Proceedings of the 2025 Production and Operations Management Society (POMS) Africa International Conference

Editors:
Wilna Bean & Dino Petrarolo

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Foreword

BACKGROUND

The 2025 Production and Operations Management (POMS) African International Conference was held from 18 to 26 November 2025 at the Future Africa Campus in Pretoria, South Africa. POMS conferences are renowned for their dynamic blend of research presentations, interactive panel discussions and valuable networking sessions, and are centred on advancements and industry trends and advancements in production and operations management. The 2025 POMS Africa International Conference again embodied these key features to provide a comprehensive and enriching experience to conference delegates from countries all over the world, including Australia, Botswana, Canada, Kuwait, New Zealand, Saudi Arabia, South Africa, Switzerland, the United Kingdom and the United States.

Conference papers and presentations focused on health and humanitarian operations management, manufacturing operations management, operational excellence, service operations management, supply chain management and sustainable operations management, along with other topics related to operations management.

SUBMISSION AND REVIEW PROCESS

Authors were invited to submit abstracts featuring novel research in the fields of production, operations and supply chain management. Abstracts were reviewed for suitability and relevance. After abstract acceptance, authors were invited to submit full papers for possible inclusion in the *Proceedings of the 2025 Production and Operations Management (POMS) Africa International Conference*, subject to a rigorous evaluation process, described below.

All submitted papers underwent an initial screening and similarity check to ensure relevance to the conference scope, compliance with formatting requirements and adherence to basic quality standards. Eligible papers were then subjected to a double-blind peer review process, with each paper evaluated by at least two expert reviewers who assessed its novelty, scientific rigor, presentation quality, overall merit and language use. This review process was managed through an online conference management system that allowed reviewers to provide online feedback and recorded all reviewer feedback and editorial decisions taken during the process.

Based on reviewer recommendations, track chairs made recommended acceptance or rejection of the full paper for inclusion in the conference proceedings. Accepted papers were revised by the authors, resubmitted and subjected to a final screening and review to verify that reviewer comments had been adequately addressed and that formatting and language standards had been met. Only papers that successfully completed this process were included in the conference proceedings.

We received 23 full paper submissions from seven local and international academic institutions. Not all of the submitted papers were accepted for inclusion in the proceedings after the peer-review process. The top five papers (as scored by reviewers) were selected for inclusion in a special edition of the South African Journal of Industrial Engineering (SAJIE) in 2025. Consequently, these papers were withdrawn from the proceedings. The remaining accepted papers are included in the full conference proceedings. No single institution contributed more than a third of the papers published in the proceedings.

PROCEEDINGS AND EDITORIAL TEAM

The editorial process of the proceedings was supported by the following team of academics and practitioners:

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Industry 4.0 for Circular Plastic Flow Improvement: A Systematic Literature Review and Conceptual Framework

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ABSTRACT

Plastics are used for various products and applications but the production and waste management operations need to be addressed to ensure sustainability goals can be achieved. Circular economy aims to reduce waste through circulation, and technology innovations are one of the enablers for this transition. This research interprets Industry 4.0 applications and associated adoption factors according to the waste hierarchy and Political, economic, social, technological, legal and environmental (PESTLE) analysis. A conceptual framework is then constructed to illustrate the factors and acknowledge the systematic perception for solution development. The Global Supply Chain Forum model is approached to visualise technology applications based on the supply chain processes, as well as demonstrate how the framework can be utilised. The framework is designed for various sectors to understand their operations in the context of these factors and determine solution approaches. This framework also emphasises the necessity of acknowledging potential impacts over time to ensure these aspects are addressed and that the solution is effective. Limitations of this framework include the need of further research to ensure factor generalisation for all sectors when the technology of interest is considered for solution development.

Keywords: circular economy, plastics, supply chains, Industry 4.0

* Corresponding author

1 INTRODUCTION

Plastics are used in different applications, ranging from packaging to aviation [1], [2]. However, these materials also lead to environmental concerns, such as pollution in oceans and climate change [3], [4].

1.1 Background

Plastic waste in oceans has physical influences on organisms and the life cycle releases emissions during production and waste management [1], [4], [5]. Strategies, such as reuse and recycling, require evaluation to improve waste management and avoid further complications for ecosystems in the future [6]. Circular economy (CE) has the objective to eliminate waste through these strategies, as well as design and maintenance [7].

CE acknowledges plastics as technical materials due to their negative impacts on the environment [8], [9]. Technical resources can imply materials with durable characteristics, meaning these materials must be circulated to enhance product life cycles and utility for waste reduction, as well as value creation. Product designs, for instance, could be altered for reuse [10]. Recycled materials could also be considered for product development.

Kirchherr et al. [11] identify technology innovation as an enabler for CE transition. Technologies can monitor materials in the system and enhance stakeholder collaboration for CE transition [8], [9]. These capabilities may be essential for the plastic value chain since a holistic perception is necessary to acknowledge concerns influencing circularity [12], [13], [14]. For example, manufacturers must understand how the product's design could influence recycling [15]. Research has analysed Industry 4.0 to promote CE practices with plastics, such as additive manufacturing for waste valorisation [16], [17]. However, the systematic perception appears to be limited in research with respect to the waste hierarchy.

Waste hierarchies may be necessary to ensure a holistic perception across the supply chain (SC) for CE transition [18]. Furthermore, using waste hierarchies are important for encouraging companies to aim for optimal SC performance in sustainability, meaning waste reduction should be concentrated for transition. Waste prevention can reduce waste and associated expenses for collection, whereas recycling uses more energy for processing, which impacts the environmental and financial performance [19], [20]. However, Dijkstra et al. [20], having categorised business models addressing plastics based on the waste hierarchy, conclude that recycling is common compared to the other strategies in reuse or prevention. However, recycling alone in a specific area of the SC is not sufficient compared to a systematic transformation for CE implementation [18]. This aspect may indicate that the business models' sustainable performance with plastics requires improvement for CE transition [20]. Nevertheless, research analysing Industry 4.0 for plastic waste management (PWM) and CE provides limited information or a lack of content regarding waste hierarchies [16], [17], [21].

