimises the plant availability. The model that was applied at the Petrochemical plant by [16] was static as the plant priority would have changed over a period of time.

4.4 Maintenance planning techniques

According to Schoemaker and Russo [18], decision-making is the process whereby an individual, group or organisation reaches conclusions about what future actions to pursue given a set of objectives and limits on available resources. In order for the maintenance planning to take place within an organisation, the shareholders must articulate their business objectives going into the future while taking into account the constraints (e.g.: availability of resources, safety policy, manpower, plant regulation framework, energy demand, statutory maintenance, etc.).

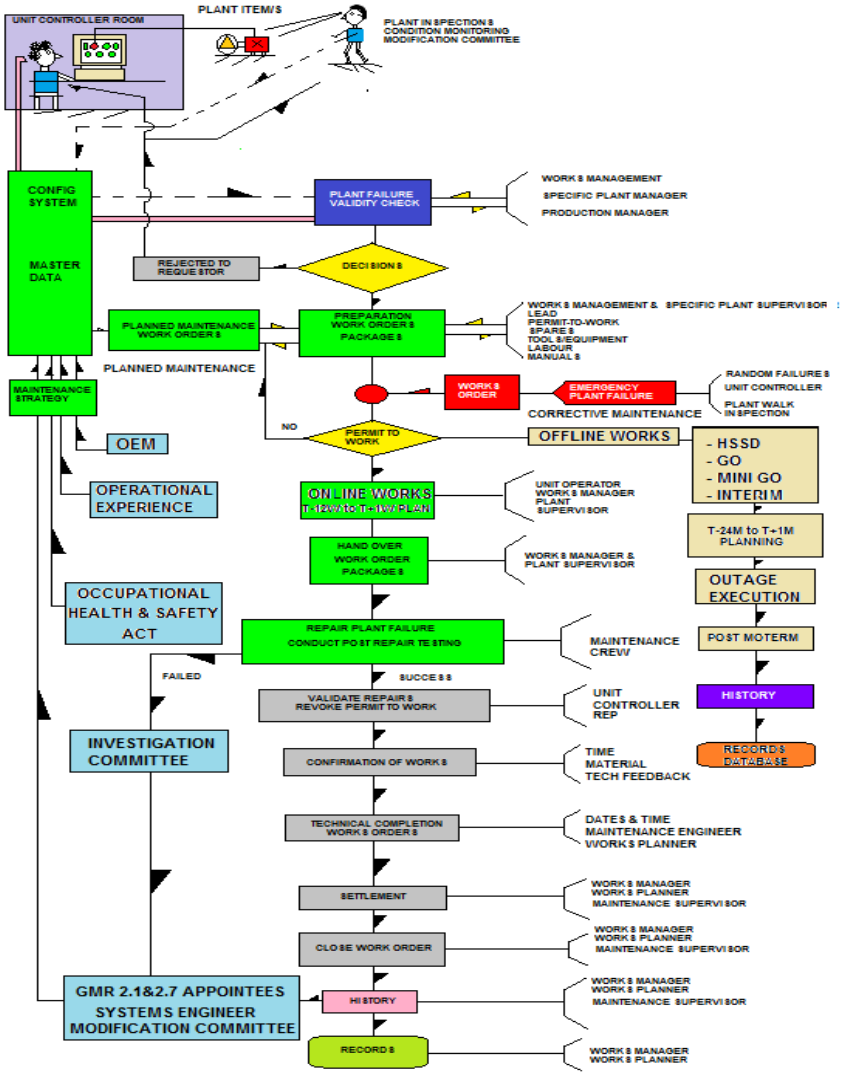


Figure 5: Power plant maintenance flow process with three (3) planning routes.

Planning is a dynamic process which requires continuous fine-tuning of the outputs against the set goals going into the future [3]. According to [11], documentation of the maintenance work is vital for planning to succeed. This document is called a “work order” or a “job card”. Kelly

[11] argues that this is not only crucial for the workshop team but it also serve to bring data and information for the effective maintenance control purposes by the management. Decision-making about the maintenance work is determined work priorities (Table 2) that have been adopted by the organisation. Maintenance work routing has three planning paths: (1) Emergency, (2) Off-line and (3) On-line as shown in Figure 5. The direction of the planning was based on the objective or subjective criticality analysis results that were generally based on some of the following: plant criticality, costs, safety criticality, environmental criticality, plant location, type of maintenance strategy and type of maintenance work.

4.5 Computerised maintenance management system (CMMS)

Van Houten, Tomiyamaz and Salomons [19] argue planning of maintenance was not based on simulated degradation mechanism or wear and tear effects on plant reliability as technology was not available compared to the digital mock-ups that were used to assess serviceability and maintainability by Boeing 777. According to the research done by [20] regarding the relevance of the CMMS planning they have found that the tool has become redundant as it was static and they have developed dynamic maintenance decision support tools that cater for the plant changes and production changes.

4.6 Gantt chart

According to [7], this as the bar chart that has start and finish times for each activity on a horizontal timescale and that its disadvantage is that is does not show interdependencies among different tasks [2] and [7]. Start and finish times has to be subjected to quality assurance if this method is applied in the industry so that project success can be realised. Besner and Hobbs [21] had conducted a survey on techniques that were used in planning and Gantt chart was ranked 4/70. This survey was based on 753 experienced project management practitioners. This is also in line with the author's experience as it continues to be used as bedrock of most of the planning courses. Progress report tool was ranked 1st while Monte-Carlo analysis ranked 70th in terms of positions.

4.7 Critical Path Method (CPM)

According to [22], CPM is a forward pass to determine the total project duration along with the earliest start time (EST) and the earliest finish time (EFT) for each activity. Activities with zero Total Float (TF) are identified as being critical and make up the critical path in the project network. This method relies on certainty in terms of the milestones duration otherwise critical path will be different from the originally determined one. Kerzner [2] defines the critical path as that sequence of tasks in a project that requires the greatest time. Besner and Hobbs [21] had conducted a survey on techniques that were used in planning and CPM tool for planning was ranked between 24-54/70. According to [2], Gantt's major drawback is its inability to show the interdependencies between events and activities.

4.8 Project Evaluation and Review Technique (PERT)

According to Cottrell [23], PERT takes into account that a project to be non-cyclic network of events and activities. The duration of a project is determined by a system flow plan in which the duration of each task has an expected value and a variance. The critical path includes a sequence of activities that cannot be delayed without risking the entire project. PERT can be used to approximate the probability of completing either a project or individual activities by any specified time without basing the schedule on the engineer's knowledge [24]. Besner and Hobbs [1] had conducted a survey on techniques that were used in planning and PERT technique for planning was ranked 59/70. According to [2] this method has more data requirements and its expensive hence the poor score.

4.9 Forecasting

According to [25], future maintenance planning is done in order to forecast the maintenance workload so that the necessary plans can be made to match the resources with the workload. In order for planning to be accurate, the data that is used to forecast must be complete, accurate and reliable. This data is composed of two sources: (1) planned outages or major shutdowns and planned & scheduled maintenance work which can be on-line or off-line - this type of work is known and planned for execution in the future. (2) Emergency work (corrective maintenance) - this work is unknown and by its nature it is not planned hence a need for the maintenance resources forecasts. These include spares, tools, plant permit-to-work, budget, specialist contractors, production plant slots, labour, project duration and project timing. Table 3 provide different forecasting techniques in the literature.

Table 3: Forecasting methods

Qualitative forecasting methods	Quantitative forecasting methods
Delphi method: *a group of subject-matter experts respond individually to a structured questionnaire or focus group session, providing forecasts and justifications. Results are combined, summarized, and returned to experts to revise for second session and third session is organised in order to reach a consensus ([25] and [26]). Expert competence level analysis has to be done in advance in order to increase the validity and reliability of the results.*	**Simple Moving Averages:** *it is an arithmetic average of the past data used to forecast the future. All data points have equal weights [26].*
Jury of Expert Opinion: is a top-down forecasting method in which the forecast is arrived at through the ad-hoc combination of opinions and forecast made by executives and experts [27].	**Simple Exponential Smoothing:** *it is a weighted moving average of the past observations where the recent observations are given higher weights [27].*
Scenario Analysis: is a systematic process to forecast a number of plausible and vividly contrasting narratives that describe possible change of key areas of uncertainty in the future [28].	**Seasonal Forecasting:** *this refers to the presence of variations which occur at certain regular intervals. Given data for at least two cycles (2 N), four simple steps are used to obtain* *forecasts for each period in the cycle [27]:* • *Calculate the overall average* μ; • *Divide each point by the average* μ *to obtain seasonal factor estimate;* • *Calculate seasonal factors* c_t *by averaging all factors for similar periods; and* • *Forecast by multiplying* μ *with the corresponding* c_t *for the given period.*
Market Survey: *is to ask clients or potential users how they forecast their future consumption of a product or service. It is also called 'user's expectation' method [29].*	**Causal Forecasting Models**: *The causal relationship in general is given as* $Y = f(x_1, x_2, ..x_n)$, *where Y is the forecasted variable computed in function of a number of know variables X. The basic assumption for a causal model is that the future value of the forecasted variable can be expressed as a mathematical function of the known current values of a set of different variables [30].*

According to [31], applied forecasting techniques for deterministic and stochastic maintenance workload planning. This involved the use of time-series methods using real-data of 171 projects at the major Portuguese aircraft maintenance center. A state space formulation of the multiplicative Holt-Winters (MHW) was selected using the bias-corrected

Akaike information criterion (AIC). This was an integrated Decision Support System for maintenance workload planning with probabilistic inference capabilities.

4.10 Project Schedule Management (PM) software

According to [32], maintenance (project) management has been practiced from the beginning of creation and they have cited the construction of the Pyramid of Giza and the Great Wall of China as examples. Owing to the complexity, schedule, scope and uncertainty of the maintenance (projects) in the 1970s a need arose which necessitated the computerisation of project management and this was done by Oracle. Kerzner [2] argues that this software must not be used as a substitute for incompetency and he further notes some of the following benefits to the maintenance planner: (1) Project summary - expenditure, timing and activity data. (2) Project management and business graphics capabilities. (3) Data management and reporting capabilities. (4) Graphical representation of cost, time and activity data.

4.11 Project Management (PM) software for simulation

According to [21], they had conducted a survey on techniques that were used in planning and the use of PM software simulation tools was ranked 69/70. This meant that this tool was not well adopted in the industry despite its advantage of providing deeper insights at the least cost. Scharpff *et al*., [33] and Hafner *et al*., [34] had conducted studies using this software and they found the following: Scharpff *et al*., [33] tackled maintenance planning and scheduling using a combination of stochastic multi-agent planning, captured in Markov Decision Processes (MDPs), and dynamic mechanism design and this was able to provide them with insights and identify both planning and scheduling challenges before the actual was implemented.

According to [34], they applied Deep Planning Network (PlaNet) that learns the environment dynamics from images and chooses actions through fast on-line planning in latent space. To achieve this, an approach of using a latent dynamics model with both deterministic and stochastic transition components was implemented. Using only pixel observations, the agents solve continuous control tasks with contact dynamics, partial observability, and sparse rewards, which exceed the difficulty of tasks that were previously solved by planning with learned models.

4.12 System dynamics tool for planning

According to Castane, *et al*. [35], applied simulation-based optimization tool for field service planning where the team had fixed service plan but were intermittently interrupted while executing scheduled maintenance by the breakdown failures of the copiers, telecommunication equipment and heavy machinery in the field. They have developed the optimisation and simulation framework that is able to cater for the stochastic events. The Anylogic model allowed the evaluation of various scenarios in solving the field service maintenance problem.

In summary, the maintenance planning tools have been developed over a period time and major finding is that planning was based on static inputs and not optimised. The various authors have developed different tools in an attempt to tackle this gap using dynamic inputs in order to get the optimal planning and there is a need to integrate these learnings in day-today maintenance planning in the power plant.

4.13 Emergency maintenance work planning

According to [3], emergency work of a plant item failure that requires immediate repair so that plant operations can be normalised. The other term that is commonly used for this tactical work is called Reactive Maintenance or Corrective Maintenance (CM). In order for the employer or user to comply with the above-mentioned regulation, Maintenance manager has to provide for emergency situations when plant failure is unforeseen. According to [36], posits that emergency response is the last line of defence that is designed to lessen the impact of loss of control. In order to ensure that this defensive line will minimise the impact of loss of control and provide for the organisational continuity, planning becomes imperative. This planning is denoted by (1) as shown in figure 4 above. One of the tools used to minimise the rate of emergency work (corrective maintenance) is through the fine-tuning of the planned maintenance programme in the plant. High rate of the emergency work translate to poorly performing planned maintenance programme and [3] rate the score of 1% for the emergent work as the best (see Table 4). The three components of emergency maintenance planning (see Table 5) have to be catered for, viz.; preparedness, response and recovery.

Table 4: Planning indicators with best practice score. Source: [3]

Planning indicator	Best practice	Planning indicator	Best practice	Planning indicator	Best practice
Planned Maintenance (PM) compliance	100%	Online backlog	2 weeks	Resource utilisation	60%
CM Ratio	20%	Labour planning effectiveness	90%	Percentage on scheduled jobs	95%
Emergency work (*Priority 1*)	1%	Material planning effectiveness	80%	Schedule compliance	90%
Sponsored work	12%	Backlog planning factor	0.9-1.1	N/A	N/A

Table 5: Three (3) components of emergency planning.

Emergency planning	Description, McNary [36]
Preparedness	Emergency preparedness process begins with the identification of credible scenarios for which appropriate response strategies are developed.
Response	The development of strategy for emergency response requires consequence assessments from a list of credible incidents and data on resources and capabilities. This can be determined using the Failure Mode Effect Analysis (FMEA) tool.
Recovery	The recovery manager needs to establish a recovery team that represents commercial, maintenance and operating disciplines in the plant. A portion of the efforts of damage's assessment to plant, and incident investigation could be integrated to avoid repetition of some of the phases.

4.14 On-line maintenance planning

On-line plant maintenance refers to the week-by-week planning and execution of maintenance programme while the plant is in operation, Table 6 below offers definitions from the various sources. Most of the repairs or services plans involve the redundant plant items, in-service plant inspections and in certain occasions plant production capacity has to be reduced in order for this type of maintenance to be executed [37]. Table 6 below captures the on-line maintenance definitions.

Table 6 - Definitions of on-line maintenance planning.

Author (s)	Definitions
INPO AP-913 [38]	On-line Maintenance activities: *Maintenance activities that can be accomplished with the plant on-load or operational.*
Koren [39]	On-line Maintenance: *Hardware and software modules can be diagnosed, disconnected for repair, and then reconnected, without disrupting the entire system's operation.*

This type of maintenance has a planning horizon of 14 weeks with the exception of the emergent plant failures that are repaired immediately so that production can be re-instated. The planning makes use of ISO 8601 work week management approach where each week in the Gregorian calendar is considered a prime element of focus and accountability. The current week is referred to as T-0W week with the “0” referring to now. The preceding week is referred to as T-1W (see table 7 below). Two weeks out is referred to as T-2W and so forth ([38] and [40]).

Table 7: Work week management rhythm ([38] and [40]).

T-12W	T-8W	T-7W	T-6W	T-5W	T-4W	T-3W	T-2W	T-1W	T0W	T+1W
DEVELOPMENT OF DRAFT PLANT		DEVELOPMENT OF RESOURCE PLAN		REVIEW OF RESOURCE PLAN	WORK SCOPE FREEZE	PERMIT PREPARATION	SAFETY REVIEW	SCHEDULE FREEZE	WORK EXECUTION	CRITIQUE REVIEW
FRONT-END PLANNING										

According to [41], increased usage of the on-line maintenance has the potential to drastically optimise the duration of the off-line maintenance (outage) which can assist the plant by increasing production time and reduction of the costs that is associated with shutdown. Reliability-centered maintenance (RCM), Condition monitoring, Risk-informed inspection and testing have been identified as good tools for optimization of the maintenance activities or minimization of the outage duration [41]. In order to ensure that the on-line planning is translated into successful maintenance plan execution [42], it is paramount that a readiness assessment per milestone is conducted so as to provide assurance that all of the necessary planning activities and resources have been catered for as per the stated plan ([38] and [40]). This assessment has been adapted from the Construction Industry Institute (CII) - Project Definition Rating Index (PDRI) small industrial projects model to suit maintenance planning [43].

4.15 Off-line maintenance planning

Off-line plant maintenance refers to the long, medium and short-term planning and execution of maintenance programme when the plant is on shutdown. The repairs plan involves the general plant services, plant modifications to address obsolescence, predictive maintenance, scheduled maintenance and scheduled statutory maintenance [37].

Literature has captured this phenomenon as Turnaround maintenance or Outage or Off-line maintenance. This type of maintenance has a planning horizon of 24 months and the plant could be on shutdown up to two (2) months. The planning also makes use of ISO 8601 work month management approach where each month is considered a prime element of focus and accountability. The current month is referred to as T-0M in terms of a Gregorian calendar with the “0” referring to now. The preceding month is referred to as T-1M (see table below). Two months out is referred to as T-2M and so forth ([38] and [40]). This type of planning applied on the off-line and on-line maintenance planning is based on the concept of front-end planning (FEP). According to [44] this is defined as “the process of developing sufficient strategic information with which owners can address risk and make decisions to commit resources in order to maximize the potential for a successful project”.

Table 8: Work month management rhythm ([38] and [40])

T-24M	T-18M	T-17M	T-12M	T-9M	T-6M	T-3M	T-2M	T-1M	T0M	T+1M
IDENTIFICATION PHASE			PLANNING	SCHEDULING	PREPARATION PHASE				EXECUTION PHASE	CRITIQUE PHASE
FRONT-END PLANNING										

In order to ensure that the off-line planning is effective, it is paramount that a *readiness assessment* is done for all the phases as planning progresses so as to provide assurance that all of the necessary planning activities and resources of the small industrial project have been catered for as per the stated plan [38] and [43]. Vichich [45] argues that industry fail to tackle the high complexity shutdowns owing to lack of concentration and effort required in the planning phase in order to achieve the best state of readiness. He further notes that organisation that scores high in the project readiness reviews have a better chance of achieving their targets (i.e. schedule and cost outcomes.) and exceed the industrial benchmarks.

Readiness review is a concept that has been adopted from Project Definition Rating Assessment (PDRA) instrument, this was developed by [44] in order to independently asses the completeness of the project scope definition and enhance the front-end planning efficiency. In this review, critical elements (T-24M to T+1M) of planning are evaluated in order for the project planner to identify the project risk factors and maximize the potential of an outage execution success.

According to [41] some of the following good practices (Table 9) that have proven to shorten the outages during the planning phase:

Table 9: Good practices planning outage

Work scope predictable up to 95%.	Usage of modern scheduling and engineering tools (Eg: Primavera, CAD, etc.)	Optimisation of the mobilisation of the human and material resources.
General proactive planning attitude	Involvement of the contractors from the early steps of outage preparation.	Planning and training in-house and outside human resources in advance.
Early execution of the planned inspection of system and components.	Identification of the tasks that are on the critical path.	Implementation of the incentives programmes (Eg: Outage schedule, quality, cost and safety).
Freeze outage scope three (3) to ten (10) months before the outage start date.	Use of the non-destructive testing devices that enable inspection without dismantling components	Checking for and reservation of materials, spare parts and consumables available on site at least 2-4 months before outage start.

Al-Turki, Duffuaa and Ben-Daya [46] argue that effective off-line maintenance planning is composed of the following pillars:

- *Organizational structure* - this must be composed of an effective, cohesive and experienced team that can communicate their plans into an excellently serviced plant without project incurring overruns. Ghazali and Halib [47] contend that off-line maintenance must be a full-time team and not temporary with the objective to retain planning and execution know-how within the organisation.
- *Planning and scheduling* - Proper planning reduces uncertainty in all aspects of the off-line maintenance work and minimises the possibility of overruns (costs, schedule, scope, etc.). Management to develop a solid relationship with spares vendors with the objective to minimise the delays on the items with long lead times. The literature has also indicated

the importance of quality assurance and control both in planning and the execution phase. Adoption of the project management technologies assists the organisation in planning for the project's needs and identification of the project constraints earlier in order to run away from failure.

- *Risk analysis* - research conducted had demonstrated the benefits of integrating the risk management into planning and execution phase. Literature had shown the benefits of using the risk-based inspection (RBI) in order to improve production capacity and minimise the off-line maintenance duration. Development and implementation of the risk management framework for all critical items in the project is essential to retain the risks (costs, scope, schedule, etc.) to be within the acceptable tolerance level.
- *Performance measure* - Off-line maintenance concentration is composed of input, output and processes. Inputs into this off-line maintenance system involve some of the following: financial resources, spares, tools, manpower, software, scope of work. Processing system for this inputs include planning, scheduling, controlling, quality control and off-line maintenance execution. Outputs of the system involve the increased production capacity and high quality products through plant that has high availability and reliability. The performance indicators of the off-line maintenance were similar to the normal maintenance key performance indicators with emphasis on planning and execution-related indicators like costs and time. Vichich [45] argues that industry fail to tackle the high complexity shutdowns owing to lack of "*rigor, focus, organizational energy*" required in the planning phase in order to achieve the best state of readiness. He further notes that organisation that scores high in the project readiness indicator have a better chance of achieving their targets (i.e. schedule and cost outcomes.) and exceed the industrial benchmarks. Critical success factors: turnaround preparation activities become a normal piece of the daily business rhythm, engaged management team, quality equipment strategies, equipment performance data, scope challenges, quality management in planning and the execution, project readiness indicator amongst others.

Reporting and learning - the importance of capturing the lessons learned from planning to execution plays a crucial role in the improvement of the off-line maintenance work. This is also vital for the future planners so that the next shutdown plan process can be enhanced. Vichich [45] presented the results of the 400 refining and chemical turnarounds or projects, in this study the effect of the turnaround outcomes was quantified and this was later compared against the turnaround risk and readiness indices. Three characteristics that were the most influence on the turnaround predictability was identified as: 1) size of the turnaround measured in direct field labour hours. 2) Amount of the capital work. 3) Turnaround interval. In this study it was also found that the team alignment and measuring of the readiness relative to the best in class was the cornerstone of a successful turnaround.

4.16 PLANNING KEY PERFORMANCE INDICATORS SCORES FOR ON-LINE and OFF-LINE

4.16.1 On-line maintenance - with 14-weeks planning horizon (Table 8 as reference).

Above in Figure 2 (b) is the hypothetical score of the on-line maintenance planning that was poorly planned. In this instance the planner did not start planning at T-12 but rather at T-6, this required the execution team to jump key millstones that are vital for successful execution of the maintenance work. The shape of the milestone is indicative of poor planning and this was scored through survey tool. Below in table 10 is the scores for the following milestones. Note that T-12W to T-7W score is zero since no front-end planning was done.

Table 10: On-line maintenance - with 14-weeks planning horizon scoresheet.

Milestone	T-12W	T-8W	T-7W	T-6W	T-5W	T-4W	T-3W	T-2W	T-1W	T0W	T+1W
Score	0.00%	0.00%	0.00%	60.00%	60.00%	60.00%	80.00%	80.00%	80.00%	60.00%	100.00%
Overall Front-end planning score	52.73%										

4.16.2 Off-line maintenance - with 24-months planning horizon (Table 9 as reference)

Above in Figure 3 (b) is the hypothetical score of the outage that was poorly planned. In this instance execution was negatively affected by lack of identifying spares that had long lead times, permits not obtained on time, contracts not placed on time, etc. and the manager had to source everything under emergency procurement which denied the management opportunity to select the best candidates and source the best materials at least costs amongst other negatives factors. Planner did not start planning at T-24M but rather at T-6M, this required the execution team to jump key millstones that are vital for successful execution of the maintenance work. The shape of the milestone is indicative of poor planning and this was scored through survey tool. Below in table 11 is the scores for the following milestones. Note that T-24M to T-12M score is zero since no front-end planning was done.

Table 11: Off-line maintenance - with 24-months planning horizon scoresheet.

Milestone	T-24M	T-18M	T-17M	T-12M	T-6M	T-3M	T-1M	T-2W	T0M	T+1M
Score	0.00%	0.00%	0.00%	0.00%	66.00%	60.00%	45.00%	60.00%	40.00%	100.00%
Overall Front-end planning score	33.73%									

5 CONCLUSION

Maintenance planner must not be under the control of the maintenance execution manager to achieve effective planning. Plant alpha-numeric system is vital for communication amongst the plant stakeholders, serve to capture history and plan the maintenance work for all plant items.

Maintenance work has to be categorised according to the risk that failure poses to the power plant. Use of qualitative criticality analysis approach has the potential rank failure incorrectly and quantitative criticality analysis is the most accurate as it is objective and this must be based on dynamic or real-time plant data analysis.

Design of maintenance work order or job order must include all critical aspects required for effective planning. Use of tools for planning is highly recommended, planning was mainly composed of on-line, off-line and emergency planning. CMMS planning, have been found to be redundant as it was static and a need for a dynamic planning is required for higher plant uptime. Gantt chart has been found to be vital for planning, Use of forecasting tools are recommended to ensure proper planning and Project software was deemed essential for planning. System dynamics tool has been successfully implemented in planning.

It is paramount that a readiness assessment was done for all the phases as planning progresses in line with model that was proposed. Hypothetical planning tool was developed and fictitiously scored using the readiness assessment approach to illustrate its vitality in the maintenance planning value chain for both on-line and off-line projects. This model can be used to illustrate the negative aspects of poor planning across the maintenance team and support teams. Effective maintenance planning developments obtained in the literature have highlighted a number of tools and techniques that are necessary to minimise the effects of uncertainty for the maintenance manager. These learnings have to be integrated into the front-end planning system in order to increase the probability of maintenance execution success. This planning tool will be implemented in the system dynamics maintenance model to be developed in the future using survey tool to obtain the scores from key planners and maintenance execution members.

6 COMPETING INTERESTS

The authors declare that they did not have competing interests.

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ELECTROSTATIC PRECIPITATORS DUST REMOVAL SYSTEM - SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

To explore the application of the Electrostatic Precipitators (ESP) system in the industry. Studies 2014-2024 that were identified met criteria using Systematic Literature Review (SLR). Themes considered included maintenance strategy adopted for the ESP system, type of technology that was applied to enhance air quality, type of technology used to improve air quality and its trends. Energy sector dominated the studies. Chinese were the leaders in the gas cleaning technology - desulfurization (SO_x), denitrification (NO_x), dust collection (PM_{10} and $PM_{2.5}$) and multi-pollutant (Hg). Nineteen different ESP technologies were identified. ESP technology had application beyond boiler flue gas cleaning. Majority of the ESPs considered had 99% efficiency. Maintenance strategy was not included in the 54 articles, the included studies focused more on enhancing air pollution control than the reliability of the ESP systems. Research output in this sector was increasing due to stringent environmental laws.

Keywords: coal-fired power station, energy, electrostatic precipitators, dust, pollution, control.

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1 INTRODUCTION

Fitzgerald, *et al*. [1] argue that majority (85%) of energy supply in South Africa is generated from the coal-fired power plants. Energy generating system makes use of coal to convert chemical energy into electrical energy, this starts when the coal is conveyed to the milling plant for pulverisation to size of a fine grain, mixed with heated air in the burner and burned in the boiler plant. After burning coal in the boiler, *coarse ash* is collected at the bottom of boiler through ash handling plant and *fine dust or fly ash* is collected through emission control plant to the dust handling plant. The chemical energy in the coal is then converted to heat energy through the heat exchangers and steam is generated. This high pressure and temperature steam is then fed to the turbine plant to convert heat energy into electrical energy through a combination of turbine rotor that connected to the electrical generator.

According Eskom [2] to dust handling plant carry 85% of the ash load while bottom boiler ash removal plant which is the coarser ash handles 15% of the remainder. These systems play a vital role in order to keep the power plant energy availability factor (EAF) high at all times and to generate electricity safely while complying with the environmental laws, solid waste regulation and general machinery regulations. The focal point of this research was to conduct systematic literature review on the *effective dust removal systems through the application of the electrostatic precipitator (ESP)* so that South African power plants dust removal systems can be enhanced.

Schutte [3] conducted a study that was funded by Eskom Power Plant Engineering Initiative (EPPEI) and reported some of the characteristics of dust in the 13 coal-fired power plants to be as described in Table 1 below.

Table 1: Eskom ash elemental analysis on an oxide free basis [3].

Stations	A	B	C	D	E	F	G	H	I	J	K	L	M
SiO_2	53.72	56.63	53.43	57.47	53.71	54.32	53.16	56.59	55.37	53.75	53.50	54.01	53.44
Al_2O_3	31.57	30.50	31.19	28.28	30.14	30.66	30.68	28.96	29.24	34.42	31.39	27.16	29.72
Fe_2O_3	3.24	3.58	4.33	6.51	5.97	4.73	5.04	4.74	5.12	5.07	3.96	4.05	3.36
TiO_2	1.72	1.59	1.91	1.53	1.72	1.75	1.79	1.65	1.71	1.96	1.88	1.62	1.73
P_2O_5	0.74	0.45	0.67	0.51	0.56	0.51	1.12	0.53	0.61	0.55	0.90	0.69	0.96
CaO	5.67	4.87	5.63	3.15	4.65	5.04	5.04	4.64	4.72	2.38	5.21	8.31	6.51
MgO	1.92	1.19	1.51	1.02	1.21	1.75	1.47	1.44	1.41	0.62	1.77	1.72	2.14
Na_2O	0.40	0.30	0.10	0.31	0.91	0.21	0.21	0.21	0.40	0.10	0.21	0.30	0.71
K_2O	0.81	0.70	0.80	0.81	0.71	0.62	0.74	0.72	1.00	0.93	0.83	0.91	0.81
SO_3	0.20	0.20	0.40	0.41	0.40	0.41	0.74	0.52	0.40	0.21	0.31	1.22	0.61
MnO	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Chou [4] posits that "dust as stated in Table 1 consists of the inorganic matter within coal that has been melted at high temperature during coal combustion, solidified while suspended in the flue gases, and collected by ESP plant or other devices before the flue gases are released into the atmosphere". ESP technology is employed to remove the air pollutants listed in Table 1 with the objective to comply with the environmental laws and protect the population's health from harm. Hill [5] defines pollution as any substance introduced into the environment that adversely affects the usefulness of a resource. Vitousek, *et al*. [6] argue that humans continue to change the earth and these changes are extensive and they further posit that this has negatively affected between 39% and 50% of the land surface. Lubchenco, *et al*. [7] posit that introduction of these substances or changes are negatively affecting the sustainability of the biosphere.

These changes threaten the very existence of the human beings as their survival depends on this ailing ecosystem [5]. In the case of power generation, the most dominant changes on earth brought by human include air pollution and water pollution. Environmental laws are contravened when ESP is defective and dust is released to the environment through the smoke stack. Sloss [8] research suggests the plans from the South African power plants operators are indicating decline of the pollutants being released to the atmosphere from the year 2025 onwards due to the installation of emission control technologies.

Schraufnagel [9] argues that anthropogenic pollutants can cause serious damage to human health, one of the first interaction with this pollutant coming from coal is the lungs followed by the other parts of the body. These pollutants vary in sizes, they are measured in µm (sub particles matter (PM)) and the smaller the more difficult the body can defend itself from these harmful substances. Refer to Figure 1 below for pollutants size comparison.

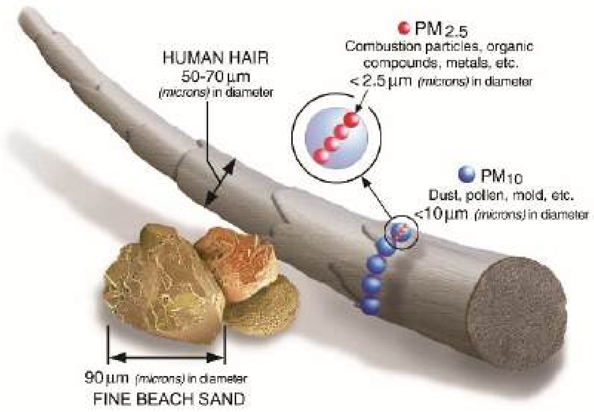

Figure 1: Comparison of coal combustion particles with human hair and fine beach sand. Source: [10].

According [11], "*$PM_{1.0\text{-}0.1}$ is the main contributor for visibility impairment in the ambient environment because their sizes overlap with the wavelength of visible light and they very efficiently scatter light*" while [12] argue that the primary $PM_{2.5}$ emissions can accelerate the formation of haze and induce an adverse effect on climate change and human health. Particulate Matter ($PM_{2.5}$) refers to atmospheric particulate matter with a diameter of less than or equal to 2.5 µm.

Eskom coal-fired power plants made use of three different types of particulate abatement technologies; Eight power plants with Fabric Filter Plants (FFP), Nine power plant use Electrostatic Precipitators (ESP) with SO_3 Flue Gas Conditioning (FGC) and one power plant with Flue Gas Desulphurisation (FGD). Below in Table 2 is the breakdown different emission abatement technologies that were used in the coal-fired power plants.

Table 2: Emission abatement technologies employed by Eskom, Source [12].

Power Station	Arnot	Camden	Duvha	Grootvlei	Hendrina	Kendal	Kriel
Type of technology	FFP	FFP	FFP and ESP+ FGC	FFP and ESP + FGC	FFP	ESP + FGC	ESP + FGC
Power Station	Kusile	Lethabo	Majuba	Matimba	Matla	Medupi	Tutuka
Type of technology	FFP and wet FGD	ESP + FGC	FFP	ESP + FGC	ESP + FGC	FFP	ESP

Majority (57.14%) of the Eskom power plants make use of ESP technology to remove the particulates and their reliability is low, thus affecting the air quality performance contract negatively and exacerbating the power plants energy availability factor (EAF). These particulate abatement technologies have disadvantages and advantages, and one of disadvantage with ESP is poor plant reliability which result in dust pollution and manual removal of dust versus through the conveyor system. Focus of this work is to identify positive attributes or systems in the published ESP studies from the other operators with the aim to transfer the learnings to South African operations.

ESP technology makes use of the electrostatics principles to capture the emission pollutants based on the law of corona that was invented by Peek [14], use of high voltage to ionise the flue gas and attract the charged particles to the collecting plates, then application of rapping and discharge the of the particulates and releasing of the clean air.

According to [15], aerosols are collected using ESP by first charging them with the corona discharge action (see Figure 2). When an electrode receives a high enough voltage, the electric field intensity surpasses the dielectric strength of the surrounding air, leading to local ionization and the production of free electrons. The high potential of the plasma surrounding the electrode subsequently causes current to flow into the neutral fluid. This is referred to as a corona discharge. In the wire-plate geometry, aerosols pass between two parallel plates across a corona wire that is maintained at a high bias voltage. The ionized air molecules in the plasma stream in the direction of the corona wire for a negatively biased wire. Freed electrons flow away from the corona wire in the direction of local field lines [15] and [16]. One of the unintended consequences of the ionization in the ESP plant is the production of the poisonous ozone gas [17].

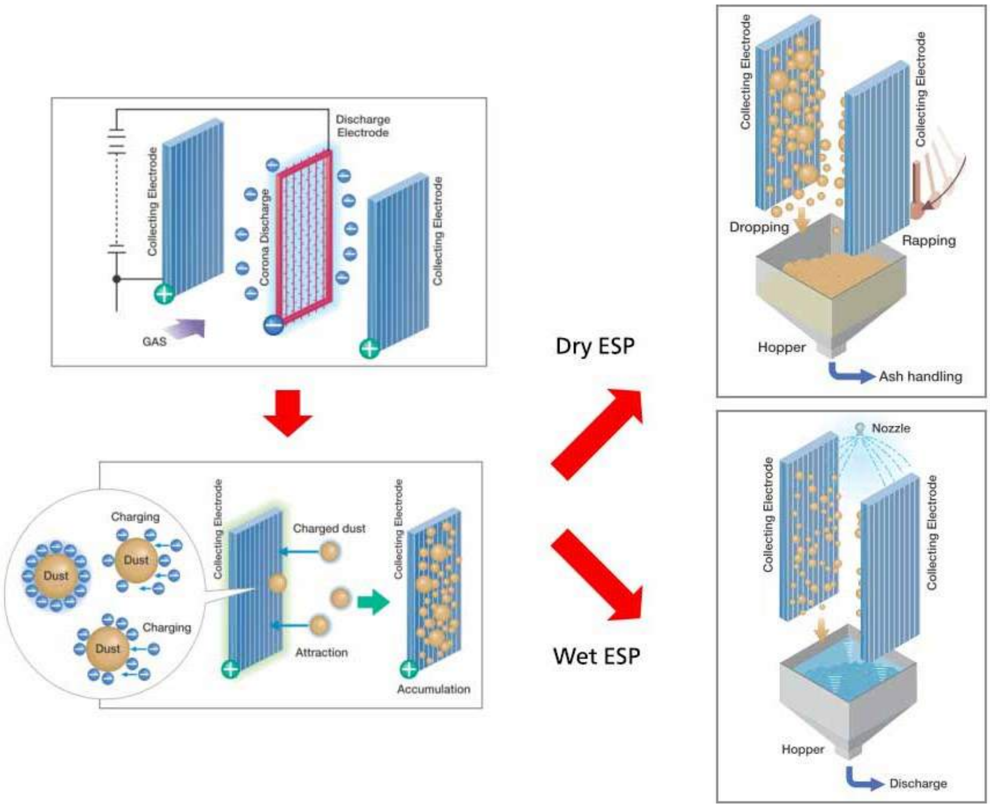

Figure 2: Mitsubishi Power - Basic Principle of dry ESP (applicable for this research) and wet ESP. Source [16].

2 RESEARCH OBJECTIVE

The background information provided above served as the basis for the adoption of a systematic literature review to examine the ESP studies conducted to date with the objective to transfer the learnings to South African power plants. The purpose of this study is to address the following query:

What are the characteristics in the published ESP system studies that can be transferred to the South African power plants with the aim to enhance dust removal system performance and its availability?

The articles that were included in this study were reviewed with focus on the topics listed in Table 3 below.

Table 3: Relevant topics for the ESP system SLR study.

Topic of interest in the included ESP studies	Description
Fuel type	This requires details of the product that had undergone combustion and its byproducts that have to be removed to meet the air quality standard using ESP. This is vital when transfer of learnings has to be adapted.
Flue gas type	It refers to the type of gas that has been produced in a particular process (Eg.: boiler, etc.) and has to be undergo cleaning of the particulates in the ESP.
Industry sector	This denotes the field in which ESP technology is applied.
ESP type	This refers to the principle that was invented by Peek and used to remove the particulates as described in Figure 1 above.
ESP technology	Technological enhancements that have been included in the original ESP technology with the aim to exceed stringent environmental laws. Eg: Wet ESP, FGD, etc.
Dust removal system type	It refers to dust conveyance system that is used to remove trapped dust for delivery to the dumping site or used in construction industry. Eg: Dust hoppers feeding directly into to the primary armored chain conveyor or into the trucks, etc.
Capacity of the ESP	This measure assesses the size of the ESP considered in the studies. This is vital when benchmarking results have to translated into the South African power plants context. Eg: Volume of flue gas cleaned per day, etc.
ESP maintenance strategy	ESP system's reliability depends on a number of variables. The changes in these variables triggers maintenance manager to repair the plant at certain time and after it has processed certain amount of dust in tons.
ESP efficiency	This refers to the ratio of air and dust that enters the ESP to the air and dust that exit the system. The higher the ratio, the higher the air quality produced by the ESP. This function is complex as it depends on a number of variables that includes some of the following: gas distribution plates, discharge electrodes, collection plates, rapper system, etc.
Type of publications	This is a measure of the included ESP studies' academic health status as they are required to be rigorous, reliable and peer-reviewed.
Country and continent generated publications	This indicator offers the ESP researchers locations that are actively advancing the technology under review. This could help in cases where benchmarking has to be undertaken.
Publication trends	This gauge, tests the activity of the ESP technology research within the selected sample. Positive trend will indicate that stakeholders have evaluated this area to be critical and have invested their resources with the objective tackle the environmental challenges while negative trends could translate to less important area for the current era.

The outcome of this study shall be used to transfer the learnings to the South African ESP plants with the objective to enhance the availability through system dynamics modelling and simulation. In the future study, modelling process shall integrate learnings from this study and separate underlying assumptions (structure, policies, and parameters) from the implied behaviour, build from the inside of the ESP dust handling plant to determine and to modify the processes (Eg: maintenance, operating, etc.) that cause desirable and undesirable behaviours like low plant availability and environmental pollution.

3 RESEARCH METHODOLOGY

Using a systematic literature review, Sciencedirect and other sources were indexed on March 1, 2024, to extract pertinent books, conference papers, journals, and theses that had an impact on the industry. After that, information was coded, taken out of the manual, and studies were included to summarize and evaluate the findings, explain how ESP technology was used to remove dust particulate matter (PM), and point out any inconsistencies or gaps in the data. This analysis mapped around 54 ESP articles in total. An explicit and repeatable search approach was employed throughout the investigation process, and studies were either included or excluded, based on the criteria. The advantages and disadvantages of this methodology were known; hence research controls were put in place to eliminate bias. There were several restrictions to be aware of in addition to its strength, researchers provided country specific cases that were subject to their interpretation and may be somewhat subjective [18].

4 SEARCH STRATEGY AND SELECTION PROCEDURE

In order to find levers that can be utilized to improve ESP plant performance and make South African power plants more environmentally friendly, the ESP research data has been evaluated and reported using the modified Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) systematic literature review criteria [19]. The research approach that was used is shown in Figure 3. In order to extract value from the selected papers, the authors reviewed the entire article when the abstract did not contain information in Table 4 and Figure 3. The search term *Electrostatic precipitator for particulate removal* was used by the search engine. Owing to the lack of structured research in the ESP studies, it was rather cumbersome to select the appropriate search words, a total of the first 63 articles were identified for the systematic review, to select the final articles to be included in this review, a practical screening was conducted, this was based on the setting of criteria and flow diagram in Figure 3.

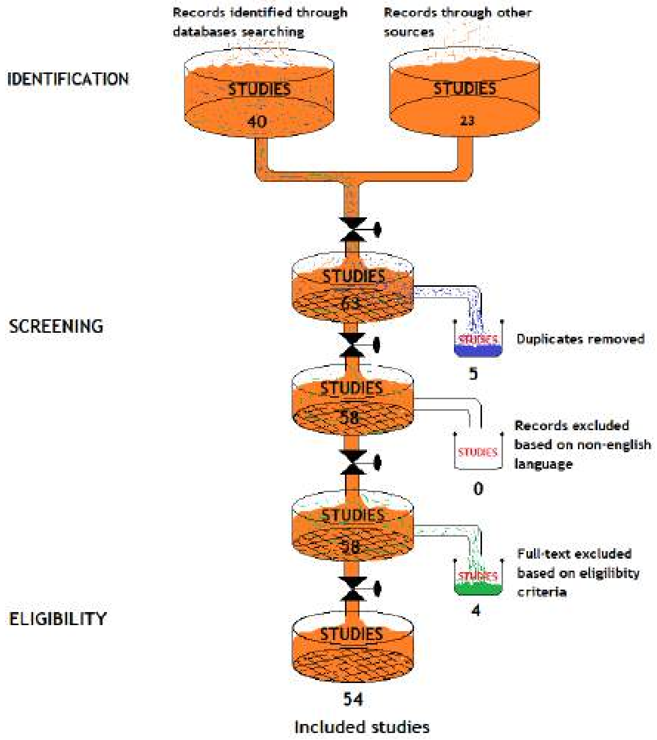

Figure 3: Systematic review flow diagram. Adapted from source: [19].

5 INCLUSION CRITERIA

The 63 records from the original search were loaded into the Mendeley program. The remaining 54 abstracts and titles were then assessed using the inclusion and criteria (Figure 3 and Table 4) after 9 papers were eliminated with reasons (see Figure 3). Studies were included if they appeared between 2014 and 2024. The 54 books, theses, journal articles, conference papers, and technical reports were included. This procedure was followed to help the critics to quickly determine whether this study could be easily replicated to increase reliance in the research findings.

Table 4: Inclusion and exclusion criteria

Item	**Description**
Language	English
Timespan	2014-2022
Search string	"Electrostatics Precipitators particulate removal”
Questions	**Review focus**
Population - who?	Electrostatics Precipitators particulate removal case studies locally and internationally.
Intervention - what?	Electrostatics Precipitators particulate removal case studies that had been duly developed and tested so that the learning could be transferred to the South African power plants.
Outcomes - expected result	Identification of the Electrostatics Precipitators particulate removal levers that can be explored and transferred to the industry in general

6 STUDIES SELECTION

The study's articles went through a two-stage filtering process, which excluded 9 articles that did not meet the inclusion criteria. Qualitative data analysis was used to scrutinize and categorize all papers that met the criteria [20]. Braun and Clarke [21] define thematic analysis as "a method for recognizing, analysing, and presenting patterns (themes) within data."

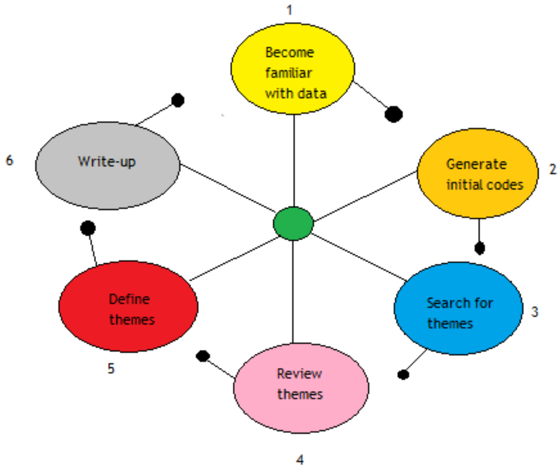

Figure 3: Framework for doing thematic analysis. Source: [22] and [23].

The results of the thematic analysis are outlined under section 7 based on articles in the reference section. The studies varied significantly and did not adhere to PRISMA guidelines, which made it impossible to conduct a meta-analysis. As a result of these and other issues, it was determined that the studies were inadequately designed when utilizing the systematic literature review and thematic analysis methodology.

7 STUDY CHARACTERISTICS

7.1 Fuel source that produced the flue gases.

Majority (61%) of the fuel that was used in these studies was coal while 26% did not indicate the type of fuel that was used. During the course of this research it became evident that ESP technology had a wider application in the general industry as this was used to remove pollutants emanating from sources such as nuclear explosion, biomass, diesel, etc. Refer to Figure 4 below for the types of fuel served as sources of energy in the various combustion chambers in the studies under consideration.

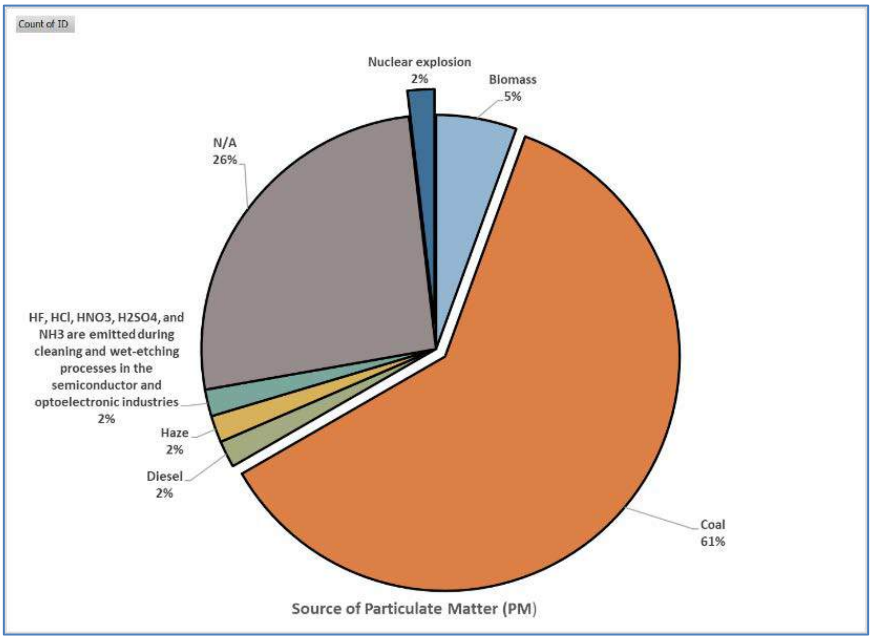

Figure 4: Sources of the fuel used in the studies.

7.2 Flue gases that was treated through ESP technologies.

In these studies, 31 different types of the “flue gases” were removed through the application of different types of ESP technologies. Dust or Fly ash (54%) constituted majority of the “flue gases” that were cleaned using this technology. Amongst these ‘flue gases” it was poultry dust, dust laden air in the offices, radionuclides (RN), etc. Refer Figure 5 for details.

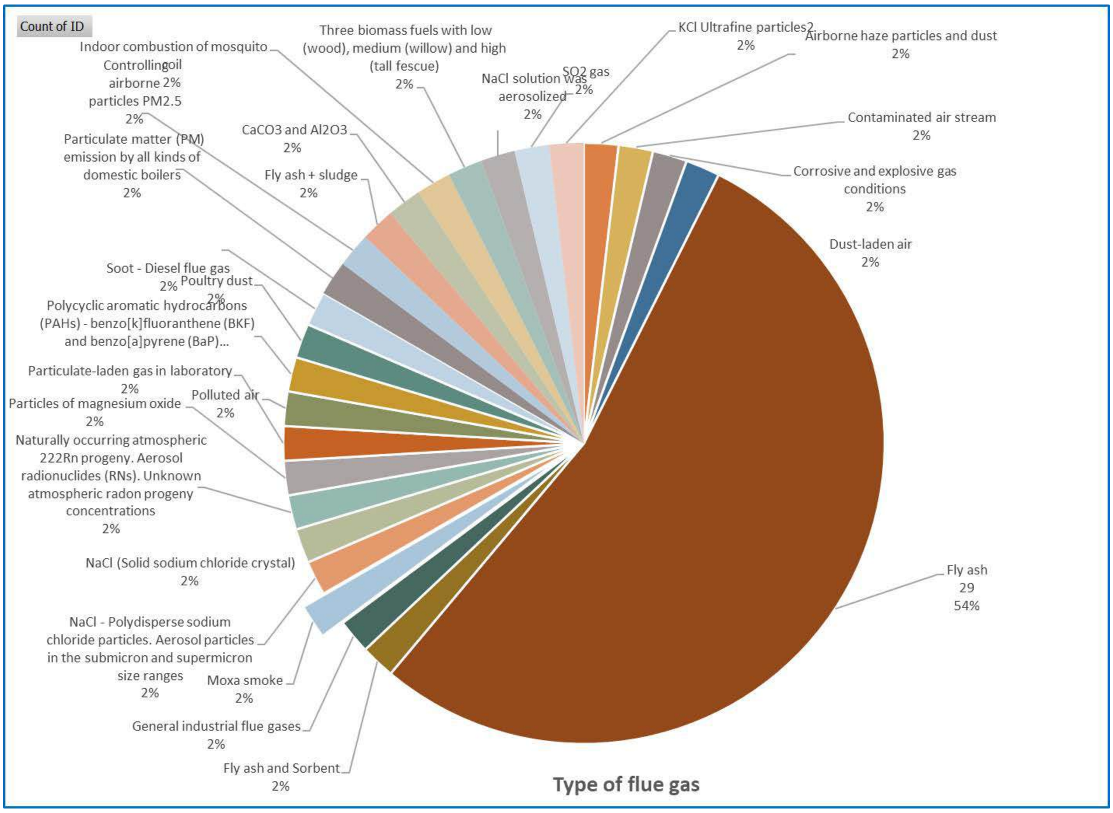

Figure 5: Flue gases that were cleaned using ESP technology in the studies.

7.3 Types of electrostatic precipitator (ESP) or air pollution control technologies in the studies.

The studies (54) that were considered made use of different types of ESP technologies, "Normal ESP" was the most common and they were similar to the ones that were in use in most of the South African power plants. In these studies, 19 different technologies were identified and the research indicated that latest research was focusing on the ultra-low emission particulate matter, which included: *filterable* and *condensable particulate matter* (see figure 7 below).

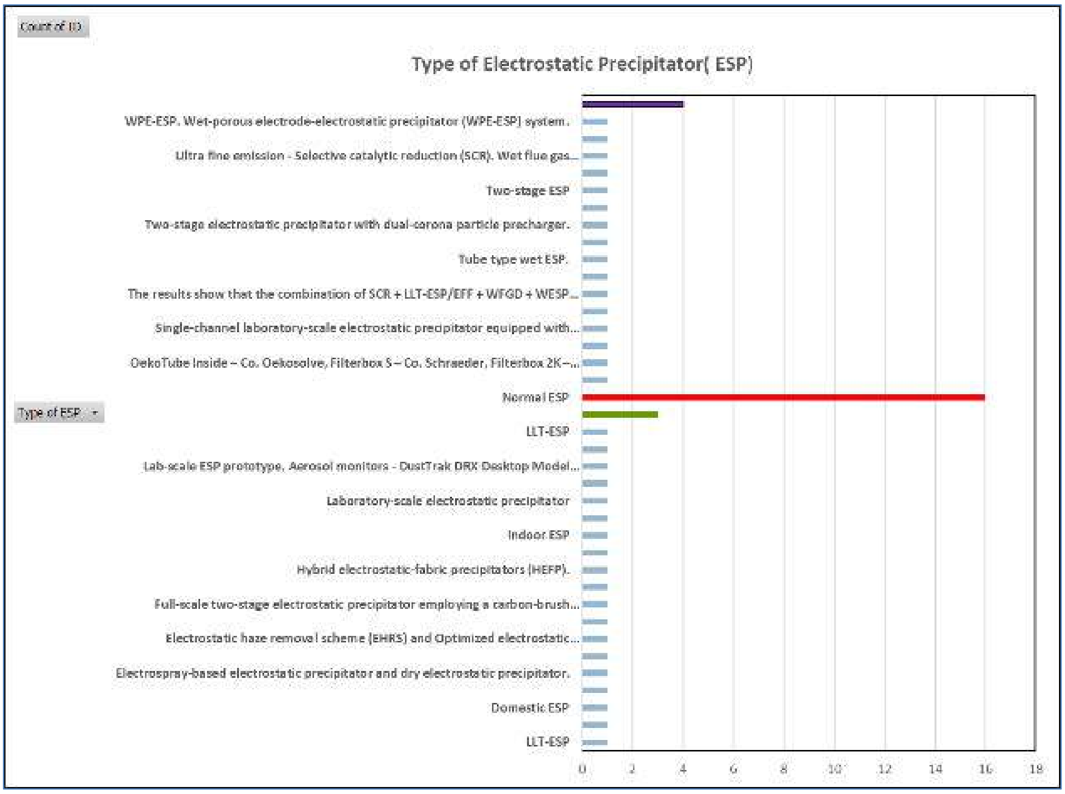

Figure 6: Different types of ESP technologies applied in the studies.

China had the most advanced air pollution control technologies, these included desulfurization (SOx), denitrification (NOx), dust collection (PM_{10} and $PM_{2.5}$) and multi-pollutant (Hg) technologies [66]. According to Garnham and Langerman [13], mercury was "a persistent and toxic substance" and the South African power plants air pollution control technologies were not removing this pollutant. Chinese studies with these advanced technologies could be adapted in the South African power plants to enhance air quality.

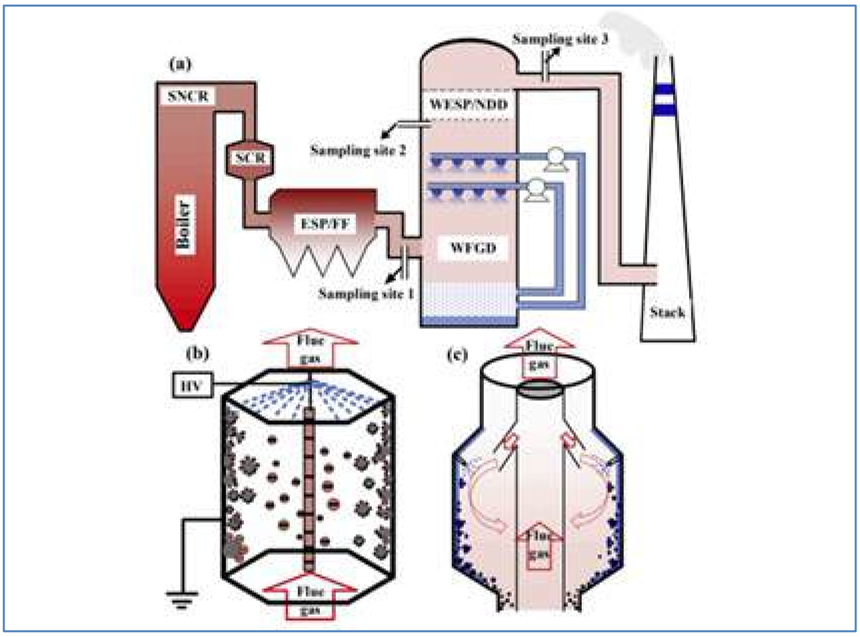

Figure 7: Ultra-fine emission technology. Source: [24].

7.4 Dust removal system from the ESP plant.

Majority (81%) of the ESPs that were considered did not cover the aspects of the dust removal system. This area was one of the most pressing in the South African power plants. In these studies, details of dust removal systems were not provided hence the student could not transfer the learnings. In the studies were this was stated, details of the dust removal system were not provided hence a need to enhance the research methodology in the future.

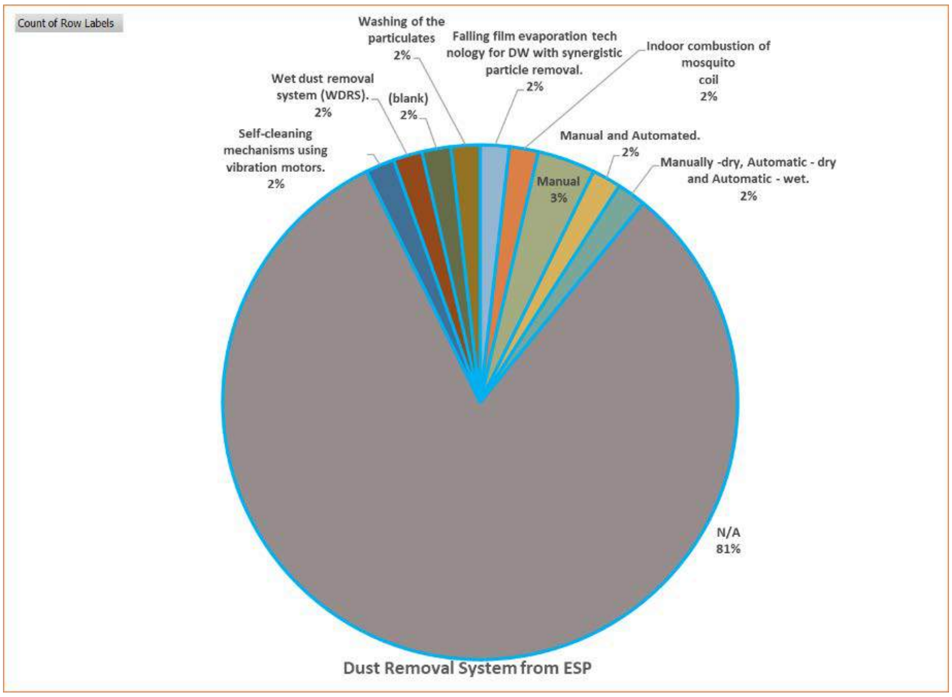

Figure 8: Dust removal systems from ESP plant.

7.5 Capacity of the ESP plant.

The authors of the 54 studies did not provide details of the ESPs' capacity that were under review and this was essential in order to compare like with like in order to make transfer of the learnings seamless. Flue gas volumetric rates were not included the studies.

7.6 Maintenance strategy of the ESP plant.

The authors of the 54 studies did not cover ESPs' maintenance strategy that were implemented in order to keep dust removal efficiency at its peak and the plant's uptime at its best level. This was deemed essential to ensure that power plant's emission is within the limits at all times.

7.7 Efficiency of the ESP plant.

The efficiency of the ESP could be defined as the ability to remove the particulate matter from the flue gas entering the system. This is usually expressed as a percentage and calculated based on the ratio of particulate matter collected to the total particulate matter entering the system. ESP performances were noted and the best that was recorded had 100% particulate removal. Factors affecting ESP Efficiency included: Particle size, type of flue gas, gas flow rate, electrodes configuration and voltage that was applied. These studies did not report on the duration of this performance parameter of the ESPs.

7.8 Industry sectors that made use of ESP plant.

The most dominant sector (72%) in these studies was the power plant sector and the second spot was occupied by household sector (11%). This was expected as the search strategy was based on the fly ash. Eleven (11) different industrial sector were identified in which the ESPs were applied.

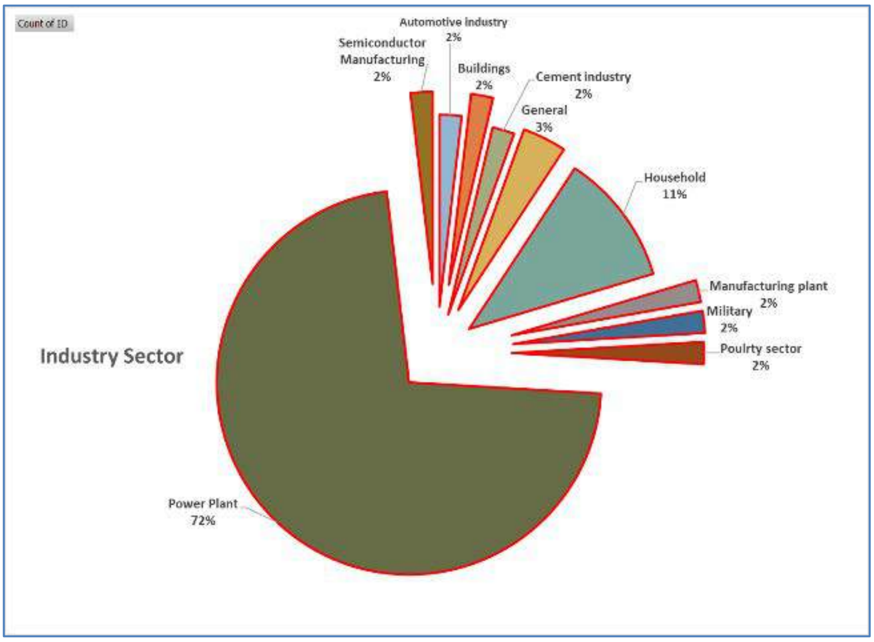

Figure 9: Industry sectors that applied ESP technology.

7.9 Authorship of ESP research Country and Continent.

Chinese researchers (52%) were the most active scientists in the ESP research technology. This performance was found to be aligned with the air pollution control advancements [25] that China had from 2013 to 2023 (see Figure 11 below for the trend).

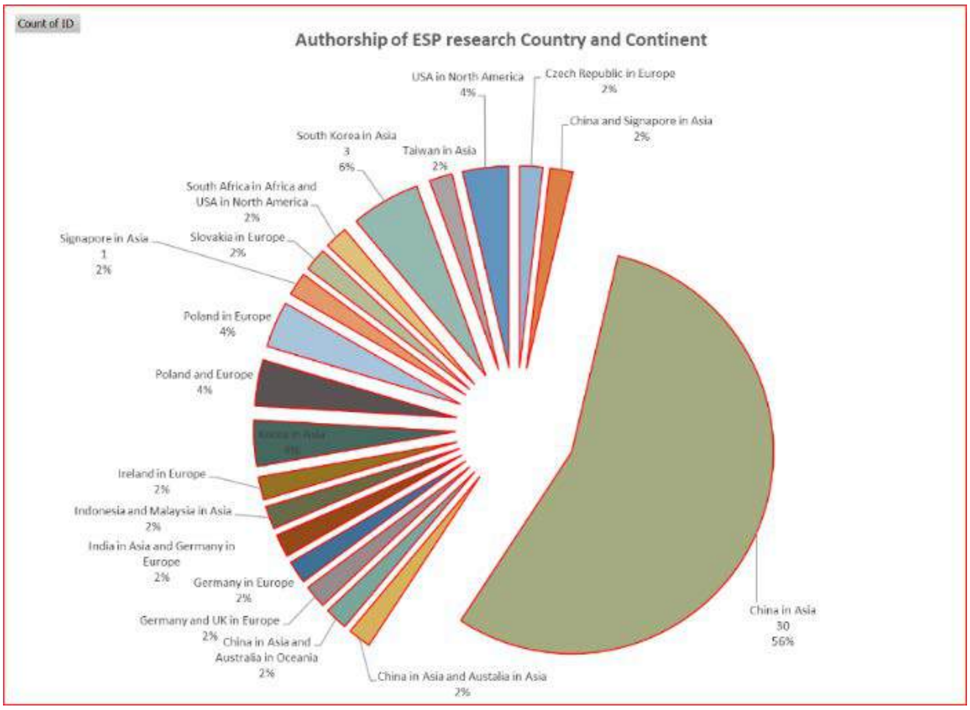

Figure 10: Authorship of the ESP case studies by country and continent.

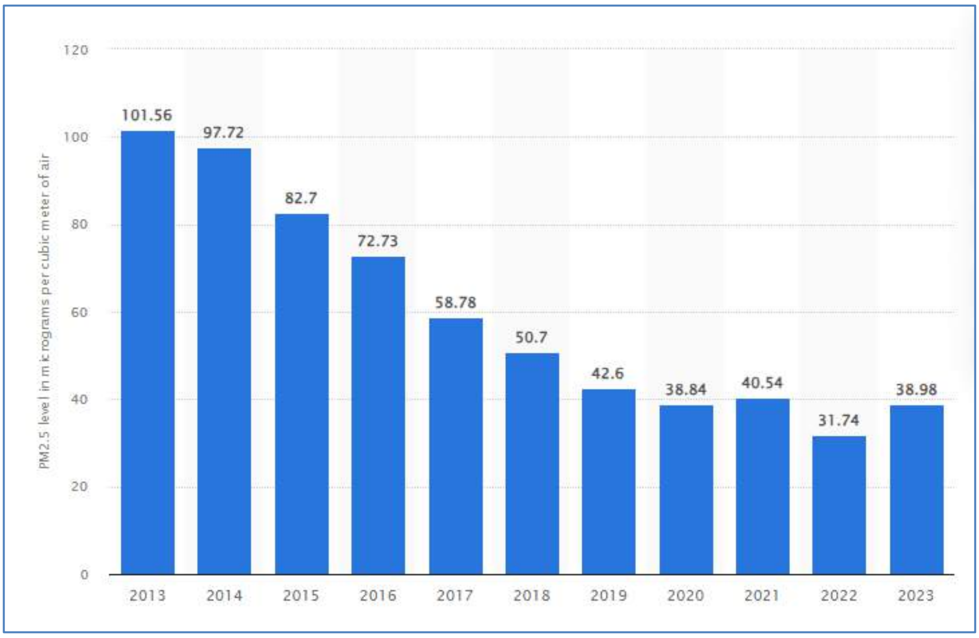

Figure 11: Average annual PM2.5 air pollution levels in Beijing, China between 2013 and 2023 (in micrograms per cubic meter of air), Source [70].

7.10 Publication type application of ESP in the industry sector.

Majority of the publications that were considered included Journals and Scientific Reports. High percentage of the studies was made up journal publications, indicating the emphasis on rigorous and peer-reviewed articles.

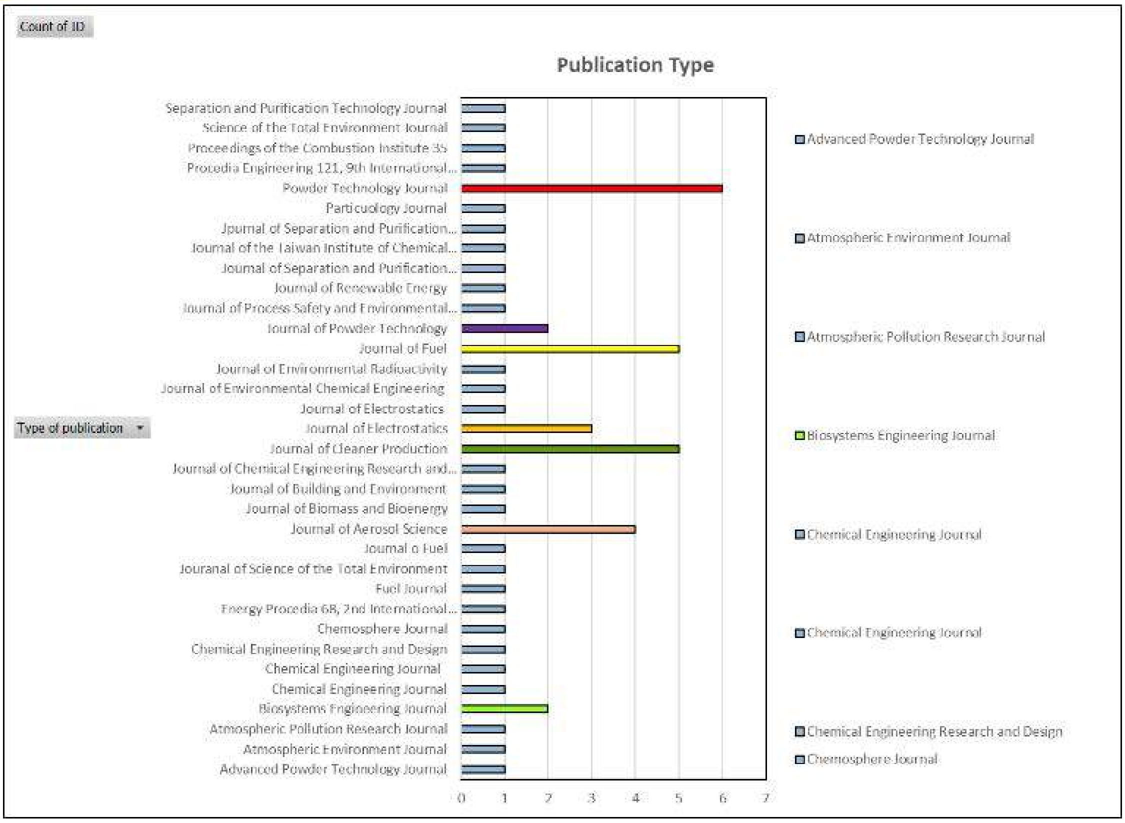

Figure 12: Type of publications included in the ESP studies.

7.11 Publication trends.

The figure indicates an upward trend, meaning that with increase in the environmental laws, researchers are forced to return to the laboratories in order to answer difficult questions of to produce the products without harming the environment or shut down the businesses.

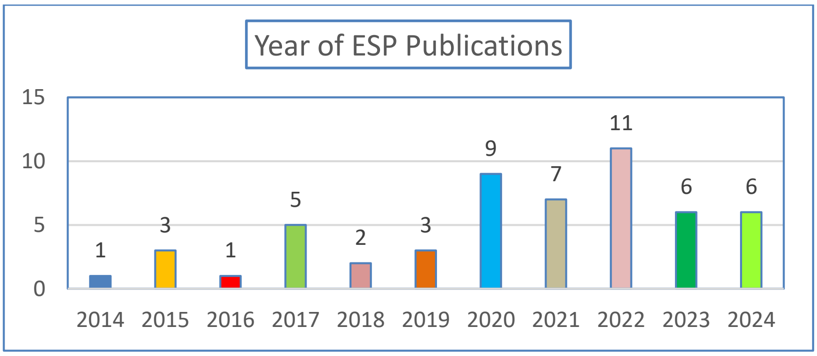

Figure 13: Publication trends in the sample of the ESP studies.

8 DISCUSSION OF THE REVIEW FINDINGS

Table 5 below provides a summary of the systematic literature review and learnings that are important for the ESP industry practitioners.

Table 5: Learnings from the literature.

Item	**Study findings**	**Notes for ESP practitioners to counter ESP replicability crisis and enhance dust removal and plant uptime.**
Fuel type	Coal was the most common fuel. Industry in general made use of ESP to clean coal's combustion products that were harmful to the environment and population.	Application of this type of technology has somehow matured and it was successful given high application rate.
Flue gas type	Fly ash as one of the substances found in the combustion products and this was the most dominant application. ESP could be used in the other industry as it was found that this could be used to clean air in the general buildings.	Research in the future must be opened to all applications so that best performance practices could transferred to the power plant sector.
Industry sector	Power plant sector was the most dominant area where ESP technology was applied. Learnings from the other power plants with ESP could help to enhance the plant uptime and retain the environment green.	There is a need for the power plant operators, academics and designers to combine forces and intensify sharing of the operational experiences so that race could be won against environmental pollution.
Maintenance strategy of the ESP	The 54 studies did not put emphasis on the ESP maintenance strategy, this could be due to the fact that industry has long won this battle and the focus was on the removal of the ultrafine emissions.	South African power plants to conduct benchmarking exercise with the Chinese counterparts to learn from their successes since their plants did not register plant downtime issues on plant maintenance literature.
ESP or air pollution control technology	Development of the ESP technology is at an advanced level, Reference section has reported a number of new technologies that are now applied by various sectors to combat pollution.	South African power plants to conduct benchmarking exercise with the Chinese counterparts to learn from their successes and implement learnings in their plants.

9 LIMITATIONS

This research was based on the publications between 2014 and 2024. It was conducted with English-speaking lenses and entered the Sciencedirect database and other sources. This provided the 63 studies, but it might have missed any other significant research that was published elsewhere or in languages other than English. Future research should therefore be aware of English-based and aim to incorporate studies from regions previously thought to be underrepresented. This could involve looking for ESP studies using alternative techniques and using translation software for non-English studies [19]. The abstracts for some of the research were not comprehensive to provide vital details of their studies.

10 CONCLUSION

Majority of the included studies (61%) indicated that ESP technology was mainly used for the removal of the coal combustion flue gas and 26% of the studies did not mention the type of fuel used for their research. Literature review revealed that ESP was not confined to dust removal as 31 different pollutants were removed using this technology to control quality of air.

Nineteen (19) different types of ESP technologies were identified through this study and this included the state-of-the-art air control technology that were used to remove ultra-low emission PM which included: filterable and condensable particulate matter and the South African power plants were lagging behind on this area.

In the studies that were reviewed, 81% did not mention the dust removal system that was employed and only 19% stated without providing details of the system employed.

Capacity of the ESPs that were studied was not provided in all 54 articles and this hindered transfer of learnings to the South African power plants.

Maintenance strategies that were put in place to eliminate the pollutants were not mentioned in the case studies that were considered. This was deemed essential as consistent elimination of the pollutants was a statutory matter for the power plant operators.

Studies considered had reported excellent ESP efficiencies but they failed to provide performance of these plant items over time.

Chinese were the leaders in ESP technology based on the number of the research outputs (52%). Advanced air pollution control technologies included: desulfurization (SOx), denitrification (NOx), dust collection (PM_{10} and $PM_{2.5}$) and multi-pollutant (Hg) technologies. Chinese plants were found to be the best source for benchmarking in the air pollution control technology.

Research trends were on an upward owing to the increase in the stringent environmental laws.

ESP studies' focus was mainly on breaking air pollution control barriers hence the reliability of their ESP dust removal system did not feature as it was anticipated by this study's researchers. This could be translated as a sign of not having the correct maintenance pillars in the South African power plants' dust and ash handling systems.

These learnings shall be applied in the development of the ESP plant system dynamics operation and maintenance model to be developed in the future.

11 RECOMMENDATION

Future studies will pay attention on the ESP plant maintenance and its support system with objective to eliminate low plant reliability as the included studies have relegated this aspect to the lowest priority rank.

To conduct a research on the elimination of ozone generated in the ESP plant in the future.

12 COMPETING INTERESTS

The authors declare that they did not have competing interests.

13 ACKNOWLEDGMENTS

The Ph.D. candidate would like to thank the University of South Africa (Unisa) for funding this research.

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DEVELOPING A PRIMARILY QUANTITATIVE INFRASTRUCTURE RISK CATEGORISATION METHOD

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ABSTRACT

South African infrastructure faces security risks including vandalism, theft, organised crime and hybrid threats. One of the legal mechanisms to counter these threats is the Critical Infrastructure Protection Act (CIPA), No. 8 of 2019. Infrastructure risk categorisation is required by CIPA sections 19 and 20 for declaration as critical infrastructure (CI). Risk categorisation evaluates the *consequences* of damage, harm or loss to CI or interference with the ability or availability of CI to deliver basic public services *to society*. The risk categorisation is part of the application for declaration as CI (CIPA section 17), but a method has not been adopted yet. The risks that impact infrastructure are contextualised in relation to risk categorisation as there is potential for misunderstanding when implementing the Act. The purpose and importance of risk categorisation are highlighted. An outline is proposed for an infrastructure risk categorisation method. Finaly, direction for future work is provided.

Keywords: security risks, Critical Infrastructure Protection Act, infrastructure, risk categorisation

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1 INTRODUCTION

South African infrastructure faces security risks including vandalism, theft, organised crime and hybrid threats [1, 2]. It is important that South Africa develop proactive and preventive approaches and frameworks to counter these threats. One of the legal mechanisms is the implementation of the Critical Infrastructure Protection Act (CIPA), Act No. 8 of 2019 which will replace the National Key Points Act (NKPA), Act No. 102 of 1980. According to CIPA section 1,

> *'''infrastructure'' means any building, centre, establishment, facility, installation, pipeline, premises or systems needed for the functioning of society, the Government or enterprises of the Republic, and includes any transport network or network for the delivery of electricity or water;'*

This article considers the development of a risk categorisation system as part of the South African Police Service (SAPS) National Commissioner's functions in terms of CIPA section 9(2)(a)(i):

> *"(2) The functions of the National Commissioner are to develop uniform standards, guidelines and protocols for approval by the Council regarding—*
>
> *(a) the manner in which—*
>
> *(i) infrastructure must be identified, categorised and declared critical infrastructure".*

Infrastructure risk categorisation as high-, medium- and low-risk is required by CIPA sections 19(1)(b) and 20(1)(b). CIPA risk categorisation evaluates **the consequences** of damage, harm or loss to critical infrastructure or interference with the ability or availability of critical infrastructure to deliver basic public services **to South African society**. Since society is dependent on the environment, any reference in this article to society includes the environment. The risk categorisation is part of the application for declaration as critical infrastructure (CI) in terms of CIPA section 17, but a risk categorisation method has not been adopted yet. The application is completed by the enterprise that owns the infrastructure and verified by the SAPS Critical Infrastructure Protection Regulator (referred to as the Regulator for brevity). A proposed application would contain general information about the applicant and information for declaration including the infrastructure sector, point or networked infrastructure and SAPS approvals. The reference to the 'Council' above is the Critical Infrastructure Council, established in terms of CIPA section 4. The Council makes recommendations to the Minister of Police (CIPA, section 19) about the risk categorisation for the infrastructure that is the subject of the application.

This article deals with two questions related to risk categorisation:

- How should the risk categorisation be implemented given the current legislation? This addresses the CIPA section 9(2)(a)(i) requirement in the short term.
- What might be proposed if the legislation were to be amended?

The article is based on work that the CSIR has conducted in collaboration with the drafters of the regulations, security managers and infrastructure operators, especially in relation to the method for risk categorisation. Inputs to the CIPA regulations are based on engineering, security, legal and systemic considerations. This article offers an opportunity to review and discuss the contributions and provides a rationale for the inputs made to the CIPA Regulations. It also offers inputs for future CIPA amendments related to risk categorisation. Hence this article is at the science, engineering and policy interface.

2 METHOD AND OVERVIEW

A literature review lays out the various risks that may impact critical infrastructure (section 3.1) as applicable to CIPA. The relationship of these risks to risk categorisation in CIPA must be mapped out to reduce misunderstanding when implementing the Act. With this groundwork, the purpose of risk categorisation is discussed (section 3.2).

Building the risk categorisation framework requires understanding the propagation of risk through the infrastructure and the risk categorisation dimensions. The legacy of the NKPA based on the concept of a "point" as the name indicates, requires a discussion of networked infrastructure for CIPA (section 4.1). For networked infrastructure, the network's structure impacts the availability of services at different endpoints differently and must be considered during risk categorisation (section 4.2). The risk categorisation dimensions related to the national societal risk are based on CIPA and descriptors are developed in section 5. Using the concepts of point and networked infrastructure and the risk dimensions, a quantitative method for categorising infrastructure as low-risk, medium-risk or high-risk is developed in section 6. The proposed method is compared against existing methods. Finally, conclusions and recommendations are provided in section 7. Ongoing and future work includes the design of the qualitative risk categorisation questions for the CIPA application.

3 LITERATURE REVIEW

3.1 The critical infrastructure risk model

This section contextualises CIPA risk categorisation within infrastructure risk assessment [3, 4]. The CI risk model illustrated in Figure 1 is based on input, enterprise (internal) and output risks [1].

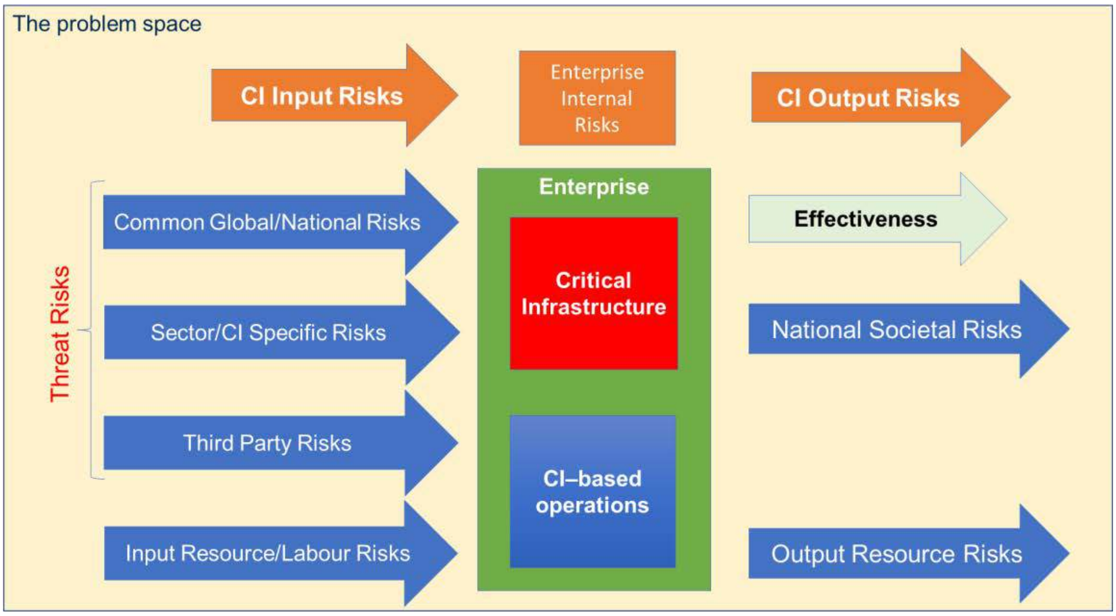

Figure 1: The CI risk model [1]

Input risk always impacts CI **effectiveness**. According to CIPA, the main measure of CI effectiveness is availability (up time / total time). The first input risk category is **security risks arising from threats to CI.** This includes *common global and national risks*, *sector or CI specific risks and third-party risks*. CIPA section 1 defines threats as:

> *'**"threat"** includes any action or omission of a criminal, terrorist or accidental nature which may potentially cause damage, harm or loss to critical infrastructure or interfere with the ability or availability of critical infrastructure to deliver*

> *basic public services, and may involve any natural hazard which is likely to increase the vulnerability of critical infrastructure to such action or omission.'*.

The second input risk category is r**esource risks** relating to insufficient capital, knowledge, skills, technology, information, communication, energy, health, sanitation, transport, and water, etc. required by the CI enterprise to ensure the availability of its services. The third input risk category is **labour** (union or strike) related risk.

Common global and national risks affect all infrastructure within the ecosystem. Examples of such risks include:

- Political risks;
- Economic risks including a global financial crash;
- Legal/regulatory risks;
- International obligations;
- Military risks;
- Organised crime risks;
- Large scale social unrest; and
- Environmental risk, of which global climate change is one.

Since these risks are common, they can be assessed by a small number of mandated organisations, for example, the National Intelligence Co-ordinating Committee, State Security Agency, South African Police Service, and the South African National Defence Force, at a national level, for the benefit of the CI community on an ongoing basis.

Third-party risks arise from parties providing systems (including information systems) and services, such as guarding, to the CI enterprise and would have access to the CI infrastructure and information.

Enterprise risks relate to the strategic, operational, and tactical management of the CI enterprise. Enterprise risks include governance and management failures, failure to manage risk, failure to develop and implement an enterprise strategy, failure to manage resources, and a lack of internal controls. Corruption is sometimes an enterprise level risk. However, in South Africa corruption is a systemic risk that impacts the CI ecosystem, called "state capture" [5]. CIPA does not make any reference to enterprise risks.

The **output risks** are, broadly, national societal risks and output resource risks. The national societal risks include economic, political, social, environmental, safety, and security risks. Output risks arise from the CI as contemplated in CIPA sections 16(1) and 16(2)(a)-(e):

> "*16. (1) Infrastructure qualifies for declaration as critical infrastructure, if—*
>
> *(a) the functioning of such infrastructure is essential for the economy, national security, public safety and the continuous provision of basic public services; and*
>
> *(b) the loss, damage, disruption or immobilisation of such infrastructure may severely prejudice—*
>
> *(i) the functioning or stability of the Republic;*
>
> *(ii) the public interest with regard to safety and the maintenance of law and order; and*
>
> *(iii) national security.*
>
> *(2) In determining whether the qualifying requirements contemplated in subsection (1) are met, one or more of the following criteria must be applied:*
>
> *(a) the infrastructure must be of significant economic, public, social or strategic importance;*

> *(b) the Republic's ability to function, deliver basic public services or maintain law and order may be affected if a service rendered by the infrastructure is interrupted, or if the infrastructure is destroyed, disrupted, degraded or caused to fail;*
>
> *(c) interruption of a service rendered by the infrastructure, or the destruction, disruption, degradation, or failure of such infrastructure will have a significant effect on the environment, the health or safety of the public or any segment of the public, or any other infrastructure that may negatively affect the functions and functioning of the infrastructure in question;*
>
> *(d) there are reasonable grounds to believe that the declaration as critical infrastructure will not have a significantly negative effect on the interests of the public;*
>
> *(e) the declaration as critical infrastructure is in pursuance of an obligation under any binding international law or international instrument;*"

The output resource risks relate to the provision of basic public services depending on the specific type of CI and include the disruption of energy, health, sanitation, transport, communication, or water services. Measurable output risk consequences include:

- Financial cost arising from the repair of CI, or, in the worst case, replacement costs;
- Costs incurred by the enterprise for alternative arrangements during the time required to repair or rebuild the CI;
- Number of deaths arising from the CI or a lack of CI availability;
- Loss of quality of life arising from the CI or a lack of CI availability;
- Opportunity cost to the public resulting from the loss of products or services arising from the CI or a lack of CI availability;
- Cost of environmental rehabilitation due to damage or degradation; and
- Loss of reputation [6].

Sections 16(1) and 16(2)(a) -(e) quoted above provide a mandate for what can be done in the risk categorisation method while the list of output consequences provides the means for realising the mandate (discussed further in section 6).

Threat risks may realise the national societal risks directly or indirectly via the infrastructure, but these are dynamic and are not directly relevant to risk categorisation. **CIPA risk categorisation is based on the national societal risks arising from the infrastructure.** The purpose of risk categorisation is important to understand so that the risk categorisation method is correctly developed.

3.2 Risk and the purpose of risk categorisation

An enterprise that relies on infrastructure will usually implement measures to secure the infrastructure. However, there may be substantial societal risk that demands more than the enterprise is willing to implement or spend to reduce the residual threat risk [7]. The Regulator and the Council represent the national societal interests using the CIPA risk categorisation to establish and maintain the required enterprise threat risk appetite. For CI categorised as high risk in terms of CIPA, there will be a low threat risk appetite with higher cost security measures than for a CI categorised as low risk (Figure 2).

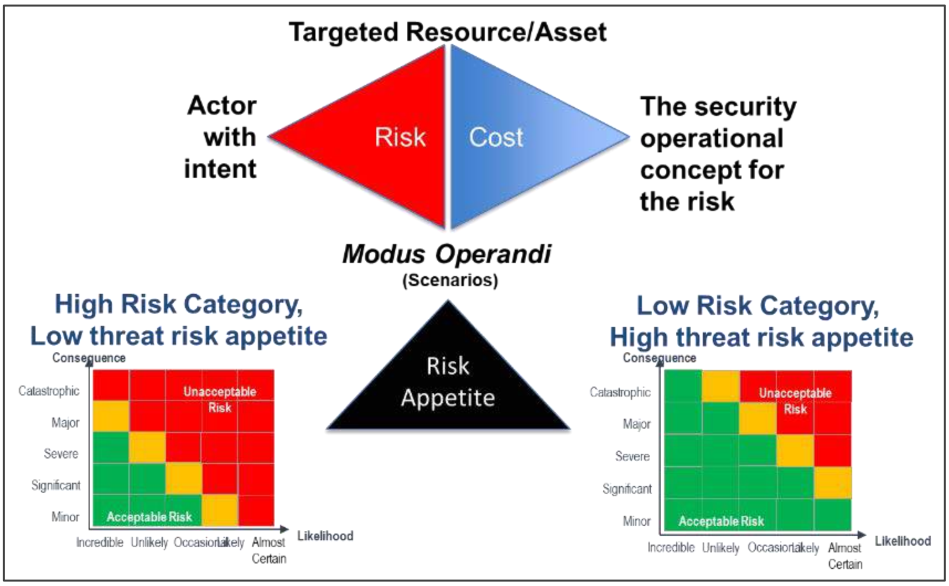

Figure 2: **Risk category determines threat risk appetite** [1]

The inherent risk is the risk that exists before any security measures are implemented due to of the value of the enterprise assets, the environment, and society. The expected value of the inherent risk is

$$R_{Ii} = P_{T_i} C_{Li}$$

where P_{T_i} is the probability of a threat event T_i contemplated in the definition of threat, which is either an attack of a criminal or terrorist nature, a man-made accident, or a natural disaster. The input risk relates to not knowing the type of threat and its probability. For any threat event there is a *coupling though the infrastructure* to a range of consequences from no consequence to the most severe. Let C_{Li} represent the sum of the total enterprise and the national societal loss arising from a threat event in monetary terms (this is the output risk listed in the previous section). Recognising that there are many threat events that will contribute to the inherent risk expressed in monetary value, the total inherent risk is

$$R_I = \sum_i P_{E_i} C_{Li}. \tag{1}$$

The security operational concept implemented by the enterprise describes what the security measures must do to mitigate threats [1]. For each malicious actor with intent against an enterprise resource or asset, with a particular *modus operandi,* an individual security operational concept is developed. It is possible to extend this to hazards, although this is not shown here due to space constraints. The total security operational concept emerges with the integration of the individual concepts. As the number of actors with malicious intent or the variety of *modus operandi* increase, the complexity of the total security concept increases.

Let P_E be the probability of the security measures being effective (evaluation of the effectiveness of security systems is outside the scope of this article but the interested reader is referred to Garcia [8]). When there is a security vulnerability, P_E is low. For this article a balanced security design is assumed, i.e. the security measures are equally effective for all threat events on different paths to the infrastructure. With mitigation of the inherent risk, the total residual risk, in monetary value, becomes

$$R_R = \sum_i P_{T_i} C_{Li} (1 - P_E) < R_T. \tag{2}$$

The residual risk must be below an acceptable threshold risk level, R_T, which represents the value of the residual risk transferred to the state that it can afford. If the acceptable threshold risk level is set too low (low risk appetite) the enterprise must bear an increased cost of the security measures. It is proposed that the Minister, advised by the Council, will set the acceptable threshold risk from time to time nationally [9]. If the probability of an attack increases or the cost of a loss is very high, the effectiveness of the security system must increase approaching 1, requiring increased spending on the security system. When the probability of an attack is low or where the cost of the loss is lower, less can be spent on security measures.

The CIPA risk categorisation is based on R_I and other factors that might not be represented in a monetary value, as high, medium, and low risk irrespective of the probability of the threat event (since this is dynamic). The design of the security operational concept must balance risk and security system cost based on the threat risk appetite arising from the CI risk categorisation (Figure 2). For CI categorised as high risk in terms of CIPA, there will be more security measures required with higher cost than for CI categorised as low risk.

The dimensions of the risk to the enterprise and society, the risk categorisation method and the required security measures are influenced by whether the infrastructure is a point or networked infrastructure, discussed next.

4 POINT VS NETWORKED INFRASTRUCTURE

This section defines infrastructure and clarifies point vs networked infrastructure and assessing the availability of networked infrastructure. These concepts are applicable to the legal concepts of critical infrastructure *and* essential infrastructure. The designation of "critical infrastructure" applies to infrastructure that is declared as such in terms of CIPA, section 20(1). Until it is declared it will be referred to only as infrastructure. "Essential infrastructure" is defined in the Criminal Matters Amendment Act, Act No. 18 of 2015, section 1 as '*any installation, structure, facility or system, whether publicly or privately owned, the loss or damage of, or the tampering with, which may interfere with the provision or distribution of a basic service to the public*'.

The remainder of this article draws on performability theory which includes dependability, reliability, availability, and safety and extended to include security by the author [10].

4.1 Defining point vs networked infrastructure

The legacy of the NKPA based on the concept of a "point" as the name indicates, requires discussing the types of infrastructure for the transition to CIPA. Within a single enterprise (i.e., a single "person in control of a critical infrastructure" as defined in CIPA, section 1), two types of infrastructure are identified in line with the definition:

> **Point infrastructure** is found on a single site and is functionally independent of other sites (but dependent on its environment). An enterprise may contain one or more point infrastructures. Under the NKPA, point infrastructure forms the basis for management.
>
> **Networked infrastructure** is interconnected and interdependent infrastructure that is functionally dependent on large parts of the infrastructure and typically provides a single service. Such infrastructure, and its corresponding service, spans a large geographical area and is connected by wireless communications or line infrastructure such as transport network, pipelines, powerlines, or fibre.

This article advocates for the concept of an infrastructure chain (IC) for managing networked infrastructure as an alternative to using point infrastructure. Networked infrastructure belonging to a single enterprise consists of one or more infrastructure chains (IC). An IC is determined based on its impact on operational availability leading to national societal risk.

An IC is a functionally dependent sub-network with at least one infrastructure element (IE) such that the loss of availability of one element in the chain results in the loss of availability of the chain. Roads, pipelines, electricity grids, for example, have this property. An IC can be identified between an endpoint or nodes where infrastructure splits or joins. One or more ICs form the end-to-end service. An end-to-end service has one or more resources that enter through the boundary and leave through the boundary.

Figure 3 presents a notional infrastructure network with petrochemical and electricity example IEs, and four ICs. The loss of availability of IE 1.1, IE 1.2, or IE 1.3 individually or in combination results in the loss of IC1, e.g., loss of a pump along a single pipeline. The total network is dependent on either IC1 or IC2 being available and IC3 being available. Operational control from a particular site also constitutes a critical infrastructure chain, IC4. Thus, the loss of either IC1 or IC2 results in the network having degraded capacity, but the loss of IC3 or IC4 results in network loss. An IC is vulnerable when there is no redundancy (a series path with no parallel path) such as IC3 in Figure 3. Thus, the infrastructure network's **structure** impacts the availability of services at different endpoints differently.

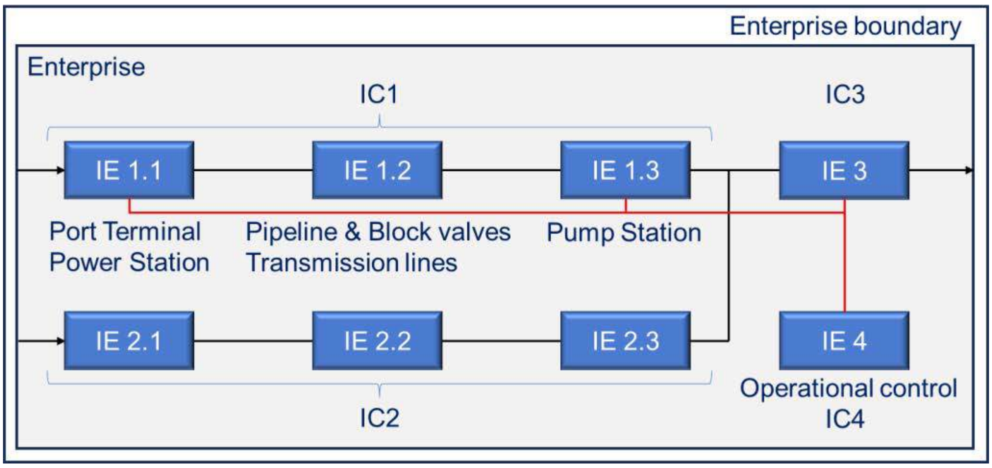

Figure 3: Identifying infrastructure chains

Defining networked infrastructure as distinct from point infrastructure is important because it impacts:

a) CIPA risk categorisation based on the network structure that cannot be achieved using the infrastructure point (IP) concept alone since *networked infrastructure propagates output risk through the network thus increasing the cost of the loss* (discussed further in the next section);
b) The design of practical command, control, and coordination arrangements between the enterprise, local, and provincial government, and other stakeholders;
c) CIPA regulations and risk categorisation application design; and
d) The Regulator's CI management approach.

A threat risk assessment must be performed for each of the IEs that form part of the chain as threats may vary geographically. For networked infrastructure a network map is required, and the risk categorisation is applied to each IC in the network. A map of ICs will be sufficient since the availability of the IC is dependent on all the IEs in the chain being available. The infrastructure ecosystem, where cross-organisational interdependencies between infrastructure are considered, must be dealt with in the future but is outside the scope of this article. The next section applies the concept of ICs to establish the availability of networked infrastructure.

4.2 Assessing the availability of networked infrastructure

The network's structure influences the risk categorisation required by CIPA sections 19 and 20. A loss of availability (CIPA section 16(2)(c)) can impact other critical or essential infrastructure within an enterprise or extend beyond it. For example, large airports are dependent on jet fuel being transported via a pipeline. If the pipeline is disrupted, then aircraft cannot be refuelled, disrupting flights. Where availability is impacted outside the enterprise, this is referred to as an input or output resource risk in Figure 1. The enterprise end-to-end service is deemed to start from the input resource to the output resource at the enterprise's boundary.

The remainder of this section focuses on the impact on availability within the enterprise. Simplifying the network structure to reveal single points of failure, Figure 3 is redrawn as Figure 4 (left) at the level of ICs. The concern with ICs is operational availability and how a loss of availability might pose a risk to society. In Figure 4 (left), IC1 and IC2 have the same risk categorisation while IC3 has a higher risk categorisation than IC1 or IC2. The output risk is contained at the output of IC3. In contrast, in Figure 4 (right), IC2 and IC3 *may* have the same risk categorisation depending on the output risk for each, while IC1 has a higher risk categorisation than either IC2 or IC3. Although IC1 does not have a direct enterprise output, if IC1 is not available, then the output risk manifests at the outputs of IC2 and IC3. This must be considered in calculating the cost of loss for IC1.

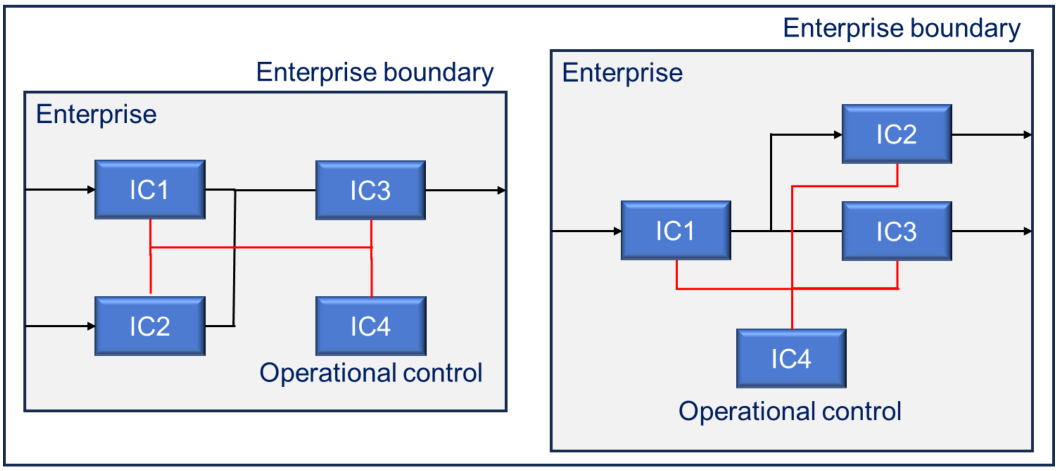

Figure 4: Identifying single point of failure in networked infrastructure with two network topologies

As a real example, an airport's airside and landside form an IC with one risk categorisation.

The operational control, IE4, and the control communications (shown in red in Figure 4) form an IC that is vulnerable to both physical and cyber-attacks. Internationally, cyber-attacks on infrastructure increased by 140% in 2022 over the previous year [11]. However, CIPA does not legislate cyber security. As a *matter of principle, the operational control has the same risk categorisation as the IC with the highest risk categorisation* if loss of operational control would lead to loss of availability or infrastructure vulnerability. In the case of Figure 4, IC4 has the same risk categorisation as IC3 (and additional risk categorisation is not required).

The following is proposed to assess how the structure of an infrastructure network impacts the operational availability and hence national societal risk:

a) For each end-to-end service, are there ICs that represent a single point of failure (SPOF)? Note the distinction between the SPOF of the IE that defines the IC (Figure 3) and the IC as a SPOF in the abstracted infrastructure network (Figure 4).
b) Evaluate the **end-to-end IC criticality index** defined as the number of end-to-end paths dependent on the IC under assessment / total number of end-to-end paths. An

end-to-end IC criticality index is in the range of 0 to 1 with an index value of 1 indicating high criticality. For the example in Figure 4 left, the IC criticality index for IC1 is ½, IC2 is ½, and IC3 is 1 and Figure 4 right, the IC criticality index for IC1 is 1, IC2 is ½, and IC3 is ½. This is a new index proposed by the author that can be calculated in an application should it be approved by the Council.

c) If there is an operations centre, the risk to availability is equal to that of the highest risk IC in the infrastructure network and therefore IC4's criticality index is 1.

Figure 5 provides a concept map summary of the infrastructure types with a focus on networked infrastructure.

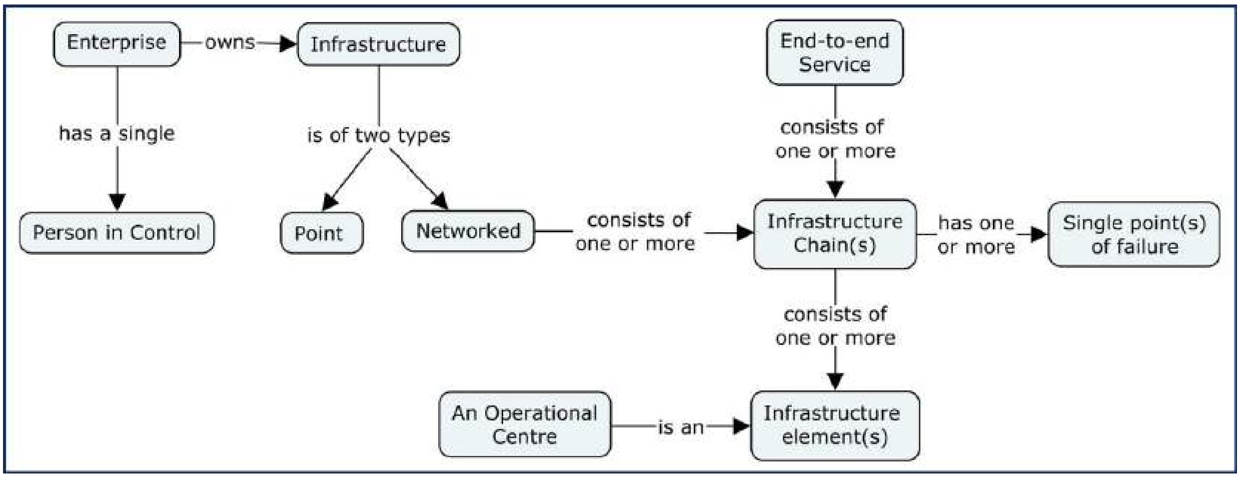

Figure 5: Concept map summary of the infrastructure types focusing on networked infrastructure

Damage, harm or loss to critical infrastructure or interference with the ability or availability of critical infrastructure all result in an impact across the various dimensions of risk categorisation and on other infrastructure. These risk categorisation dimensions are presented in the following section.

5 THE RISK CATEGORISATION DIMENSIONS

Based on CIPA sections 16 and 17, the risk categorisation dimensions are related to the national societal risk. Other aspects required under section 17(2) are addressed in the application form or in a physical security assessment. The proposed risk categorisation dimensions and corresponding definitions are presented in Table 1. Based on a modern view of security studies [12], national security in section 16(1)(a) and 16(1)(b)(iii) is included as political, economic, safety and security (from a public perspective), maintenance of law and order (from a government perspective), social, and environmental impacts. The military component of national security is not considered as a risk categorisation dimension. Attempts were made to ensure risk dimensions are, as far as possible, mutually exclusive to avoid assessing the same risk more than once. For each risk categorisation dimension, descriptors are proposed.

Table 1: Risk impacts and consequences

Risk categorisation dimension (reference to CIPA)	**Descriptor**: Impact arising from damage, harm or loss to infrastructure or interference with the ability or availability of critical infrastructure to deliver basic public services…

1	Economic impact (16(1)(a))	…on the economy in a geographic area resulting in loss of business revenue and profits, personal wages, jobs, taxes, and the infrastructure replacement cost.
2	Political impact (National Security in section 16(1)(a))	… that would interfere with activities or relations of the State (multinational, bilateral, and within the State).
3	Safety and Security impact / Maintenance of law and order (16(1)(b)(ii), (16(2)(b)))	… that makes the public feel unsafe (exposed to injury) and insecure (exposed to malicious threats). … that impairs or requires reactive policing, supported by legislation and prosecution.
4	Social impact (16(2)(a))	… to people and communities in a geographic area.
5	Environmental impact (16(2)(c))	… that will disrupt the environmental functions, i.e., supplying resources, assimilating wastes, sustaining life, and providing aesthetics.
6	Basic public services impact (16(1)(a), (16(2)(b)))	… that will disrupt communication, energy, health, water, sanitation, or transportation.
7	Public health and safety impact (16(2)(c))	… that would disrupt behaviours required for the maintenance of good health (e.g., boiling water), interfere with the human environment, medical care, or result in harmful physical influences (e.g., radiation).
8	Impact on other critical or essential infrastructure (16(2)(c))	… that causes a loss of an input resource to other infrastructure.
9	Impact on public when declared CI (16(2)(d))	Impact on the public resulting from a loss of access or rights to places declared as critical infrastructure.
10	Impact on international obligations (16(2)(e))	… is a breach or a potential breach of an international instrument (agreement, convention, or decision, etc.) adopted by the South African Government.

6 CATEGORISING INFRASTRUCTURE RISK

Given the purpose of risk categorisation and evaluation in section 3.2, the concepts of point and networked infrastructure (sections 4) and the risk categorisation dimensions (section 5) this section will develop the concept for the system of categorising infrastructure referred to in CIPA. CIPA section 19(1)(b) says the Council must:

> *(b) consider the potential risk category of such an infrastructure, taking into account—*

> *(i) the prescribed system of categorising infrastructure in a low-risk, medium-risk or high-risk category;*
>
> *(ii) the probability of failure, disruption or destruction of the infrastructure in question or threat thereof; and*
>
> *(iii) the impact and consequence of failure, disruption or destruction of infrastructure or threat thereof;*

CIPA does not explicitly state whether the risk is the inherent or the residual risk. Section 19(1)(a) requires consideration of the various dimensions in Table 1 related to the national societal risk. Based on equation (1), the inherent risk is determined as

$$R_I = \sum_i P_{E_i} C_{Li}.$$

The information required to determine the probability referred to in section 19(1)(b)(ii) will have to be collected by security managers and checked by the Regulator. However, the probability of a threat event, P_{E_i}, requires a threat risk assessment which is not explicitly mentioned in CIPA. This makes the assessment of the probability difficult to operationalise beyond a very subjective assessment *at the application stage*. Furthermore, the probability of a threat event is dynamic and cannot be known exactly and similar consequences may result from different threat events. Arson and an accidental fire can have identical consequences. Hence, it is proposed that probability is not considered *before declaration* as critical infrastructure in a future CIPA amendment.

A combination of quantitative and qualitative risk methods is proposed for risk categorisation, with the Council applying judgement based on the evidence. A **quantitative assessment** of the sum of enterprise cost and societal loss is proposed based on the objective measures of output risk listed in section 3.1. Let the conditional probability density function of the consequences given the specific threat event i be denoted as $P(C_L|T_i)$ and C_L represents the range of the sum of the total enterprise and the national societal loss arising from a threat event in monetary terms. The loss for a threat event i, C_{Li} represents serious consequences of at least 95% of the cost consequences resulting from threat event i. Using the conditional cumulative distribution function C_{Li} can be written as $P(C_L \leq C_{Li}|T_i) = \int_0^{C_{Li}} P(C_L|T_i) dC_L = 0.95$. The cost, C_{Li}, normalised by the maximum cost of loss over all infrastructure applications is then mapped to a high-, medium-, or low risk category (refer to line graph in Figure 6, which assumes a linear division of normalised cost). The use of consequences for managing threat risk is consistent with approaches used in nuclear [13, 14]. It is recommended that infrastructure not be considered for declaration as critical when the normalised cost of loss is sufficiently low to avoid unnecessary administrative burden on the enterprise or the Regulator.

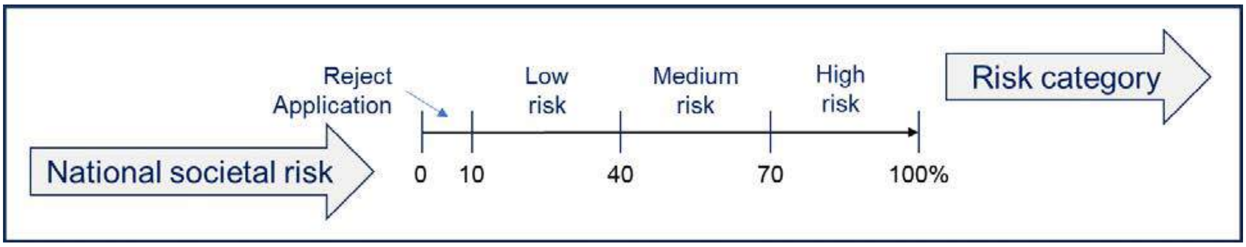

Figure 6: Mapping the national societal risk to the CIPA risk category

A **qualitative assessment** is proposed for consequences that are not easily assessed in monetary value, for example political consequences, based on a weighted sum of consequence questions evaluated on a Likert scale using the risk categorisation dimensions in Table 1.

CIPA section 17(4)(b) requires that the National Commissioner of Police conduct a physical security assessment. This assists in determining any security measure vulnerabilities to threat events resulting in low effectiveness. Following a successful application for infrastructure to be declared as critical, it is recommended that threat risk assessments (which are broader than a physical security assessment) be mandatory at least yearly and that the residual risk be evaluated.

The remaining task is to design the questions for each risk dimension in a way that removes as much subjectivity as possible and allows for comparison. This is done by anchoring the questions quantitatively and is the subject of future work.

7 CONCLUSIONS AND RECOMMENDATIONS

Defining precisely which risk is being referred to in the context of the CIPA risk categorisation was a necessary first step to developing a risk categorisation method. This article has extended the NKPA concepts to deal with infrastructure points *and networked infrastructure*. The networked infrastructure concept and the methods introduced in section 4 provides:

1. Methods for identifying ICs in networked infrastructure and supports practical risk categorisation of an IC since if one infrastructure element is not available, then the chain is not available, but the societal impact is approximately the same for an infrastructure chain;
2. Risk categorisation based on the network structure that cannot be achieved based on an IP concept alone since *networked infrastructure propagates output risk through the network thus increasing the cost of the loss*;
3. The NKPA operated at the infrastructure element level, but for networked infrastructure ICs will reduce the administrative burden with broader infrastructure coverage; and
4. A basis for developing and understanding the infrastructure ecosystem (although more work will be required at the ecosystem level in the future).

A combination of quantitative and qualitative risk methods is proposed for risk categorisation, with the Council applying judgement based on the evidence. A quantitative assessment of the consequences is proposed based on the sum of cost enterprise and societal loss (the measures of output risk listed in section 3) at the 95th percentile. This cost of loss, when normalised, can be mapped to a high-, medium- or low risk category. It is recommended that infrastructure not be considered for declaration as critical when the normalised cost of loss is sufficiently low to avoid unnecessary administrative burden on the enterprise and the Regulator. A qualitative assessment of consequences based on a weighted sum of consequence questions arising from the risk categorisation dimensions in Table 1 is proposed for consequences that are not easily assessed in monetary value, for example political consequences.

Threat risks may realise the national societal risks directly or indirectly via the infrastructure, but these are dynamic and are not used for risk categorisation. The assessment of the probability of a threat event is difficult to operationalise *at the application stage* beyond a very subjective assessment without spending time and money. Hence, it is proposed that probability is not considered *before declaration* as critical infrastructure in a future CIPA amendment. It is proposed that the application for declaration as CI be digitised to allow the risk categorisation to be calculated automatically based on information entered by the applicant. Following infrastructure being declared as critical, it is recommended that threat risk assessments are mandatory at least yearly and that the residual risk be evaluated (which requires determining probability and consequences). The risk categorisation method requires further work to determine the questions, the anchor values and to evaluate the method.

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DIGITAL TWIN ABILITIES IN CELLULAR MANUFACTURING: ILLUMINATING PATHWAYS TO SUCCESS

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ABSTRACT

This paper explores the integration of digital twin technology and machine learning in cellular manufacturing to enhance predictive maintenance and operational efficiency. By creating virtual replicas of physical assets, digital twins facilitate real-time monitoring and predictive analytics, enabling manufacturers to optimize production processes and resource allocation. The paper emphasizes the application of failure mode and effects analysis under uncertainty, highlighting a structured approach to prioritize defects based on risk, detectability, and severity. A case study in brake pad manufacturing illustrates the significant reduction in defect occurrences achieved through these technologies. The findings underscore 168 occurrences before machine learning and 76 after machine learning, the transformative potential of data-driven approaches in improving production performance, sustainability, and decision-making in modern manufacturing environments.

Keywords: Digital Twin, Failure mode and effects analysis, Machine Learning, Operational Efficiency, Predictive Maintenance.

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1 INTRODUCTION

Digital twin technology has gained popularity that optimizes various industrial processes, including cellular manufacturing. This technology has emerged as a transformative concept in the realm of cellular manufacturing, offering a virtual representation of physical assets and process. It creates a digital replica that mirrors the behaviour and characteristics of their physical counterparts, which enables real-time monitoring, predictive analytics, and decision-making in manufacturing environments. This technology plays a crucial role in optimizing production process, enhancing efficiency, and improving overall performance in cellular manufacturing setups.

The implementation of digital twins in cellular manufacturing involves the integration of advanced technologies such as Internet of Things, Artificial Intelligence, and data analytics to create a synchronized digital replica of the manufacturing cell. This virtual representation allows for the simulation of various scenarios, predictive maintenance, and the optimization of resource allocation within the manufacturing cell. By leveraging digital twins, manufacturers can gain valuable insights into their operations, identify potential bottlenecks, and make data-driven decisions to streamline processes and improve productivity.

Furthermore, digital twins in cellular manufacturing facilitate the converge of physical and digital worlds, enabling seamless communication between the virtual and physical environments. This integration enhances visibility, control, and monitoring capabilities within manufacturing cells, leading to enhanced operational efficiency and reduced downtime. The use of digital twins in cellular manufacturing underscores the shift of industry intelligent, data-driven manufacturing practices that prioritize optimization, flexibility, and adaptability in the face of evolving market demands.

The integration of digital twin technology in cellular manufacturing addresses pressing challenges faced by the modern manufacturing environments. These challenges incorporate the need for enhanced efficiency, flexibility, reduced downtime, and quality control.

Through use of digital twins in cellular manufacturing facilities can achieve significant improvements in efficiency and cost savings, paving the way for success in modern manufacturing environments.

The significance of this paper extends beyond immediate cellular manufacturing operational improvements. Which strives for companies to maintain an edge through innovation and efficiency. The successful adoption of digital twin technology can lead to substantial economic benefits, encompassing cost savings, productivity, and resource allocation.

This paper aims to illuminate the pathway to success in cellular manufacturing through integration of digital twin abilities. It examines the capabilities and benefits of digital twins, by demonstrating how this technology enhances operational efficiency, flexibility, and overall manufacturing success. The analysis is supported by case studies, operator insight, and a review of a comprehensive understanding of transformative potential of digital twins in cellular manufacturing.

2 OBJECTIVES

The objective of the paper is to leverage machine learning algorithms to analyze the collected data, enabling the identification of patterns and trends that may not be apparent through traditional analysis methods. This can improve the predictive capabilities of the failure mode and effects analysis process through a priority score table and pareto chart.

3 INDUSTRY TRENDS AND CONTEXT RELEVANCE

The manufacturing industry is experiencing significant disruptions due to technological innovations and changing market dynamics, leading to a shift towards embracing digital technologies to stay competitive [1]. With the rise of data-driven companies and the increasing adoption of industry 4.0 technologies, manufacturers are facing challenges in keeping pace with technological advancements and leveraging data to drive operational improvements [2].

In response to these industry trends, manufacturing facilities are increasingly focusing on digital transformation initiatives to drive productivity gains and operational resilience [1]. Companies are recognizing the value of data-led manufacturing approaches, with an average productivity gain of 17-20% reported by embracing data-driven practices [3]. The integrating of digital twins, Artificial Intelligence technologies, and advanced analytics is enabling manufacturers to optimize processes, improve asset management, and enhance quality assurance practices to meet evolving customer demands and regulatory requirements [4].

4 TECHNOLOGICAL INTEGRATION

- Digital Twins: The use of digital twin technology can optimize cellular manufacturing processes by simulating operations, identifying bottlenecks, and improving decision-making.
- Industry 4.0: The integration of IoT, big data, and automation technologies enhances the capabilities of cellular manufacturing systems, allowing for real-time monitoring and adjustments.

5 DIGITAL TWIN TECHNOLOGY IN CELLULAR MANUFACTURING

Digital twin technology plays a crucial role in optimizing cellular manufacturing by providing a virtual representation of production processes. This technology allows manufacturers to simulate various scenarios, identify potential bottlenecks, and improve layout designs, ultimately leading to increased efficiency and reduced costs. Digital twin simulations can help analyze different configurations of machines and workflows, resulting in significant improvements in production lead times and machine utilization rates [5]. Figure 1 illustrates the physical to digital world.

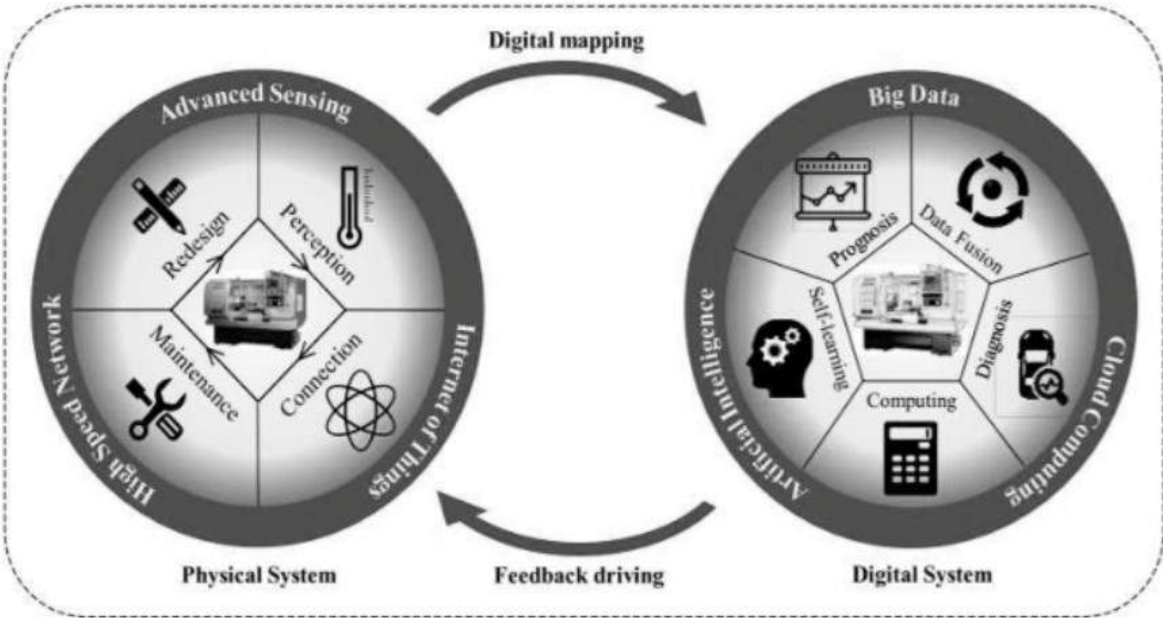

Figure 1: Digital twin technology framework adapted from Glatt [6] et al. (2021)

Additionally, digital twins facilitate real-time monitoring and decision-making, enabling manufacturers to respond quickly to changes in production demands and operational challenges. By integrating digital twin technology with flexible cellular manufacturing systems, companies can enhance their production capabilities and ensure better resource allocation [7]. The application of digital twin technology in cellular manufacturing is instrumental in achieving smarter, more efficient manufacturing processes [8].

5.1 Cellular manufacturing overview

Cellular manufacturing is a production approach that organizes machines and workers into cells to enhance efficiency and flexibility in manufacturing processes:

5.1.1 Definition

- Cellular Manufacturing involves grouping similar products into families and processing them in dedicated cells of machines, which are operated by coordinated teams of workers. This method is rooted in Group Technology and Lean Manufacturing principles.

5.1.2 Benefits

- Reduced Manufacturing Time: By minimizing movement and setup times, cellular manufacturing streamlines production.
- Improved Quality: The focus on part families allows for better quality control and consistency.
- Increased Flexibility: Cells can be quickly reconfigured to accommodate different products or changes in demand.
- Enhanced Productivity: The organization of similar tasks reduces waste and improves resource utilization.

5.1.3 Design considerations

- Part Families: Identifying groups of similar parts that can be manufactured together is crucial for effective cell design.
- Machine Grouping: Machines are arranged in a way that optimizes workflow and minimizes intercell movement.
- Layout Types: Various layouts can be employed, including manual handling, semi-integrated handling, and flexible manufacturing systems.

5.2 Cellular manufacturing challenges

Cellular manufacturing is a production strategy that organizes work into self-contained cells, focusing on efficiency and flexibility. However, it faces several challenges:

Unplanned Downtime: Machine failures can disrupt production schedules, leading to increased maintenance costs and negatively impacting on-time delivery to customers. Maintenance inefficiencies can result in unforeseen breakdowns, further contributing to downtime.

Resource Allocation: Careful planning is required to prevent underutilization or overallocation of resources within cellular manufacturing. Poor resource management can hinder overall efficiency and productivity.

Cellular manufacturing is a powerful approach that aligns with modern manufacturing needs for efficiency, quality, and flexibility. By leveraging advanced technologies and optimizing workflows, manufacturers can significantly enhance their production capabilities and responsiveness to market demands.

5.3 Applications of digital twin technology in manufacturing

Digital twin technology in manufacturing has diverse applications, including predictive maintenance, real-time monitoring, and process optimization [9]. By utilizing digital twins, manufacturers can monitor machine performance in real-time, detect potential issues proactively, and schedule maintenance activities efficiently to prevent costly downtime [10]. Additionally, digital twins enable enhanced quality control by monitoring production processes, detecting defects early, and reducing the likelihood of defects in finished products.

These applications demonstrate the versatility and effectiveness of digital twin technology in improving manufacturing operations.

5.4 Importance of digital twins in manufacturing

Digital twin technology has several key applications in manufacturing:

- Real-Time Monitoring: Digital twins enable continuous tracking of manufacturing processes, providing immediate insights into equipment performance and operational efficiency. This helps identify anomalies and optimize workflows in real-time [11].
- Predictive Maintenance: By simulating the physical state of machinery, digital twins can predict potential failures before they occur, reducing unexpected downtime and maintenance costs. This proactive approach enhances equipment reliability and extends machinery lifespan [12].
- Process Optimization: Digital twins allow manufacturers to simulate various scenarios and analyze operational data, helping to identify inefficiencies and optimize workflows. This leads to improved production efficiency and reduced waste [13].
- Quality Assurance: Assist in maintaining quality standards by monitoring production parameters and identifying potential quality issues early in the manufacturing process, ensuring near-zero-defect production [14].
- Training and Simulation: Digital twins can be used for training purposes, allowing new employees to interact with a virtual model of the manufacturing environment, enhancing learning without the risks associated with real-world operations [15].

6 METHODOLOGY

This study employs a mixed-methods approach, integrating digital twin technology and machine learning to enhance predictive maintenance and operational efficiency in cellular manufacturing. The methodology is structured to ensure a seamless connection between theoretical concepts and practical applications. Which has integrated both manual and automated data collection techniques to enhance the reliability and comprehensiveness of the findings.

6.1 Data Collection

Case Study: Brake Pad Manufacturing

Company A: Implementation of digital twins to improve production flexibility and real-time monitoring.

A case study was conducted in a brake pad manufacturing setup to illustrate the practical application of the proposed methodology. The implementation of digital twin technology and machine learning resulted in a significant reduction in defect occurrences, demonstrating the effectiveness of the approach in a real-world scenario [16]. Specifically, the digital twin enabled continuous real-time monitoring, while machine learning algorithms provided predictive maintenance capabilities, reducing machine downtime, and improving overall operational efficiency [17].

Data collection was conducted using two primary methods:

- **Manual Data Collection:** Semi-structured interviews and structured observation checklists were used to gather qualitative insights from operators about potential failure modes and their effects [18]. This approach allowed for the exploration of emergent themes and provided a deeper understanding of the subject matter [19].

- **Automated Data Collection**: Internet of Things sensors were implemented to continuously monitor machine performance and gather quantitative data in real-time [20]. This data was stored in a centralized database for easy access and analysis [21].

6.2 Data Preparation

The collected data was cleaned and preprocessed to ensure accuracy and eliminate inconsistencies or biases [22]. For automated data, integrity was maintained, and relevant features were extracted for analysis [23].

6.3 Failure Mode and Effects Analysis

The study utilized failure mode and effects analysis to identify potential failure modes, their causes, and effects on the system. Risk priority numbers were assigned based on the severity, occurrence, and detection ratings of each failure mode [24]. This structured approach helped prioritize defects and facilitated targeted interventions.

6.4 Digital twin and Machine Learning Integration

Digital twin technology was employed to create virtual replicas of the brake pad manufacturing machines. These digital twins enabled real-time monitoring and simulation of various scenarios to identify potential bottlenecks and optimize workflows [25]. Machine learning algorithms were then applied to analyze historical failure data captured by the digital twins, predicting potential future failures, and refining the failure mode and effects analysis process [26]. This integration allowed for more accurate and proactive maintenance strategies.

7 RESULTS AND DISCUSSION

The results of failure mode and effects analysis table typically include several key components that help organizations assess and prioritize potential failure modes. Below Table 1, is a structured of machine downtime collected information for each component:

Table 1: Table of machine defects process

Defect No.	Potential Defect	Potential Consequences of the Defect	Potential Causes of the Defect	R (Risk)	W (Detectability)	Z (Severity)	P (Priority)
1	Cable Breakage	Machine downtime, safety hazard	Wear and tear, lack of maintenance	7	4	9	252
2	Sensor Failure	Incorrect readings, operational inefficiency	Calibration issues, aging sensors	5	3	8	120
3	Software Glitch	Production halts, data loss	Bugs in code, outdated software	6	2	10	120
4	Hydraulic Leak	Loss of pressure, equipment failure	Seal degradation, improper installation	4	5	7	140

7.1.1 Explanation of Components:

- Defect No.: A unique identifier for each potential defect.
- Potential Defect: Description of the failure mode.
- Potential Consequences of the Defect: The impact of the defect on operations or safety.
- Potential Causes of the Defect: Root causes identified through analysis.
- R (Risk): The likelihood of the defect occurring, typically rated on a scale (1-10).
- W (Detectability): The ability to detect the defect before it causes a failure, also rated on a scale.
- Z (Severity): The impact of the defect on the end user or system performance, rated on a scale.
- P (Priority): The calculated priority score, derived from the formula (P = R x W x Z).

Table 2 below shows the priority score table when machine learning is applied.

Table 2: Priority score table before machine learning

Defect No.	R (Risk)	W (Detectability)	Z (Severity)	Priority Score (P)
1	7	4	9	252
2	5	3	8	120
3	6	2	10	120
4	4	5	7	140

7.1.2 Explanation of results

- Defect No. 1 has the highest priority score of 252, indicating it should be addressed first due to its high risk, low detectability, and severe consequences.
- Defect No. 2 and Defect No. 3 both have a priority score of 120, suggesting they are of equal importance for attention.
- Defect No. 4 has a priority score of 140, which is lower than Defect No. 1 but higher than Defects No. 2 and 3.

These scores help prioritize maintenance efforts and resource allocation effectively to mitigate risks associated with potential defects [27].

Characteristics: Manual data collection, static assessments based on historical data, and limited predictive capabilities. Risk assessments are subject to human bias and may overlook emerging patterns or trends [28].

On the Table 3, a priority score table is a structured format used to rank alternatives or assets based on specific performance metrics or evaluation criteria. The purpose of this table is to facilitate decision-making by providing a clear comparison of the performance of different defects, helping to identify which ones should be prioritized for maintenance before machine learning.

Table 3: Priority score table before machine learning

Defect No.	R (Risk)	W (Detectability)	Z (Severity)	Priority Score (P)	Notes
1	8	5	9	360	Improved detectability through real-time monitoring.
2	6	4	8	192	Enhanced risk assessment using predictive analytics.
3	5	3	10	150	Data-driven insights led to better prioritization.
4	4	6	7	168	Continuous learning from operational data.

Characteristics: Automated data processing, dynamic risk assessments based on real-time data, and enhanced predictive maintenance capabilities. Machine learning models continuously update the failure mode and effects analysis, providing more accurate evaluations and reducing downtime [29].

The integration of machine learning transforms the failure mode and effects analysis process from a static, manual approach to a dynamic, data-driven methodology, significantly improving the identification and management of risks associated with potential defects [30].

On Table 4, it is when machine learning is being deployed to formulate new risk priority numbers shown the improvement.

Below Table 4, Figure 2 and 3, shows machine learning before it was deployed and after. This chart is a type of graph that displays the frequency or impact of problems in a process, helping to identify the most significant factors contributing to an issue. It typically consists of bars representing individual categories of problems, arranged in descending order of frequency, along with a cumulative line graph that shows the total impact of the categories. This visualization is based on the pareto principle, which states that roughly 80% of effects come from 20% of the causes, allowing organizations to focus on the most critical issues for improvement.

Table 4: Pareto table of defect numbers Before and After Machine Learning

Defect No.	Frequency Before ML	Frequency After ML	Cumulative Frequency Before ML	Cumulative Frequency After ML
1	30	15	30	15
2	48	16	78	31
3	72	36	150	67
4	18	9	168	76

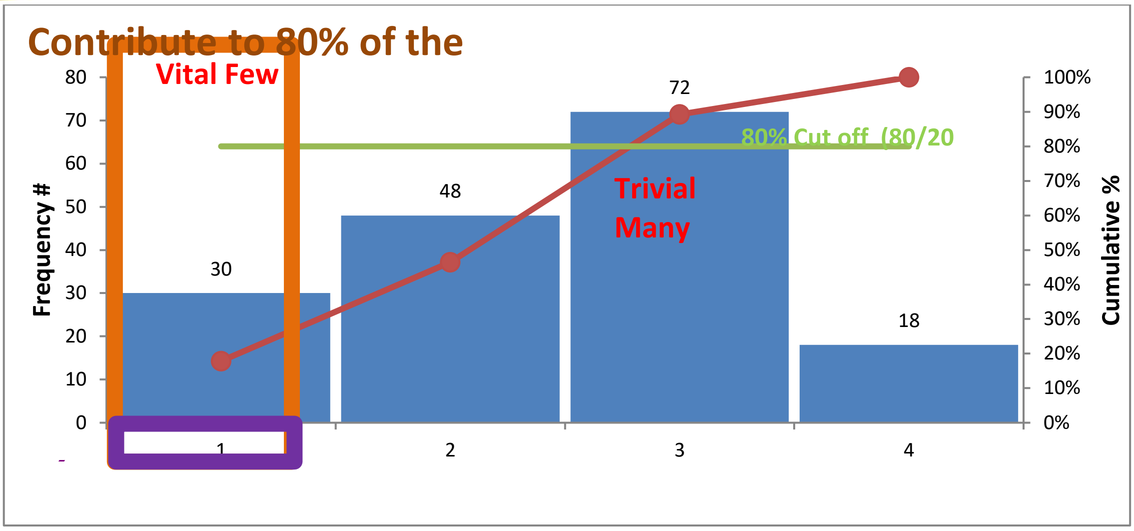

Figure 2: Pareto chart before Machine learning

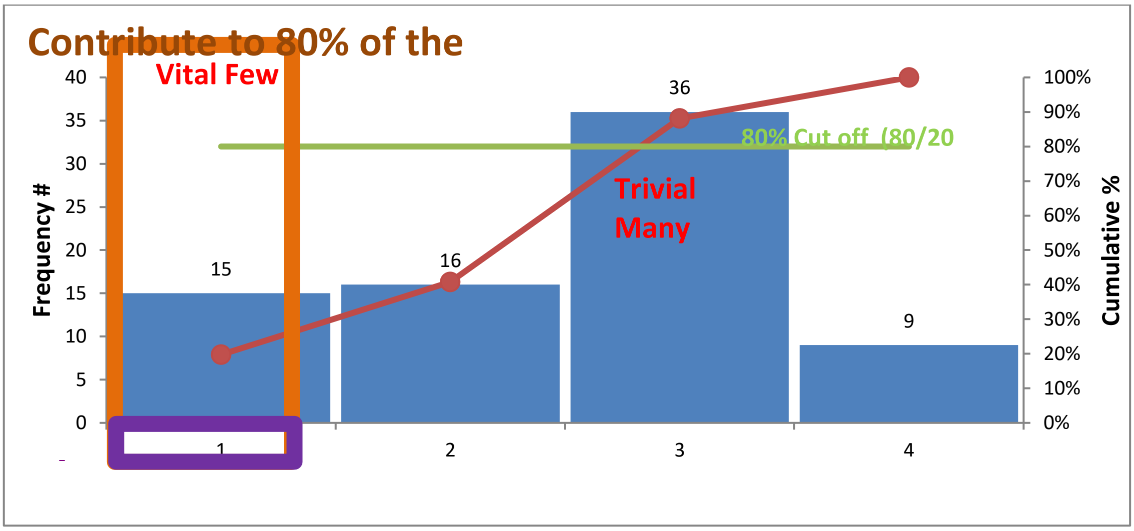

Figure 3: Pareto chart after Machine learning

Key Insights

The case study results indicated a substantial improvement in defect detection and reduction. Before the implementation of digital twin and machine learning technologies, the frequency of defects was high, leading to significant machine downtime and production delays [31]. After the integration, the frequency of defects was reduced, with a total of 76 occurrences compared to 168 before the implementation, indicating improved detectability and predictive maintenance capabilities [32]. This demonstrates the transformative potential of combining digital twin technology with machine learning in enhancing operational efficiency and decision-making in manufacturing environments [33].

8 CONCLUSION

The integration of digital twin technology in cellular manufacturing presents a transformative opportunity for enhancing operational efficiency and risk management. By creating a virtual replica of manufacturing processes, digital twins enable manufacturers to simulate various scenarios, identify potential bottlenecks, and optimize layouts and workflows. This capability not only leads to improved productivity but also facilitates informed decision-making, ultimately reducing costs and enhancing competitiveness in the industry [34].

When applied to the failure mode and effects analysis process, digital twins can significantly augment the traditional methodologies by providing real-time data and predictive analytics. Machine learning algorithms can analyze historical data captured by digital twins to predict failure modes and assess their impacts more accurately. This integration allows for the calculation of priority scores for defects, enabling organizations to focus their resources on the most critical issues [35].

The ability to visualize and analyze data through digital twin simulations empowers manufacturers to refine their failure mode and effects analysis processes, ensuring that they address the most significant risks effectively. By leveraging these advanced technologies, companies can illuminate a pathway to success, fostering a proactive approach to risk management and continuous improvement in their manufacturing operations [36].

The synergy between digital twin technology and machine learning in the failure mode and effects analysis process not only enhances defect prioritization but also drives overall operational excellence, paving the way for smarter, more resilient manufacturing systems [37].

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CONCEPTUAL FRAMEWORK TO ENHANCE GROWTH AND COMPETITIVENESS OF LOWER-TIER AUTOMOTIVE SMMES: A REVIEW

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ABSTRACT

Lower-tier Small, Medium and Micro Enterprises (SMMEs) within the automotive industry face challenges in growing their businesses and meeting the requirements of firms that supply directly to the Original Equipment Manufacturers (OEMs), which are Tier 1 suppliers and automotive assembly customers. Due to this, automotive assemblers and Tier 1 companies tend to import the required components from abroad. This leads to reduced business opportunities for local companies, and it impacts the creation of jobs and the growth of the economy. The aim of the paper is to conceptualize a framework that presents factors that contribute to the growth and competitiveness of suppliers in the South African automotive industry. The framework was synthesized from a literature review of research that was done in the South African environment. The framework provides the public and private sectors with a guide to providing sustainable support to suppliers in the automotive industry. It is useful to suppliers in the automotive industry who experience challenges in growing their businesses and in meeting customer requirements.

Keywords: Conceptual Framework, SMMEs, Growth, Competitiveness, Lower tier, Automotive industry, South Africa

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1 INTRODUCTION

As a major contributor to national growth in many countries, including South Africa, the automotive industry is among the largest manufacturing sectors in the world [1]. Aside from its magnitude and related economic influence, the industry encompasses a range of industrial processes and generates several offshoots for downstream industries, such as suppliers in the automotive supply chain [1].

Although much smaller than in other years, manufacturing still makes up a sizeable portion of South Africa's gross domestic product at 4.9% in 2022 and the industry has remained essential to the nation's economy [2]. Vehicle and automobile component production, the largest manufacturing industry in the nation's economy, accounted for a significant 21,7% of value addition in domestic manufacturing output in 2022 [2].

Production indicators produced by Statistics South Africa show that manufacturing production decreased by 3.4% in January 2021 compared to January 2020 [3]. Lamprecht [4], emphasizes the need to grow the manufacturing sector based on the current socio-economic challenges, indicating that the sector provides the highest impact and multiplier effects than most other sectors in job creation.

Barnes [5] states that in South Africa, the automotive sector has a long history and has benefited from extensive government assistance. Domestic sales and output, on the other hand, have long trailed behind competitive developing market producers. Imports and exports have increased rapidly since the government incentivised Motor Industry Development Programme (MIDP) established in 1995. Investment levels have risen, although not to the same extent as in more active comparative countries, and the component industry has been on a downward trend since 1999.

Petrillo, et al [8] and Ghazali, et al [9] state that SMMEs need to remain competitive constantly, due to challenging business environments and the increasing global competitiveness levels. SMME business owners need to review and implement business strategies and production processes and implement continuous improvement to reduce costs and maximise customer service levels and grow their businesses.

SMMEs are susceptible to a variety of macro environmental variables that impact their businesses, but some of the most pressing difficulties that SMMEs encounter include marketing, management, social, human resource, and financial issues [10]. SMME growth is related with a wide range of success variables. An entrepreneur's education and abilities, access to financing, personal attributes, creativity and invention, risk, culture, government assistance, and policy development are all factors that might be personal, internal, or external to an organisation [11]. Ngcobo and Sukdeo [12], posit that additional emphasis should be paid to understanding the crucial elements that contribute to the growth of SMMEs.

Lower tier SMMEs have a significant role to play in job creation and economic growth in South Africa, but they are constrained by the ability to be competitive and grow their businesses. The role requires that these lower tier SMMEs adopt and utilise contributory factors that influence their growth and competitiveness in the automotive industry. This paper aims to:

a) Analyse frameworks and success factors that have been developed for SMMEs enhancement in South Africa.
b) Conceptualise a framework that presents contributory factors that influence lower tier SMMEs growth and competitiveness in the South African automotive industry.

The framework seeks to address the knowledge gap on lower tier automotive sector SMMEs utilisation of contributory factors to grow their business and become competitive.

2 LITERATURE REVIEW

With the elimination of local content rules under the MIDP, import competition has increased strain on the automotive supply chain. Under the Automotive Production and Development Programme (APDP), which replaced MIDP, the component sector has been under pressure in recent years. This can be seen in the low and falling local content levels to around 40% in South African assembly automobiles, as well as the significant number of components imported by the domestic industry [5].

For industrializing nations, such as South Africa, that are hoping to maximize the benefits of integration into the automotive global value chain for local development, building a local supplier base of component manufacturers continues to be a critical development priority [6]. Local content must be both deepened and broadened to achieve higher levels of localisation by growing the lower tier suppliers. Many domestically produced first-tier components are primarily made up of imported sub-components [5]. This implies that those sub-components are not being manufactured by local lower tier suppliers, that are made up of small, medium and micro enterprises (SMMEs).

When investigating the reasons why lower tier SMMEs are not benefitting from local production opportunities, Sharma and Naude [7] state that component manufacturers in South Africa are not internationally competitive, and as a result, local automotive assemblers or original equipment manufacturers (OEMs), frequently import lower-cost components from elsewhere, which leads to reduced business opportunities for the local lower tier SMMEs and in turn hinders job creation and economic growth.

Lower tier SMMEs in the automotive sector struggle to access business opportunities in the automotive supplier chain as they are deemed to be uncompetitive when compared to global counterparts. This in turn has an effect on their ability to become competitive and grow their businesses. As stated by Barnes et al [13], the development of the automotive supply chain, localization, and transformation are important goals for the South African auto industry's future. The 2035 South African Automotive Masterplan [32] lays out goals to accomplish this, but doing so will undoubtedly require a major effort from all parties involved in order to align their business strategies with legislative goals. SMMEs in the supply chain therefore need to play a role in shaping their businesses to access opportunities. There are certain business strategies and contributory factors that they can adopt to influence their growth and competitiveness.

Various researchers in South Africa have discovered and recognised growth enhancing approaches for SMMEs. A selection of research frameworks in Table 1 were selected by the author for evaluation, as these frameworks ere developed for SMMEs in the South African environment and focus primarily on the success factors of SMMEs. The authors of these frameworks identified specific factors that enhance different types of SMMEs within different South African operating environments. These sample of papers indicate a similar approach and the outputs from the various authors take into consideration the challenges for businesses operating in South Africa. Researchers' frameworks give insight into many elements that might enhance SMME growth. Financial prudence, funding support, innovation, quality products and services, cash flow management, markets, collaboration, business linkages, customer relationship management, knowledgeable and skilled manpower, technology, regulatory factors, macroeconomic factors, infrastructure, and marketing are some of the common variables that many of the academics agree on. A few researchers agree that strategy and competition are important variables, the majority of them do not.

Table 1: Previous SMME Enhancing Frameworks in South Africa (Source: Authors compilation)

Author	Framework Factors Identified	Shortcomings
Ramukumba, 2014 [14]	Generate enough cash, attract repeat customers, competitive pricing, advertising & promotion, skilled workers, product performance, competitiveness	Internal focus but competitiveness included
Lekhanya and Mason, 2014 [15]	Financial factors such as source of funding, infrastructural factors such as roads and transportation and access to electricity, and business environment factors such as lack of skills and labour costs	Limited factors and other internal factors such as marketing, strategy and innovation are not included
Tshikhudo, Aigbavboa and Thwala, 2015 [16]	Producing quality work; cash flow management; contractual understanding; a business plan; effective communication channels in the firm; maintaining good relationships with clients; proper record keeping; sensible operating costs; recruiting qualified staff and availability of effective marketing strategies	Internal focus mainly and no mention of strategy and innovation
Sitharam and Hoque, 2016 [17]	Technological capabilities, managerial competence and skills and access to finance, external factors, regulatory factors, macroeconomic factors, competition, globalization, crime and corruption	Mixture of success and failure factors
Cant and Rabie, 2018 [18]	Access to a strong client base with sufficient buying power and a need/demand for the product or service within the community	Limited factors with focus on marketing and no mention of strategy or innovation
Urban and Ndou, 2019 [19]	Access to finance and markets, institutional support, skill and competency development	Limited factors with no mention of strategy or innovation
Mang'unyi and Govender, 2019 [20]	Market penetration strategy, pricing, quality of services, customer base, competitive advantage and customer satisfaction	Not comprehensive, strategy and competitiveness included
Maduku and Kaseeram, 2021 [21]	Owner's education, owner's financial literacy, business age, experience, income, advertising budget and employee growth and access to capital	Internal focus and no mention of strategy, innovation and marketing
Leenutaphong, Sornsaruht and Deebhijan, 2021 [22]	Organizational culture, and human resource management, supply chain management, lean manufacturing, logistics management, outsourcing, employee value-added, labor productivity and total factor productivity	Internal focus on competitiveness, employees and logistics, but no mention of strategy, innovation and marketing

Factors found to be influencing the growth and success of SMMEs in different sectors in South Africa have been explored in several studies, as shown in Table 1. In this work and in related references it was observed that researchers identified internal or external factors that can influence business growth and success, however the factors were not structured into practical business guiding principles that SMMEs can use to enhance their businesses. In contrast to this, Van der Merwe et al [25], followed a grounded theory approach using systematic literature reviews that were previously published and identified a high growth promoting framework of core focus areas against which SMMEs can assess their businesses and pinpoint opportunities for expansion and improvement. These SMME evaluation areas are Business Modelling, Strategy, Strategic Alliances, Innovation and Marketing. Additional to this, a requirement for any SMME in the automotive sector, is that they must be competitive when compared to their global counterparts. These studies do not make such an association as a business imperative.

OEMs and Tier 1 firms are importing lower-cost components from overseas suppliers, which necessitates local suppliers, particularly at the lower tier levels, to focus on cost reduction, quality improvement, and production via operational excellence [7]. Firm-level competitiveness, which necessitates effective operational performance as well as competitive labour, overhead, and materials costs, is a necessary prerequisite for the development of the automobile sector [26].

Hosono, et al [27] developed an African framework (shown in Figure 1) for SMMEs based on an empirical study on the linkages between Kaizen and placement in the Global Value Chain on seventeen Tier-2 enterprises. They observed that bringing Kaizen to Tier-2 enterprises had a good influence on Global Value Chain stage upgrades and eventually business development. Kaizen is a Japanese concept and means “change for better” [28]. It was translated in the Western culture as “continuous improvement,” and was introduced to improve efficiency, productivity and competitiveness in Toyota Japan, due to increasing competition and the pressure of globalization [28, 29].

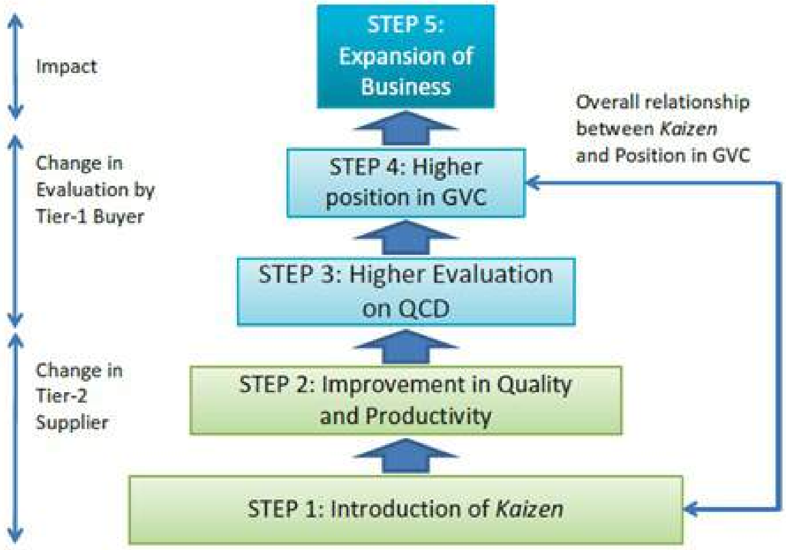

Figure 1: The impact from Kaizen on position and business (Source: Hosono, et al. (2020)

Kaizen provides SMMEs with a mechanism for simple innovation. According to Hampel-Milagrosa, et al [30], SMME upgrading is simply growth by innovation that causes an increase in any target variable, such as sales, returns on investment, assets, or workforce size. Thus, the term has two aspects: innovation, which is qualitative, and company expansion, which is quantitative. Innovation is a growth strategy that is within the control of an entrepreneur, compared to growth factors such as increased market demand, competition and input price changes, which can be rarely influenced by entrepreneurs [30].

Barnes and Morris [31] state that through benchmarking of South African component manufacturers based on businesses' desire to maintain ongoing development and increased operational effectiveness in order to increase their global competitiveness, market drivers and critical success factors were developed to measure their competitiveness (included in Table 2). These drivers and measures must be adopted by SMMEs to improve their competitiveness in order to compete globally.

Table 2: Competitiveness market drivers and success measures (Source: Barnes and Morris, 2008)

Market Driver	Critical Success Measures	Indicative Value
Cost control	Total inventory levels Raw material holding Work in progress (WIP) levels Finished goods holding	Measuring inventory is a sound proxy for measuring cost control at manufacturers. Firms with low inventory operate just in time (JIT) systems and are thus in control of their costs
Quality	Customer return rates Internal reject rates Internal scrap rates Internal rework rates Return rates to suppliers	Three quality areas are key: Customer returns, internal defects and supply quality. Customer returns reveal quality satisfaction but offer insufficient indication of internal quality performance. Firms may have poor internal systems but provide quality products by following checks at the end of processes. Low customer returns need to be supported by low defects and strong supplier quality
Value chain flexibility	Customer lead times Throughput times Production lost to changeovers Supplier lead times	Value chain flexibility is determined by the speed at which a firm accepts a customer order & converts this to a delivered product. Key value chain variables are the flexibility of its suppliers, the flexibility of is operations and the flexibility of its customer interface. Each of these needs to be measured to ascertain the value chain flexibility of the firm
Value chain reliability	Customer delivery reliability Production time lost to breakdowns Predictive/Preventative maintenance Supplier delivery reliability	No firm can operate flexibly, without high levels of consistency. Measuring value chain reliability is thus as critical as measuring flexibility. Operational reliability is moreover a central OEM requirement, with on time and in full delivery one of their key demands. Measuring this indicator, along with the reliability of a firm's own operations and that of its suppliers is essential
Human resource development	Provision of training and expenditure Employee suggestions Employee turnover Absenteeism rates Accident frequency rates Labour unrest downtime	The dimensions to change are manpower, machines, materials and methods, but it is the first that determines ability to deal with the others. Analysing whether firms are investing in employees, fostering continuous improvement, maintaining good industrial relations and generating worker commitment is thus critical
Product development	R&D expenditure Contribution of new products to total sales	A success determinant fur any component firm is its ability to bring new products to market. The product development process is however complex given global lead sourcing. R&D spending (investment in new product development) thus needs to be disaggregated from new product sales (the life cycle of products being manufactured)

The term 'growth' or 'expansion' refers to an SMME's ability to do more business. It also means that the SMME's resources, systems, and structures need to expand, but not proportionally. Internal growth refers to expanding the SMMEs' market share, producing new goods, and expanding into new areas. The external expansion extends beyond the confines of the present business and necessitates a positioning of the SMME within the industry value chain [35]. SMMEs must see growth and development from four key perspectives: financial, strategic, structural, and organisational, due to the multi-faceted structure of organisations. The changes in how a small business interacts with the environment are referred to as strategic growth. The changes in the SMME's internal structures, managerial roles and duties, relationships, and resource systems are referred to as structural growth. The changes that occur in the procedures, culture, and attitudes of an organization as it grows and develops are referred to as organizational growth [35].

3 CONCEPTUAL FRAMEWORK

Lower-tier firms need to constantly strive for global competitiveness as OEMs and Tier 1 firms are importing lower-cost components from overseas suppliers, which necessitates local suppliers, particularly at the lower tier levels, to focus on cost reduction, quality improvement, and production via operational excellence [7]. SMMEs need to remain competitive constantly, due to challenging business environments and increasing global competitiveness levels. SMMEs need to review their business strategies and production processes and implement continuous improvement to reduce costs and maximise customer service levels [8, 9]. It is, therefore, necessary that lower-tier SMMEs align the business factors to become competitive.

This conceptual framework was developed by using theory synthesis to integrate concepts between various literature streams and creatively connecting previously unconnected parts, which provide an improved understanding of the subject [32]. By combining prior research and theories into a fresh, higher-order viewpoint that connects phenomena that were previously thought to be separate, integration will provide a new view of the concept [33].

The development of the conceptual framework firstly analysed previous research on SMME success factors in South Africa, to understand what factors play a role in the south African environment as shown in Table 1. These factors were then compared to the success factors required for participation in the automotive industry as explained in Table 2. The analyses showed that the focus areas proposed by Van der Merwe et al [25] provides a more comprehensive framework of key growth factors for enhancing SMME growth and competitiveness, when compared to the other researchers. However, there are certain gaps in the framework of Van der Merwe et al [25], when compared to the automotive success factors, which are firm-level competitiveness, which necessitates effective operational performance as well as competitive labour, overhead, and materials costs, is a necessary prerequisite for the development of the automobile sector [34].

By expanding on the existing conceptual frameworks, the proposed framework (Figure 2), considers and highlights the important linkages between business factors, growth, and competitiveness. The proposed conceptual framework underscores the need for alignment between the business factors, growth, and competitiveness, that lower-tier firms require to compete globally. The conceptual framework (Figure 2) proposes that the independent variables of business modelling, business strategy, strategic alliances, innovation, and marketing can contribute to the dependant variables of growth and competitiveness of Tier 2 to Tier n SMMEs in the automotive sector. The business strategy must include a focus on Cost control, Quality, Value chain flexibility, Value chain reliability and Human resource development as key competitiveness market drivers and success measures, for SMMEs to improve their competitiveness and be in a position to compete in the global market. This will, in turn, lead to sustainable SMMEs. It is envisaged that lower-tier firms adopting the independent variables will enable the achievement of the dependent variables of growth and competitiveness and will enable SMMEs to be sustainable. The conceptual framework promotes sustainable development, growth, and competitiveness when combined with the other components.

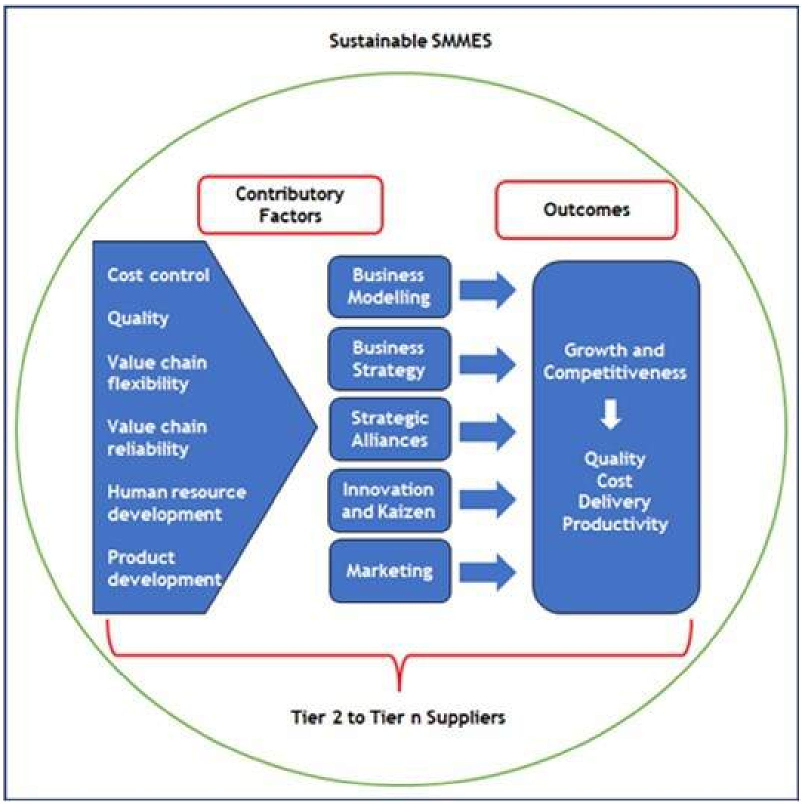

Figure 2 : Conceptual framework for enhancement of Tier n SMMEs (source: author)

4 CONCLUSION

Lower-tier SMMEs in the automobile sector encounter difficulties in expanding their businesses and satisfying the needs of their Tier 1 and OEM clients. As a result, OEMs and Tier 1 firms frequently import components from other countries. This results in less business prospects for local businesses, as well as a negative influence on job creation and economic growth.

Lower-tier suppliers that can enhance and expand their companies to international standards and have a better chance of winning business from Tier 1 and OEM clients, who now buy a percentage of their components from other countries. Components will then be manufactured or value added in South Africa. This leads to higher contribution to GDP, enhanced economic growth and job creation.

The conceptual framework provides a foundation for a quantitative study that will provide insight into the research's objectives, which will focus on the factors and their relationship to the long-term development, growth, and competitiveness of lower-tier SMMEs in the automotive industry. An empirical study has not been conducted on these factors and therefore little is known about the underlying associations between these factors and their impact on businesses. The fundamental mechanisms behind this connection remain mostly unknown and this study aims to provide an understanding of the impact of these factors to businesses and fill the knowledge gap by investigating the relationship between the contributory factors and growth and competitiveness of lower tier SMMEs in the automotive sector.

It is envisaged that the insights provided will enable businesses, government, academia and the industry stakeholders to develop robust support mechanisms, policy and programmes to grow the lower tier automotive supply base, which in turn will grow the economy and create an environment for employment growth.

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THE IMPACT OF AUTOMATION ON EMPLOYMENT IN SMALL AND MEDIUM ENTERPRISES (SMES): A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

The purpose of this study is to examine and explore the impact of automation on employment in small and medium enterprises (SMEs). Digital manufacturing technologies such as automation can improve product quality and reduce waste. The understanding the impact of Industry 4.0 can give SMEs a competitive edge and improve their bottom line. SMEs are at risk of being disrupted by the fourth industrial revolution(4IR), automation has the workforce looking into the future with fear given it replaces the workforce with machines. A systematic literature review (SLR) was conducted to achieve this goal, using articles from the Scopus and Web of Science databases. A structured methodology was followed, 42 articles were selected based on predefined criteria. Journals, countries, and article growth were analysed using Rayyan software for screening and coding of studies in a SLR. The selected articles were analysed to identify correlations among Industry 4.0 technologies, SMEs, and employment. This process identified 17automation on employment and its impact supported by Industry 4.0 in SMEs, including employee skill development, Internet of Things (IoT) and virtual reality. Additionally, the results demonstrate the impact of automation, particularly Industry 4.0 technologies on employment can assist SMEs to transition new roles and gain competitive edge in the market. This study contributes to theory by synthesizing previous knowledge of three approaches that had not been studied before and identifying research gaps for future work, such as the correlation between Industry 4.0 technologies, and automation on employment in SMEs. Lastly, this research will guide SMEs managers and leaders, workforces, manufacturers, and technology providers in designing and implementing technologies to facilitate Industry 4.0 for operational profits in SMEs.

Keywords: Automation, Employment, SMEs, Productivity

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1 INTRODUCTION

SMEs are at risk of being disrupted by the fourth industrial revolution(4IR). Therefore, should we be afraid of or excited about automation? Automation replaces jobs that were previously done by humans with machines which increases unemployment and decreases the labour share. However, it may be welcomed as a driver of growth and wealth. Automation eliminates jobs and aggregate labour share, and (2) Automation raises productivity, which raises consumer demand, which raises market share and employment prospects [1]; [2]. Labour scientists are divided over all the benefits of introducing technology to increase productivity, and they are particularly impacting studies of robotics, artificial intelligence, and automation. On the other hand, data shows that creating efficient technology can destroy jobs faster than people find new uses for the unemployed. As a result, people may experience massive unemployment and widening income gaps that must be reduced by redistributing income and unemployment. The impact of automation differs on industry and vocation. However, automation has the potential to provide new job possibilities in various sectors. Workers all over the world are in upheaval as technology advances. The deployment of Automation may present a challenge and an opportunity for those in the working class. Researchers recognized the importance of identifying current trends and have performed research to assess the influence of automation. Due to technological advancements, less people are required to produce products, leading in a "winner-takes-all" economy in which a minority of highly talented individuals’ controls the market. While technological advancement is advantageous, SMEs must address the issues of job displacement and income inequality. Additional research into the impact of automation will provide a great understanding of its implications on labour. The growing use of automation in diverse areas needs great knowledge of its impact on employment.

1.1 Automation and employment in SMEs

An early study on automation discovered that automation replaces humans in positions that need a high level of routine and manual labour, while also assisting workers in tackling nonroutine and cognitive difficulties [1]. From a different view of the argument, Arntz et al [2]contended that specific employment functions, rather than entire occupations, were at risk of automation. However, Aghion et al [3]introduced the "negative" viewpoint, in which the most direct effect of automation is the destruction of jobs and the downward pressure on wages. The effect can now be reduced. According to [4], automation reduces work balance, thus encouraging the creation of start-up activities (before the next automation) and alleviating this problem; This, in turn, increases the demand for labour, causing wages to fall. [5] Noted that investment in automation is linked to a decrease in the productivity of middle-class workers, especially in management activities, but an increase in the productivity of low-skilled and high-skilled workers [5]. These shifts from skilled workers to highly skilled workers according to [6] and [7] can also lead to increased productivity.

The impact of automation in SMEs is expected to emerge new business models resulting in improved business processes and, ultimately, increased company competitiveness [8] [9] In all industries, the process of incorporating new technologies is underway to reduce costs, increase productivity, and provide clients with solutions tailored to their individual needs [10].The expected higher-order benefits of automation include improved, potentially interrupted, invention capability, improved monitoring and diagnosis of multifunctional systems, and Intelligent systems' increased self-awareness and subsequent self-maintenance. improved flexibility at a cheaper cost, increased productivity brought on by environmentally friendly and more customised products, enhancing access to public services like education, health, local services, and personal information will ultimately improve the manufacturing process with new service models and business models, increased market penetration, and global penetration through e-commerce [11]. Automation can provide several benefits for SMEs. Some of the advantages of automation for SMEs include the relief of stress on employees as automation can take over more straightforward repetitive tasks, Increased productivity because automation can improve labour productivity and reduce the time required to complete tasks, Reduced costs as automation can reduce labour costs and the risk of employee burnout, which can harm the productivity of the organization, Greater efficiency because automation can improve efficiency by reducing errors and improving the consistency of work, Faster ramp-up time for new employees as processes are defined and automated according to standards, it becomes easier and faster to train new employees and Improve work-life balance leading to happier and more productive workers. Overall, automation can help SMEs to improve their operations, reduce costs, and increase productivity.

1.2 Challenges faced by Manufacturing SMEs

The scholarly consensus on automation in everyday work has evolved to a labour-replacing perspective. The theory is that while "routine" automation eliminates routine tasks, it increases the need for routine tasks that machines cannot perform. Many studies have shown that productivity and routine work disappear. Returning to the firm's work, some talk about workforce shifts in the industry [6]; [12] ; [13]. When it comes to embracing automation, [8] SMEs face more problems using automation than large enterprises because they do not have fully automated production and therefore have a high proportion of manual and mixed activities. They are thus recommended to switch to networked production to maintain their competitiveness in international markets. According to the same source, the top difficulty is a lack of competent people, followed by investment requirements. According to Turkes et al [14], a lack of knowledge is also a barrier to the development of automation implying that there is a lack or no internal training on obtaining digital skills, and no specialists to push the deployment of new technologies. Therefore, SMEs require meticulous planning to handle their major concerns and fund the necessary investment expenses [15]. Large corporations are SMEs' frequent competition hence they struggle to attract professionals in these corporations and struggle to acquire and employ modern technologies. Because large firms have easier access to finance, they are thought to be the ones who test and patent breakthrough technology solutions, making it more difficult and expensive for SMEs to employ them [8].

According to Serumaga-Zake & Van der Poll [11], Manufacturing SMEs encounter a variety of obstacles in their daily operations. These include: automation substitution of labour throughout the entire economy; worker displacement by machines exacerbating the unemployment gap (job insecurity); and automation substitution of labour across the entire economy; High-skilled personnel earning high wages as contrasted to low-skilled workers earning low wages, exacerbating social tensions; a lack of sufficient financial resources to buy the requisite technology; and technical skills issues in operating automated production systems. Another difficulty for SMEs is the lack of appropriate policies that require government help to expedite the use of 4IR technologies [11].

Some of the disadvantages of automation on employment in SMEs include Job Uncertainty, Experts believe that 57% of existing manufacturing jobs will be automated in the long term. This can lead to job uncertainty and loss of employment for workers. Less Human Touch. Automation can also lead to less personal interaction between employees and customers, which can negatively impact customer satisfaction. Shift in Employee Balance because the number of managers in an organization decreases with automation in the workplace. This means that the balance of employees shifts, and some employees may need to be retrained or let go. Initial Cost. High capital investment that needs to be invested in a high-performing environment can be very successful, especially for small businesses with limited funds. Need for Regular Staff Training. Often, employees fear the idea of losing their jobs to machines, and this can lead to resistance to training. In conclusion, while automation can save time and money, streamline business processes, and enhance customer service, it also has its drawbacks. SMEs should carefully consider the pros and cons of automation before making any decisions. Although automation has the potential to increase productivity, reduce costs, and generate new employment possibilities in developing industries, it may also result in worker displacement in industries where automation is used.

1.3 Automation, productivity and greater efficiency

According to Frohm et al. [16], The overall goal of automated systems is to be more efficient, reliable, and accurate than human workers. Also, generators must work, and they work cheaper than workers. There are some arguments against the efficiency, reliability, and accuracy of the machines. It can be said that a more reliable system is also a more secure system. It might also be claimed that removing the operator from system control protects people from their actions, hence improving overall system safety [16]. According to the findings of previous studies by Wei et al. [17] the key driving force for automation is to give opportunities for enhanced efficiency and production. Automation also allows for cost savings, which, together with enhanced efficiency and productivity, leads to increased competitiveness in the market. Many businesses recognize that introducing automation will create opportunities to improve the work environment [17]. According to Ulrich et al. [18], production has a critical role in growing salaries, overall employment, and demand, so benefiting the whole sector economy. Automation has increased productivity not only at the corporate level but also at the industrial and national levels [19]. Even after the financial crisis, both production and productivity in the US manufacturing industry increased consistently as automation advanced. There is a link between productivity, company competitiveness, and growing demand, and automation plays a crucial part in this [20].

1.4 Automation, decreased employee stress and greater work-life balance

This aspect has been largely disregarded in the surrounding dialogue and literature, which frequently focuses on worker displacement caused by automation and AI. This apparent lack of concern for well-being may be explained in part by the widely held belief that workers who are not replaced by technology are complemented by it and so better off as a result. People's fear of automation stems from their concern about losing their jobs and how quickly they can find new jobs in the same or another field to avoid becoming financially stressed. If automation does not replace but rather augment human employees, they will not fear it and may see it as a tool to achieve more productivity and improved personal economic well-being, unless employees appreciate the specific activities being replaced [21]. DeCanio [22] demonstrates that the introduction of automation would reduce human employee wages due to the substitution effect. As a result, humans have every reason to dread not just being displaced by technology, but also having difficulty obtaining new jobs in newly created occupations [21]. While automation has an impact on employment, income, and salaries in the labour market, just as a coin has two sides, automation has an impact on both employees and employers. Automation may increase employee workload, but it can also aid reduce physical exertion and repetitive tasks [23].

Investing in Employee Training, SMEs should invest in employee training to help them acquire new skills that will be in demand in the future. This will help employees adapt to the changing work environment and reduce the risk of job loss. Focus on Creativity and Innovation, SMEs should focus on creativity and innovation to stay ahead of the curve. SMEs should collaborate with the public and private sectors. This will help them stay up to date with the latest trends and technologies and ensure that they are prepared for the future. Evaluate the Impact of Automation, SMEs should evaluate the impact of automation on their business and workforce. This will help them identify areas where automation can be beneficial and areas where it may not be necessary. Plan for the Future, SMEs should plan for the future by considering the long-term impact of automation on their business. This means thinking about how automation can help them grow and scale their business while also considering the potential impact on their workforce. In conclusion, SMEs can prepare for this impact by, focusing on creativity and innovation, collaborating with public and private sectors, evaluating the impact of automation, and planning for the future. By taking these steps, SMEs can ensure that they are prepared for the changing work environment and can continue to grow and thrive in the future.

2 MATERIALS AND METHODS

Inclusion criterion. only studies that provide information on the impact of automation on employment in SMEs, and the impact of emerging technologies on employment were Included. Studies on other topics were excluded from this study. only studies written in English were included. Identifying studies. The study search started by using the keywords “The impact of automation on employment in SMEs”, “The benefits of automation on employment”, “the negative impact of automation on employment”, “advantages and disadvantages associated with automation”, “the impact of emerging technologies on SME’s”, “employment in SME’s” and “the impact of automation in SME’s.” The title indicated the importance of each document. If the content seems to discuss the impact of employment in SMEs as the title, the full report including author, year, title, and description was downloaded for further analysis. Google Scholar, one of the most frequently used databases by researchers across various disciplines was used to search for manuscripts or articles. Advances in technology have changed the way of archiving hence publication dates are limited to 1998 and 2023 (for publications over the last 25 years) so that analysis can be based on the latest data to determine data retrieval and synthesis.

After examining the first 20 pages of search results, 43 related articles were found. Later, the keywords were changed to “Automation’s general impact”, “the impact of automation on labour” and “the impact of new technologies on SMEs”. After the initial search of the list, 38 studies were identified in total. Scan for inclusion. The Abstracts of 38 studies were further read to determine their relevance to the research topic (impact of automation on employment in SMEs). A total of 17 studies were evaluated and found relevant hence the full text was accepted for quality assessment. Evaluation of quality and eligibility. The full text was reviewed to assess the quality and relevance of the studies. Journals and books were rated as good research and therefore included in the review. Some professional publications and online submissions have been removed due to the lack of peer review. Only a few studies with valid information were included. This study carried out performance and competency evaluation work. A total of 21 studies were excluded after careful review: they were excluded due to a lack of guidance on the research topic; because they were not relevant to what the researcher wanted to achieve. The final stage of the comprehensive literature search included 17 studies overall from the initial search. Overall, we included a total of 17 studies in this study.

3 RESULTS AND DISCUSSION

3.1 Data analysis

From each study, we gathered information on two issues: (1) the positive impact of automation on employment in SMEs and (2) the negative impact of automation on employment in SMEs. At first, the researchers gathered data from the articles/journals one by one for analysis. After reviewing several articles, the researcher agreed on what to extract from the articles. The full text of the 17 studies was reviewed for the positive and negative impacts of automation on employment in SMEs. A table was formulated to summarise the findings from each study. The table included the name of the authors, the title of the study, the year the study was published and the positive and negative impact of automation on employment in SMEs according to the author. The last column on the table is the overall author’s view on how automation impacts employment in SMEs. Descriptive statistics was used to further analyse the data reviewed in the 17 papers. The researcher made use of graphs and tables to further summarise the information.

3.2 Articles included in the study

Table 1 - Depicts the summary of all the 17 papers included in this study.

AUTHORS	PAPER TITLE	DATE	POSITIVE IMPACT	NEGATIVE IMPACT	OVERALL IMPACT
Domini et al. (2022)	Threats and opportunities in the digital era: automation spikes and employment dynamics	2019	-Net firm growth. -Lower separation rates.	-	Positive
Balasubramanian et al. (2023)	Analysing the impact of automation on employment in different us regions: a data-driven approach	2023		-Decline in employment rate. -Limited job opportunities. -Job displacement.	Negative
Aghion et al. (2019)	The direct and indirect effects of automation on employment: a survey of the recent literature	2021	-More productive workforce. -Increased demand for products. -Increased market size. -Increase in well-paid jobs and decreases in low-paid jobs. -Modernises the production process.	-Reduced jobs -Aggregate labour share. -Polarization of the job market. -Reallocation of workers.	Positive
Dasmadi et al. (2023)	Exploring the future of work: impact of automation and artificial intelligence on employment	2023	-Increase in productivity. -Job creation for skilled workers.	-Job replacement (mechanical, analytical and intuitive work)	Positive
Le Roux et al. (2018)	Automation and employment: the case of South Africa	2018	-New business models. -Motivates employees to gains skills. -Computerization of work. "race with machines as opposed to against machines"	-Computerization of work. -Decreased demand for low and medium-skilled labour.	Positive
Lawrence et al. (2017)	Managing automation: employment, inequality, and ethics in the digital era.	2018	-Work will be transformed by automation not eliminated. -Increased productivity. -Enables higher wages. -Broadens prosperity rather than concentrates wealth. -Increased employee ownership trusts (EOT's) -Reduces working times	-Increased in inequalities of wealth, income and power.	Positive

Maroof et al. (2018)	Impact of automation on employment (challenges & opportunities)	2018	-Greater output. -Higher quality. -Improved safety. -Reduction of waste. -Higher customer satisfaction.	-Job reduction	Positive
Wassily & Faye (2000)	The impacts of automation on employment.	1963-2000	-Job transformation. -Increase in number of jobs.	-Job reduction due to job transformation.	Positive
Burghgrave (2023)	The impact of automation on employment within California	2023	=Cost reduction within production.	-Decline in wages of law-skilled workers. -Job polarization. -Expanding offshoring opportunities.	Negative
Serumaga-Zake et al. (2021)	Addressing the impact of fourth industrial revolution on South African manufacturing small and medium enterprises (SMEs)	2021	-Improved innovation. -Reduced costs. - Increased Productivity. -Monitoring and diagnosis of systems. -Flexibility.	-De-centralized smart factories/structures. -Shop-floor entities as the workers of the future.	Positive
Jadhav & Gawande (2020)	A study of impact of automation on industry and employees	2020	-Improve quality. -Improved efficiency of workers. -Improved safety. -Improved productivity. -Help achieving goal of industry. -Help in maintaining work life balance.		Positive
Vermeulen (2018)	The impact of automation on employment: just the usual structural change?	2018	-Increased productivity. -Increased demand for labour and skills. -Increased earnings.	-Mass unemployment. -Income inequality.	Positive
Hwang & Kim (2022)	Does the adoption of emerging technologies improve technical efficiency? Evidence from Korean manufacturing SME's	2022	-Increased productivity. -Drives innovation.	-Job polarization.	Positive
Frohm et al. (2006)	The industry's view on automation in manufacturing	2006	-Increased productivity. -Cost reduction. -Increased efficiency. - Increased competitiveness.	-Variations in production. -Increase in low-skilled workforce. -Job reduction.	Positive
Thek (	Th9e impact of automation on employment in Malaysia	2017/2018	-Increased worker productivity. -Decreased production costs.	-Polarization of the labour market. -Insufficient skills.	Positive
Chui & Mischke (2019)	The impact and opportunities of automation in construction	2019	-Increased productivity. -Increased wages for workers with advanced skills.	-Job displacement -Increased wages for workers with advanced skills.	Neutral

Carbonero et al. **(2020)**	Robots worldwide: the impact of automation on employment and trade	2020	-Increased employment opportunities.	-Drop in global employment.	Neutral

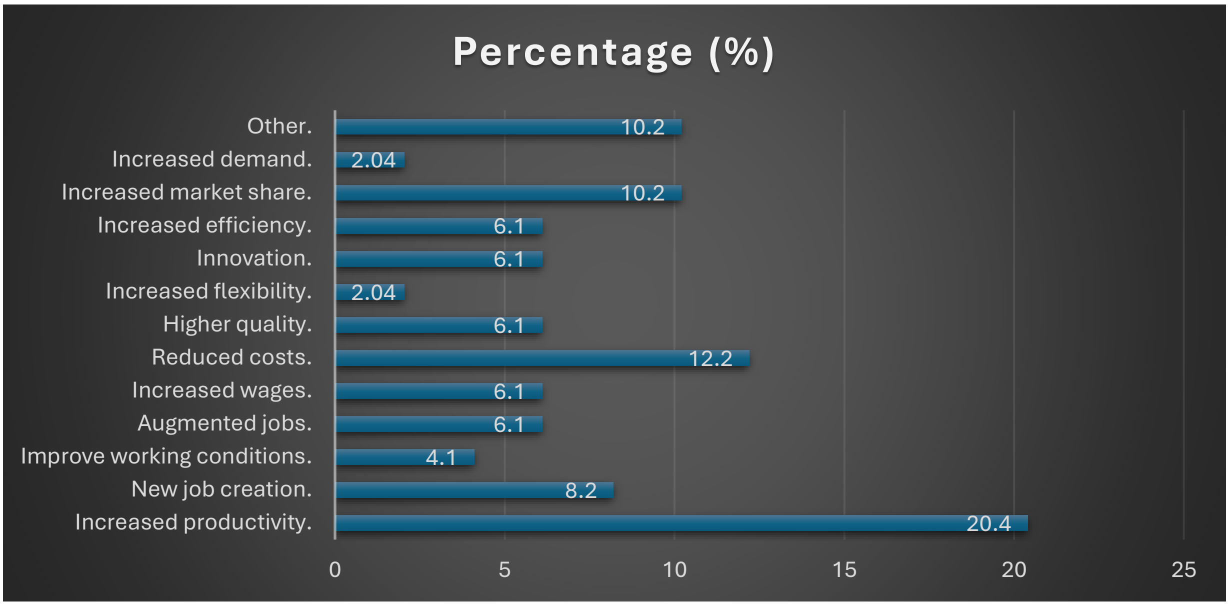
3.3 Positive impact

According to the data collected from the 17 papers, we identified 12 themes associated with the positive impact of automation on employment in SMEs. Namely, increased productivity, new job creation, improved working conditions, Augmented jobs, increased wages, reduced costs, higher quality, increased flexibility, innovation, increased efficiency, increased market share and increased demand. Everything else that does not fit into any of the above-mentioned themes was classified under the “other” theme. The table below (Table 2) depicts the positive impacts of automation on employment as per the reviewed papers. Table 2 - The positive impacts of automation on employment in SMEs.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	QTY	%
Increased productivity			0	0		0				0	0	0	0	0	0	0		10	20.4
New job creation			0	0								0					0	4	8.2
Improve working conditions								0			0							2	4.1
Augmented jobs				0	0	0												3	6.1
Increased wages						0						0				0		3	6.1
Reduced costs	0							0	0	0				0	0			6	12.2
Higher quality							0	0			0							3	6.1
increased flexibility										0								1	2.04
Innovation						0				0			0					3	6.1
Increased efficiency					0						0			0				3	6.1
Increased market share	0		0		0			0			0							5	10.2
Increased demand			0															1	2.04
Other						0		0		0	0			0				5	10.2

In Table 2 we see that “increased productivity” was deemed as the most positive impact of automation on employment by 20,4% of the authors. Automation can increase productivity and efficiency in SMEs, leading to the creation of jobs. Employees who can work with machines are said to be more productive than those without them. The second most positive impact is “reduced costs” with 12,2%. “Other” impacts and “increased market share” have 10,2%, which means that the papers reviewed show that the two themes have the same impact on employment. “ Increased demand” and “increased flexibility” have the lowest positive impact, only 2,04% of the authors out of a 100% deemed them a positive impact on employment. We see that out of all the authors, not one of them selected all these themes as positive impacts. The table also shows that all the authors had different opinions on what exactly impacts employment in a positive way. Each Author had an average of 2-5 reasons why they think automation has a positive impact on employment in SMEs. In this table, we also see that author 2 believes that automation has no positive impact on employment in SMEs. Figure 1 below summarises the information in table 2.

Figure 1- the positive impact of automation on employment in SMEs.



3.4 Negative impact

According to the data collected from the 17 papers in Table 1, we identified 5 themes which are associated with the negative impact of automation on employment in SMEs. Namely, Job loss, displacement of workers, resistance to change , unequal distribution of impact (wages) and job polarization. Everything else that does not fit into any of the above-mentioned themes was classified under the "other" theme. The table below (Table 3) depicts the negative impacts of automation on employment as per the reviewed papers.

Table 3 - The negative impacts of automation on employment in SMEs

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	QTY	%
Job loss			0		0		0			0		0		0			0	8	27.6
Displacement of jobs		0	0	0	0			0						0	0	0		8	27.6
Resistance to change																		0	0
Unequal distribution of impact (wages)							0		0			0				0		4	13.8
Job polarization		0	0						0				0		0			5	17.2
other			0						0	0				0				4	13.8

Table 3: Impact and Quantity

Impact	Quantity	%
Positive	13	76,47
Negative	2	11,76
Neutral	2	11,76

In Table 3 depicts that "Job loss" and "Displacement of workers" were deemed as the most negative impacts of automation on employment in SMEs by 27,6% of the authors. Automation can lead to job loss and displacement, particularly in industries that rely heavily on manual labour workers (SMEs). Workers who can be replaced by machines may find it difficult to find new jobs, especially if they lack the skills needed for new positions. The second most negative impact is "Job polarization" with 17,2%. "Other" impacts and "Unequal distribution of impact" have 13,8%, which means that the papers reviewed show that the two themes have the same impact on employment. "Resistance to change" according to the authors does not have any impact on employment because 0% of authors selected it as one of the negative impacts of automation on employment in SMEs. We see that out of all the authors, none of them selected all the themes in one paper as having negative impacts on automation. The table also shows that all the authors had different opinions on what exactly impacts employment negatively. Each Author had an average of 1-3 reasons why they think automation has a negative impact on employment in SMEs. In this table, we also see that author 1 and 11 believes that automation does not have a negative impact on employment in SMEs. Figure 2 below summarises the information in Table 3.

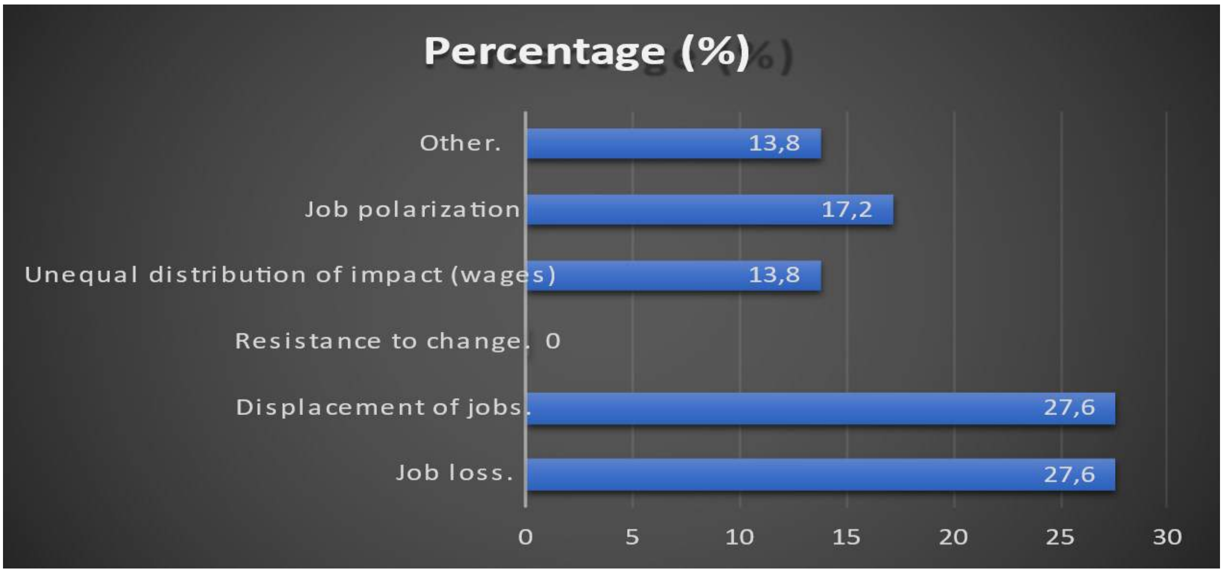


Figure 2 - the negative impact of automation on employment in SMEs

Upon careful review of the papers from 17 different authors. We found 12 themes when it comes to the positive impact of automation on employment and 5 themes when it comes to the negative impact of automation on employment. Each author identified the positive and the negative impact that is brought about by automation on employment and to conclude their studies according to the information they gathered, they had to choose whether they believe automation has a negative or positive impact on employment. 13 Authors as per the papers reviewed believe that automation has a positive impact on employment in SMEs, 2 Authors believe that automation has a negative impact on employment and 2 authors believe that automation has both a negative and positive impact on employment in SMEs. Figure 3 below depicts the conclusions gathered from the reviewed papers.

Figure 3 - the overall impact of automation on employment in SMEs.

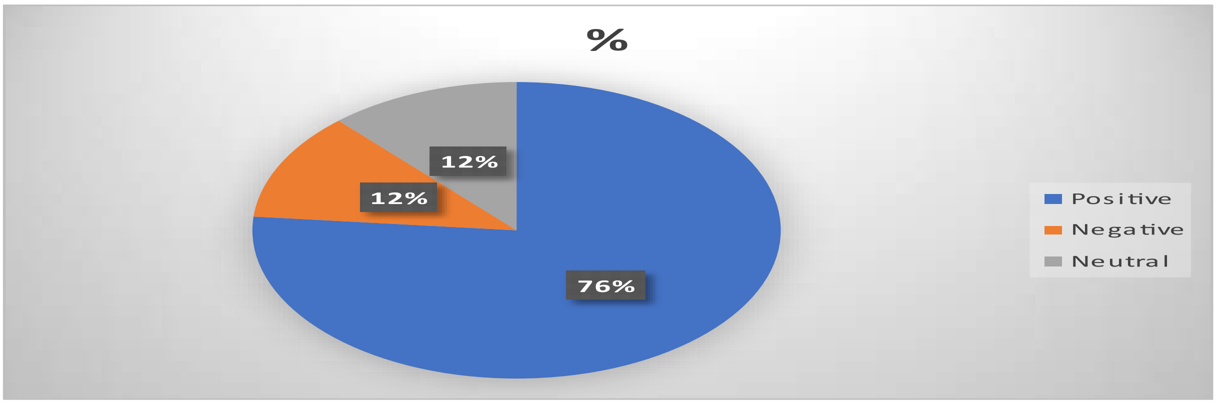


Table 4 and Figure 3 conclude that automation indeed does have a positive impact on employment in SMEs as per the 17 authors.

4 CONCLUSION

This study examined 17 articles investigating the impact of automation on employment in SMEs. Where 13 articles or authors agreed that automation has a positive impact on employment, with two having an alternative view, automation negatively impacting employment in SMEs, and lastly, two authors thought automation has both a negative and positive impact on employment. From the article, we concluded that automation has both positive and negative effects on employment. On the other hand, automation increases productivity and efficiency in many industries, enabling companies to produce more products and services with fewer workers. This could create new jobs as consumer spending increases and the economy expands. On the other hand, day-to-day workers or workers with lower levels of education are at risk of losing their jobs to automation. Automation also creates inequality in the labour market, as many producers and workers lose their jobs, or their wages fall. However, it is worth noting that even if some jobs are automated, the jobs will not decrease in these jobs, workers will get new jobs. The overall impact of automation on the job market is complex and varies by industry, job type and location. Some businesses and governments will take important steps to reduce the negative impact of automation on business, such as investing in education and training for employees. To reduce the negative impact of automation on business, businesses must work together to develop strategies to support employees and help them adapt to new jobs. This may include participation in education and training to help employees acquire new skills, financial support, and job training.

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ECONOMIC SUSTAINABILITY ASSESSMENT OF ENERGY SOURCES FOR DECENTRALIZED GENERATION

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ABSTRACT

A decentralized energy system provides significant opportunities for deployment of renewable energy sources most of which are locally available which increases access to clean energy for remote and off grid communities. The dependency on fossil fuel-based energy sources has been growing over the last few decades mainly due to global increase in energy demand leading to significant increase in environmental degradation. Energy sustainability has five major dimensions, namely technical, social, economic, environmental and institutional dimensions each with unique measurable indicators. This study addresses the economic dimension and indicators energy sources selection for use in decentralized power generation. In this study, the feasible energy sources for use in decentralized generation are presented and compared in terms of their economic characteristics. For decentralized energy (DE), or distributed energy (DE) systems, electricity generation, and storage is done close to the point of use effectively reducing transmission and distribution costs and exploitation of local energy resources. The power produced may be connected to a local distribution network system or to high voltage transmission system directly or via local distribution network system. The DE strategy involves use of small energy systems that may operate stand-alone systems or connected to the public electricity grid. Indicators examined in the economic sustainability analysis include price of energy resources, levelized cost of energy, and job creation potential which have significant economic impact to society. In the economic sustainability assessment of energy sources for distributed generation. The study showed that diesel power plants, fuel cells and battery storage supply the most expensive power source while, bagasse cogeneration, onshore wind and solid biomass offer the cheapest solution based on lifecycle assessment or levelized cost of energy. However, in terms of fuel cost, the renewable sources have no direct resource price making them more competitive while coal, solid biomass and diesel are the most expensive to acquire.

Keywords: Energy economics; energy sustainability; decentralized generation; power generation; dimensions of sustainable energy; energy sustainability indicators; energy sustainability; energy sources; sustainable energy transitions

1 INTRODUCTION

The main characteristic of decentralized energy systems compared with centralized energy systems is their location closer to the site of energy consumption [1] . This allows for more optimal exploitation of energy resources and a wider application energy at increased eco-efficiency. Decentralization is a relatively new concept in electricity sector of many countries[2]. The traditional power industry is based on development of large, central power stations which transmit power across long transmission and distribution lines to consumers often located far away from energy sources and power plants unlike decentralization which seeks to locate power stations closer to the end uses [3, 4]. Since end users are widely spread across a region, sourcing energy and electricity in a similar manner reduces the transmission and distribution costs and environmental costs[1, 5]. In this study, decentralised energy systems are defined as small-scale energy generation systems designed to deliver energy to local customers. These energy systems may be stand-alone or may be grid connected or both [6, 7].

When compared with the centralized energy systems, integration of distributed power systems in distribution and transmission networks effectively changes the commercial mechanisms of the power system in aspects of operation, maintenance as well as investment costs and financial benefits which should be resolved before deployment [8, 9]. Managing energy sustainably needs a set of adequate energy resources and corresponding conversion technologies for optimal delivery of energy from different sources for various electricity applications [10, 11]. To attain sustainable power systems, focus should be placed on key areas like energy efficiency and diversity, social value and public acceptance, power supply reliability, technological innovation, competitive and cost reflective pricing, market-sensitive interventions, standard requirements, regional integration, and power quality. Successful energy transition requires progress in these key areas [12, 13].

There are different indicators and parameters applied in measuring sustainability of energy sources[14]. These could be based on cost of electricity generated, the levelized cost of energy or generated electricity, water demand and socio-economic impacts among other factors[15, 16]. Energy sources vary in terms of cost of electricity produced, price of produced power, efficiency of generation, resource needs and investment costs [17] These variations may also be a function of technology applied, geographical locations and the political environment which may influence the indicators through policy intervention hence the need for detailed and careful selection of indicators and analysis [18, 19].

1.1 Problem Definition

Energy access remains a global challenge with close to 1.2 million people mostly in rural areas in developing countries have no access to electricity. Lack of access to clean energy has led to energy poverty and diseases like acute respiratory illness due to in-house pollution, high infant mortality caused by to the lack of refrigeration facilities for medicines and vaccine as well as inability to power incubators and negative impact on education quality and access. These energy related challenges can be addressed by adoption of distributed energy systems [20-22].

Although renewable energy resources are key to the energy transition, they face challenges in terms of resource availability, resource access, resource location, security of supply, sustainability, and affordability. The intermittence and variability of sources like wind and solar makes their use and reliability complex making it necessary to use dispatchable sources, most of which are non-renewable[23]. Therefore, optimal planning and dispatch in decentralized generation is very important. This requires pertinent information on all feasible of sources, both renewable and non-renewable to ensure that the power systems are affordable, reliable and have limited environmental impacts [24, 25].

1.2 Rationale of the study

There is overwhelming evidence that the world is facing changing climatic conditions due to the greenhouse effect which has led to an increase in average global temperature, and related consequences like drought, storms and desertification [26]. The global anthropogenic activities have led to about 1 ^{o}C rise in average global temperature above prehistoric level and is further projected to reach 1.5 ^{o}C between the year 2030 and 2052 if current greenhouse gas emission rates are maintained [27, 28]. The Paris Agreement of the 21st UNFCCC Conference of Parties (COP21) of 2015 aims at reducing average global temperature rise to below 2 °C above pre-industrial levels and preferably 1.5 °C the pre-industrial temperature which calls for drastic measures to reduce anthropogenic emissions [29]. Studies have shown that the climate is changing mostly because of the anthropogenic activities. The report by Intergovernmental Panel on Climate Change (IPCC) for 2021 indicates that several climate changes are already irreversible but adds that we still have hope for the future if action is taken to mitigate further changes [25, 30].

2 METHODOLOGY AND NOVELTY OF THE STUDY

In this study, energy sources for potential use in decentralised generation are analysed in terms of sustainability indicators like availability, feasibility and economic sustainability. The study seeks to identify short term and long-term economic consideration in selection and exploitation of decentralised energy systems within the broader perspective of sustainable energy transition which can be evaluated within five dimensions, namely social, environmental. Economic, institutional and technical dimensions This study adopted secondary method of data collection and analysis from recent primary and secondary data obtained from original research findings, theses, and dissertations, conference papers, peer review journal publications and technical reports from credible indexes like google scholar, Scopus and web of science covering studies across the globe.

Most studies on energy sustainability tend to concentrate on the environmental dimension of energy sustainability while researchers looking at sustainable development more holistically also tend to concentrate on the three pillars of sustainability, namely economic, environmental, and social pillars[26-28]. Most past reviews on energy sustainability tend to focus on energy sources within the three pillars of sustainability but very few if any focus on decentralised energy sources within the five dimensions of energy sustainability, which is the focus in this study making it unique.

3 ENERGY SUSTAINABILITY

Sustainability has become a major concern today because of growing concerns over the climate change caused by anthropogenic greenhouse gas emission [29]. Electricity is a very import product because it a global energy carrier which is needed to support life, welfare and global sustainable development [9, 30-32]. Currently, humanity is faced with a significant challenge to achieve new sustainable development Goals (SDGs) by the year 2030 [30, 33]. Sustainable energy and power generation refers to production and use of electricity in a way that that does not compromise the ability of future generations to meet their own energy and electricity needs [34, 35]. Sustainable energy also refers to energy sources that do not get depleted in a time frame that is relevant to humanity and thus contribute to the sustainability of all species on planet earth [36]. Sustainable Energy, needs significant changes in the way the way electricity is produced, stored, transmitted, distributed and consumed with use of clean energy playing an important role in unlocking sustainable development[37-39].

It is in the Johannesburg world summit of 2002 that correlation between sustainable development with energy became a significant global concern and issue [15, 40]. Selecting the most the most appropriate energy systems in an energy mix is considered as a strategic decision in the realization of sustainable energy and sustainable development[41, 42].

3.1 Dimensions of Energy Sustainability

Energy and power systems can be assessed by a five-dimensional approach consisting of technical, environmental, social, economic, and institutional sustainability in energy sustainability assessment[15, 41, 43]. Therefore, energy sustainability seeks to achieve technical sustainability, political or institutional sustainability, social sustainability, environmental sustainability, and economic sustainability which can be achieved by the development and use of renewable energy and sustainable resources[44, 45]. Figure 1 illustrates the 5 main dimensions of energy sustainability.

Figure 1: Dimensions of energy sustainability [44]

Figure 1 above summarizes the main dimensions of energy sustainability particularly electricity. It is deduced from figure 2 that the five key dimension of energy sustainability are environmental, social, political/institutional, economic, and technical sustainability.

3.2 Economic Sustainability

Economic energy sustainability refers to the ability to meet energy demand in a cost-effective manner. Economic sustainability can also be expressed as a measure of access to requisite energy financing for resource development. The cost-effective energy operation ensures that the energy system is viable and feasible making the investment attractive to investors and financiers [44]. The economic dimension of energy sustainability is thus concerned with economic of an energy system or power system[25, 46].

Economic sustainability of energy resources is concerned with attaining operational stability in terms of cash flow, liquidity and ensure fair income and benefits to investors and other stakeholders in energy systems without exploiting consumers [9, 47, 48]. An energy system is said to have attained economic sustainability if they remain intact and stable while activities and processes are equitably accessible to all in a fair manner [49]. Therefore, economic sustainability requires energy systems to continuously generate competitive goods and services to so as to manage debts, pay bills, remunerate employees and guarantee sectorial balance [48, 50, 51]. It is important for energy systems to remain profitable and useful from one generation to another generation [52], Energy systems are made economically sustainable by being operated profitably by investors or utilities while energy products and services remain competitive and accessible to all in the society[51, 53]

4 ENERGY SOURCES FOR DECENTRALIZED GENERATION

Distributed generation which is the core function of decentralized energy systems is also known as embedded generation, dispersed generation, on-site generation, and decentralized generation. Whereas both heat and electricity can be generated in a decentralized manner, it is difficult to transport heat over long distances compared to electricity [2, 6]. It is for this reason that heat generation and use has been traditionally done onsite, while power generation has traditionally been done in centralized power systems. For this reasons, decentralized power generation facilitate efficient use of combined heat and power resulting to higher system's efficiency with electricity and heat production [1, 5].

3.1. Energy Sources and their Characteristics

Decentralized energy systems (DES) are the most opted alternatives and sustainable solutions to growing future energy needs. Decentralized generation leads to significant reduction in transmission and distribution losses with negligible footprints. The decentralized energy systems can be solo operated but may be affected by variable resource availability. Different distributed energy resources can be used for electrification purposes as grid connected or standalone or hybrid systems [8]. Decentralized energy systems have proved to be viable substitutes where generators are located closer to load centers to mitigate transmission and distribution losses[17].

There are diverse sources of energy that can be used in decentralized heat and power production by applying different conversion technologies as summarized in table 1 below

Table 1: Summary of energy options for the global transition[15, 25, 31, 54-56]

	Energy resource	Characteristics features	Contribution to the transition and sustainability
1	Hydropower	Hydropower is renewable and is gotten from moving water which runs hydraulic turbines. Hydropower is affected by weather	Hydro has contributed clean power for many years. Significant potential remains in small and mini hydropower schemes in decentralized and centralized generation.
2	Solar Energy	Solar is a variable renewable energy supplied by natural radiation from the sun. the energy is affected by weather and may be unpredictable intermittent in some cases	Solar has a useful role in the transition as a renewable energy resource but development in solar cells technology and smart grids will enhance their uptake contribution to grid electricity.
3	Wind Energy	Wind is natural and renewable and can be developed as onshore or offshore wind power stations.	Wind resources are significant but variable in supply. Their huge contributions lie in the transition to smart grids and development of energy storage facilities.
4	Hydrogen	Hydrogen can be made by electrolysis and mainly by steam methane reforming	Hydrogen will play a leading role in the development of fuel cells and as a fuel to replace fossil fuels.
5	Biogas	Biogas can be produced by anaerobic digestion of biodegradable biomass feedstock like energy crops, plant waste, animal waste. Relevant policy measures necessary to make them competitive	Biogas is a renewable energy resource with and is low carbon energy resource that can substitute fossil fuels in domestic, industrial, transport and power generation. Biogas can be upgraded to biomethane for direct substitution of natural gas applications and as a feedstock for industrial operations
6	Biomethane	Biomethane can be made by upgrading biogas or syngas	Can replace natural gas in almost all applications
7	Biodiesel	Made from biomass as a renewable energy resource	Can be used as a substitute of fossil fuels in transport and power generation.
8	Bagasse	Bagasse is green energy which is a solid byproduct of sugar cane milling	Can be used for heat and power generation by sugarcane factories.

			Bagasse cab also be used to produce bioethanol which is an energy resource
9	Solid Biomass	Biomass can be obtained as waste products, forest products or energy crops	Biomass can be used in power plants for heat and power generation.
10	Geothermal Energy	Geothermal energy has significant potential but huge upfront costs, investment risks and long project delivery tools have kept its contribution and growth low.	Since geothermal has no fuel costs and operates at high load and capacity factors, it is ideal for base load electricity supply. Increased use of geothermal will reduce electricity price, reliability and cut greenhouse gas emissions
11	Producer gas	Huge quantiles of animals, plants, and combustible industrial wastes, most with significant energy potential, are produced continuously globally.	Various waste to energy technologies exists with more efficient systems being needed for efficient waste to energy conversion.
12	Nuclear energy	Nuclear power projects based on nuclear fission have long delivery periods and have huge capital investment requirements which retards deployment. Nuclear power is clean while uranium reserves are huge and have very high energy density which guarantees a large supply of low carbon electricity at high load factor and capacity factor	Conventional nuclear power plants are huge in capacity and may not be ideal for decentralized generation. The solution to this challenge is to adopt the small modular reactors (SMR) for low demand/capacity and faster deployment. SMRs are also ideal for decentralized generation development is encouraged for faster growth of nuclear power.
13	Ocean /marine energy	This is a renewable energy resource mainly in the form of tidal power, wave power, osmotic and ocean thermal. Ocean thermal is limited by the low thermal gradient over which heat transfer is to take place.	The role of marine energy in the energy transition can be enhanced by investing in efficient technology for extraction of energy with low thermal gradient in ocean thermal.
14	Natural gas	Natural gas is nonrenewable source but cleaner than coal, diesel and petrol and global resources are huge.	Natural gas can substitute heavy polluters like coal and petroleum like diesel and petrol as fuel. The main challenge is delay in the transition to zero carbon target and investment risk involved with the transition.
15	Coal	Coal is nonrenewable and currently the largest source of global electricity. There huge coal in several countries which complicates the energy transition in these countries.	Coal produces is a source of reliable dispatchable power but has high carbon emissions. It can stabilize generations. Consumption should gradually be reduced by substitution.
16	Oil	Oil produces high carbon emissions together and pollutants like nitrous oxides (NO$_{X)}$ and (Sulphur dioxide) SO$_2$ and particulates. High reserves in some countries hence slow transition	Oil can continue to place an important role as a dispatchable source of energy for energy systems stability and peak power applications by application of efficiency measures like cogeneration and use of more efficient conversion

From **Error! Reference source not found.**, it is observed that both renewable and n onrenewable energy sources have an important role in decentralized generation and hence play a role in energy sustainability. As an example, coal and oil are nonrenewable but are easily accessible and are dispatchable sources of energy for grid and off grid energy supply.

Renewable energy sources particularly wind and solar, and to some extend hydro have the greatest potential but are significantly affected by reliability of supply due to intermittence and variability in resource supply. The main solution to these challenges is investment in storage, smart grids and micro grid technology infrastructure which effectively increases the cost of investment[31, 57].

The unpredictable and unreliable nature of supply for variable renewables is a significant risk to energy security and the grid stability hence power/energy system, reliability for the traditional grid. This which increases the demand for smarter and resilient grids for decentralized generation[58, 59]. The use of smart grids increases the ability to absorb small producers and variable supplies especially for wind and solar and small hydro sources and which have a significant role in the global energy transition[59, 60].

5 ECONOMIC INDICATORS OF SUSTAINABILITY

Decentralized energy projects mainly make use of local labor from rural areas, local businesses, local material, local investors, and other local services [61]. This ensures that energy or electricity revenue is invested back to local communities in various forms like materials payments, taxes, payments for materials and labor and dividends to local investors [62]. This implies that decentralized generation leaves more economic benefits compared with imported fossil fuels or imported grid power [3, 63]. It is necessary to make informed investment decisions because different sources of energy have different socioeconomic value like e.g. biofuel projects create jobs as compared to solar and wind power energy projects The cost and price of generated electricity is another economic consideration [2, 15, 64].

The Economic dimension in sustainability assessment is important because energy cost influences the adoption of technology and its penetration. The various performance indicators of the economic dimension of energy sustainability assessment include investment costs, the fuel price increase sensitivity, plant average availability factor, costs involved in grid connection, energy or plant peak load response, and energy security of supply. Very important economic investment indicators are private costs, availability factor and costs of power grid connection[58, 60, 65].

5.1 Energy Resource Price

The price of energy is an important factor in sustainability as it affects the price of electricity and the demand[66]. It is a measure of the direct cost of resource acquisition which is taken as zero for natural resources, while related costs may be treated as production or generation cost. Various factors affect the price including availability and taxes imposed by the state e.g. carbon tax. The price of an energy resource is what is paid for acquisition and is usually based on prevailing market price.

Table 2: Energy resource price[15, 17, 25]

	Energy resource	Market Price Range (USD)	Average
1	Hydropower	0	0
2	Solar Energy	0	0
3	Wind Energy	0	0
4	Hydrogen	0.5-8.5/kg	4.5/kg
5	Biogas	2-20 2/MBtu	11/ MBtu
6	Solid biomass	44-85/tone	64.5/tone
6	Biomethane	0.45--0.75/LGE	0.6/LGE
7	Biodiesel	50-69/litre	54.5/liter
8	Bagasse	9-22	10.5/MT
10	Producer gas	6.5 per mmBtu	6.5 per mmBtu
11	Uranium	120-130 /kg	225/kg
12	Wave energy	N/a	N/a
13	Tidal power	N/a	N/a
15	Natural gas	2.63- 2.78/MMBtu	2.705 MMBtu
16	Coal	130-137.14 /kg	133.6/kg
17	Heavy Fuel Oil	0.6-0.644 /kg	0.622/kg
18	Diesel	1.20-1.25/liter	1.225/liter
19	Petrol	1.25-1.30/liter	1.275/liter

From Table2, it is noted that the price of energy resources varies with type of energy resource, while factors like quality and freight charges affect the final acquisition cost of the same energy resource. The zero cost for renewables implies that natural renewable sources should be the cheapest since they are freely supplied by nature.

5.2 Levelized Costs (LCOE)

The levelized cost of energy (LCOE) or levelized cost of power is a metric used to gauge the average cost of electricity generation over the entire lifetime of an energy generating system. The levelized cost of energy is used to determine the viability and competitiveness of power generation or energy projects based on the life cycle costs[17, 67]. LCOE method is widely applied to compare different power generation technologies by considering fixed and variable costs as a single cost metric and is used to measure the average net present cost of generating electric power over the power plants entire life. The metric does not capture all costs that affect the cost of electricity e.g. system costs[9, 32, 68]. Table 3 compares the energy sources based on their levelized costs obtained from various sources globally.

Table 3. Levelized cost of Energy [9, 15, 17, 25, 32, 68-70]

	Energy resource	Levelized cost of energy (USD)/MWh	Average USD/MWh
1	Hydropower	50-70	60
2	Solar PV-Utility scale	49-185	117
	Solar PV-Roof top	117-282	199.5
3	Wind Energy-Onshore	33-35	34
4	Wind power-Offshore	79 - 81	80
5	Nuclear	141- 221	181.5
6	Coal	68-166	117
7	Combined cycle natural gas turbines	39-101	70
8	Bagasse	9-22	15.5
9	Hydrogen fuel cells	278 - 322	300
10	Battery energy storage	270-442	356
11	Biogas systems	50-190	120
12	Solid biomass	40.5 -46.3$	43.4
13	Biomethane	80-200	140
14	Magneto hydrodynamic generation	212.2 - 218.9	215.6
15	Geothermal energy	40-140	90
16	Diesel power plants	300-500	400

The levelized cost of the various energy and power sources presented in table 3 can be diagrammatically presented in figure 2 below

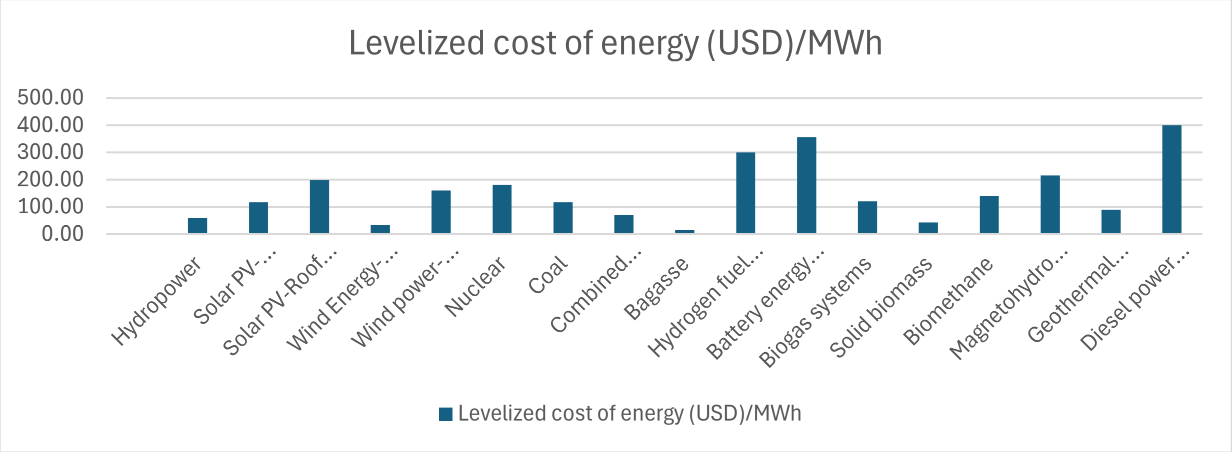

Figure 2: Levelized cost of energy from different sources[17, 25]

From figure 2 and table 2, shows globalized levelized cost of different sources based on data across different power plants globally. It is noted that diesel power generation, battery energy storage and hydrogen fuel cells have the highest values of levelized cost, while bagasse, offshore wind and solid biomass have the lowest levelized cost of energy which demonstrates that the lifecycle cost of renewable energy sources are lower than lifecycle cost of fossil fuel sources of energy.

5.3 Job creation potential by energy sources

Different energy sources have varying degree in job creation potential as demonstrated in figure 3 below.

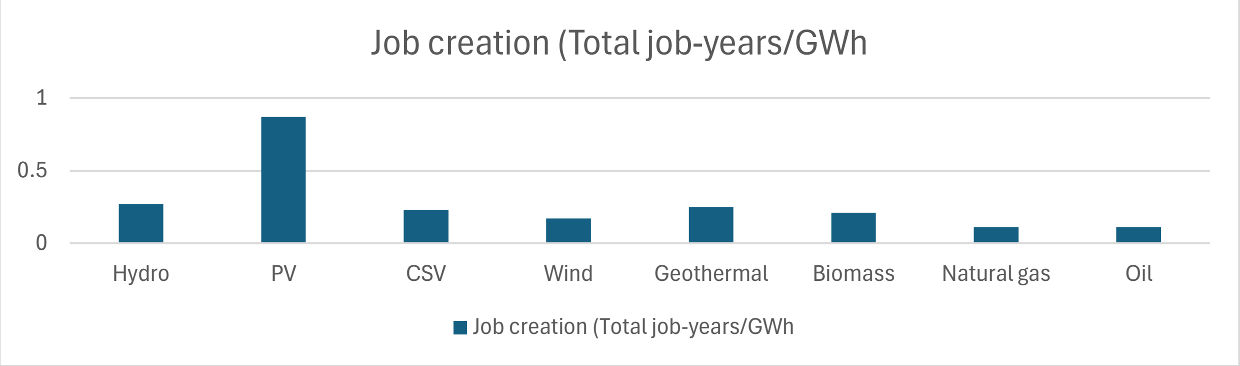

Figure 3: Job creation potential of energy sources for power generation[15, 17, 25]

From figure 3, it is noted that solar PV has the highest job creation potential followed by hydro and geothermal while oil, natural gas which are fossil fuels have the lowest. This generally implies that renewable sources of energy have significant job creation potential compared with fossil fuel sources.

5.4 Operational Flexibility and Costs

Irrespective of technology, all generators share the following characteristics which influence the plant's operational characteristics and cost:

i.) Ramp rate

Ramp rate or ramp time refers to the amount of time taken from the moment a generator is turned on to the moment it starts generating energy at lower operating limit normally expressed in hours [h]. Ramp rate influences how quickly the energy system takes to increase or decrease production/generation [MW/h] or in [% of capacity per unit time]. Typical ramp rates are presented in table 4

Table 4: Typical ramp and run times for power plants[15, 17].

Technology	Ramp Time	Min. Run Time
Simple-cycle combustion turbine	minutes to hours	minutes
Combined-cycle combustion turbine	hours	hours to days
Nuclear	days	weeks to months
Wind Turbine (includes offshore wind)	minutes	none
Hydroelectric (includes pumped storage)	minutes	none

From table 4, it is noted that nuclear energy sources plants have the longest ramp time and minimum run time making it ideal for baseload applications. Hydropower being dispatchable and combined cycle combustion turbines have shortest ramp time and low minimum run time making them ideal for peak and intermediate load applications. Although wind turbines have low ramp time and low minimum ramp time, they cannot be dedicated for peak load since wind is not dispatchable.

ii.) Capacity and lower Operating Limit

Capacity refers to the maximum output of an energy system normally expressed in [MW]. While the lower Operating Limit (LOL) refers to the minimum amount of power that can be produced by an energy system or power plant also expressed in [MW][17, 67].

iii.) Minimum Run Time

Minimum run time of a power plant or energy system refers to the shortest duration of time that a power plant or energy system is expected to operate once it is turned on, in [h][17, 67].

iv.) No-Load Cost

No load cost refers to the cost of turning an energy system and keep it “spinning," ready to supply more power output, in [$/MWh]. Another way of looking at the no-load cost is the fixed cost of operation; i.e., the cost incurred by the generator that is independent of the amount of energy generated[17, 67].

v.) Start-up and Shut-down Costs

Start up and shut down costs are costs that are incurred in starting and stopping a power plant or energy system and is normally expressed in [$/MWh][17, 67].

6.1. Relationship between Operating costs and Operational Flexibility

Flexibility is important in energy system to enable the energy system to meet varying load and energy supply conations. Less flexible energy systems are generally used to meet the base load while the flexible systems can meet intermediate and peak loads. Operational costs are influenced by the operational flexibility of the energy systems[4, 17]. Figure 4 demonstrates the relationship between operating costs and

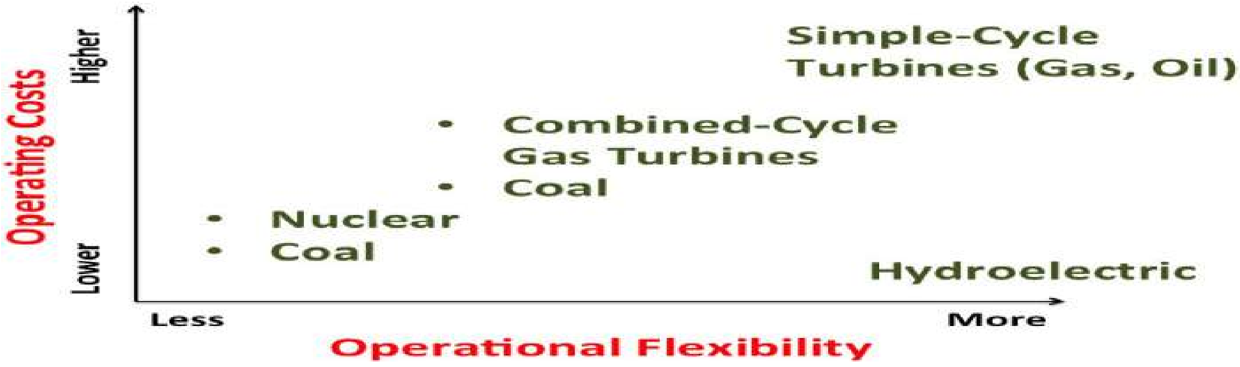

Figure 4: Relative comparison of operating cost and operational flexibility of energy systems and power plants[17]

Figure 4 shows that coal and nuclear mainly used in central stations are less flexible and are associated with lower operational flexibility. Flexibility of an energy system is mainly determined by the minimum run time and ramp times of the energy source and varies significantly with the types of power plants, type of fuel, and conversion technology applied. Hydropower which is a dispatchable renewable is highly flexible but has lower operational costs. The simple gas turbine running on oil, natural gas or kerosene have the highest operational costs and are generally used in peaking supply. [17, 46].

In power transmission and distribution, the cost structure is different from that of power generation, because of absence of fuel cost element. The cost of loading a transmission line with additional electricity is almost zero (unless the line is operating at its rated capacity limit). Therefore the economics of power transmissions and distribution is dominated by the capital costs[45, 46].

7 RESULTS AND DISCUSSION

A sustainable power system strategy should enable social equity, preserve the environment from degradation, and maintain a sound economic base. A sustainable energy system should also preserve the natural capital for sustained economic generation and equity across human generation. Sustainable energy transition requires application of sound economic policy instruments and an effective institutional mechanism to deliver economically feasible energy future [15, 16].

Energy sustainability assessment is important because of the ever-growing demand for energy, environmental impacts, and significance of energy to socioeconomic development. Many decentralized energy sources like wind, solar, geothermal and biomass, are inherently renewable and more environmentally friendly compared to traditional fossil fuels. Therefore by shifting towards decentralized generation concept, more renewable energy sources are exploited in power generation and other applications including heating and cooling leading to reduced pollution and greenhouse gas emissions thus mitigating the impact of climate change and increasing energy access [5, 15, 43]

Measures to realize sustainable energy transition including the use of sustainable energy resources, employing advantageous energy carriers, efficiency improvement for energy systems, mitigating environmental impacts of energy systems, and improving peoples living standards and their lifestyles, increasing energy affordability, improve community acceptance and guarantee equity. Electricity generation and distribution should be structured such that current distribution model contributes to actual economic and financial growth levels and willingness to pay by the people. Through proper planning and execution of power systems, DES should both supply power rural areas and be used in a broader sense to improve and up-grade judicious energy resources utilization[71].

A well-planned distributed energy system should maximize the use the use of local energy resources most of which are renewable and sustainable and still can be connected to the grid for maximum economic benefits to local communities in terms of revenue and job creation with solar energy demonstrating highest job creation capacity over its life cycle for maximum socioeconomic and environmental benefits needed for the sustainable energy transition. In as much as we have significant opportunities for distributed generation in all energy markets, there exist a wide range of potential economic barriers which may vary with the conversion technology applied and the specific energy resource that need to be considered in planning for a successful implementation by selecting most viable and come up with measures to overcome the identified challenges for successful and cost effective decentralized generation.

8 CONCLUSIONS

Sustainable energy is best analysed within five dimensions of sustainability, namely social, economic, environmental, institutional or political, and technical. A sustainable energy transition strategy typically consists of three major technological changes namely, energy savings on the demand side, generation efficiency at production level and fossil fuel substitution by various renewable energy sources and low carbon nuclear. For the transition to remain technically and economically feasible and beneficial, it is important to develop and identify policy initiatives that enable the global electricity transition towards a sustainable energy and electricity system that is environmentally benign but still remain economically competitive and sustainable. Although renewable sources energy holds the key for sustainable energy transition, a sustainable energy mix will incorporate all other energy sources in a way that addresses the five dimensions of energy sustainability through measures that enhance efficiency of existing non-renewable sources which still have an important cost reduction and stabilization role and most of them are still economically superior and technically dispatchable and so controllable.

Various energy sources are available for selection and use in heat and power generation for decentralized generation. Whereas some energy resources have been in use for many years like coal, natural gas, oil, hydro and biomass, some resources are still under development and require massive investment in infrastructure and technology development. They include hydrogen, biomethane, ocean thermal, ocean osmotic, wave and tidal energy. Most renewable energy resources like wind and solar are supplied freely by nature but require investment in infrastructure and technology which add to the final cost of energy. Decentralized systems typically use renewable energy sources, including small hydro, combined heat and power (CHP), biomass, solar and wind power. A decentralized energy system can increase security of supply, reduce transmission losses and lower carbon emissions

In the economic sustainability assessment of energy sources for distributed generation, it was established that, diesel power plants, fuel cells and battery storage supply the most expensive power source while, bagasse cogeneration, onshore wind and solid biomass offer the cheapest solution based on lifecycle assessment or levelized cost of energy. However, in terms of fuel cost, the renewable sources have no direct resource price making them more competitive while coal, solid biomass and diesel are the most expensive to acquire.

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