1.2 Research problem

This research focuses and extends the studies by Sahu et al. [22], Lei et al. [23], and Bag et al. [24] to address the lack of a systematic perception through the application of the waste hierarchy and various adoption factors. For example, Lei et al. [23] performed a systematic literature review (SLR) and analysed the influences of Industry 4.0 on CE to acknowledge the technologies' capabilities in a holistic perception for CE implementation. The applications were arranged according to CE practices, such as waste reduction, maintenance and recycling. The authors included a study from Nara et al. [25] evaluating Industry 4.0 in the plastic sector and indicated that the Internet of Things (IoT) could be approached to reduce expenses for CE. Nevertheless, Lei et al. [23] did not assess factors for adoption as comprehensively as Sahu et al. [22] or Bag et al. [24].

The lack of a systematic perception hinders opportunities to enhance the sustainable performance since this viewpoint assists in managing barriers preventing transitions throughout the value chain tiers from raw material production to plastic recycling [26]. Sahu et al. [22] evaluated factors regarding CE and Industry 4.0 adoption, ranging from concerns influencing employment to the need for government involvement. These authors did not consider the waste hierarchy for the technologies and acknowledged that research was limited regarding SC management for the technologies and CE. Bag et al. [24] assessed Industry 4.0 enablers for sustainability in SC, yet waste hierarchies and the plastic value chain were not analysed for transition.

This research aims to extend the research from [22], [23] and [24] since these studies indicate potential opportunities to enhance the holistic perception of the plastic value chain for adopting Industry 4.0 and promoting CE transition. For instance, Sahu et al. [22] acknowledged various factors for CE and Industry 4.0 technologies but did not concentrate on the plastic value chain. This aspect is essential since factors influencing circularity can relate to various considerations, such as economic, technological and legal concerns, emphasising the need for a holistic perception to promote circularity [12]. Lei et al. [23] and Bag et al. [24] also did not consider plastics as the main concern for Industry 4.0 adoption. Therefore, this research aims to extend these studies to enhance the holistic perspective and acknowledge factors influencing Industry 4.0 adoption for plastic circularity.

1.3 Research question

This research aims to improve the systematic perception for Industry 4.0 adoption and enable circularity in the plastic value chain. However, Sahu et al. [22] claim that Industry 4.0 adoption may not be the same for each organisation as the factors depend on the country or sector of interest. For instance, obstacles for India include concerns affecting employment and the need for integration regarding processes and digital technologies. Denmark may experience barriers related to employment considerations yet Denmark has more drivers for adoption compared to India, including technology accessibility to promote circular flows. Developed countries have also conducted more research on the technologies and CE, whereas the research for developing countries is in the initial stage.

Companies may also need to acknowledge the context of their environment for Industry 4.0 adoption since certain organisations, such as small businesses, may select one of the various technologies to satisfy budget constraints [23]. These aspects may imply that companies need to interpret their system in a holistic viewpoint to understand and manage the respective factors influencing Industry 4.0 adoption for CE transition. Therefore, these concerns are addressed through the following research question: "How could organisations implement CE practices using Industry 4.0 technologies to improve PWM in SCs?".

The research design explains the selected concepts to answer the research question, followed by the research methodology, SLR and a conceptual framework. The SLR is performed since Lei et al. [23] considered an SLR to acknowledge Industry 4.0 influences on CE in a holistic perception. This research conducts an SLR to understand the technology applications in this perception for PWM, as well as to determine factors impacting adoption for CE transition. The information is used to develop a conceptual framework, concluding with future research opportunities for refinement and improvement.

2 RESEARCH METHODOLOGY

2.1 Research design

The research design approaches the waste hierarchy and PESTLE analysis to design a conceptual framework consisting of the holistic viewpoint and adoption factors [27], [28]. The research also considers alternative solutions when the technology is not applicable or available, as well as the Global Supply Chain Forum (GSCF) model to visualise Industry 4.0 applications for PWM [29], [30].

2.1.1 Circular economy and waste hierarchy

CE and the waste hierarchy share similarities where CE includes a value creation approach to extend product life cycles and promote cost-saving opportunities through maintenance as the inner loop, followed by reuse, refurbishment and recycling [8], [9], [11]. This order is due to the increasing expenses of using energy and resources for processing. The waste hierarchy prioritises waste prevention for environmental performance and economic benefits since prevention promotes cost-saving opportunities for waste collection and processing [20], [27]. Recycling, however, increases the expenses and reduces these benefits. Therefore, maintenance and waste reduction can be more effective than recycling in PWM, which aligns with Kirchherr et al. [11] regarding the CE objectives in waste reduction and maintaining value.

The hierarchy promotes incremental change and illustrates which strategy may be preferable, such as recycling as a more appropriate alternative than recovery or disposal, rather than indicating reduction as the overall objective in waste management [31]. Incremental adaptations alone are not sufficient for CE since systematic transitions have greater impacts on sustainability performance [11]. However, upscaling is an enabler for CE transition. This enabler may need to be considered for CE solutions in the plastic value chain as Lisiecki et al. [32] indicated that factors can relate to different perceptions, such as social or policy concerns, and that these factors must be managed to promote scalability. This statement aligns with the need for a holistic perception of the plastic value chain to ensure circular flows and sustainability [13], [26]. Therefore, the waste hierarchy is approached to not only arrange Industry 4.0 applications according to each strategy, but also to acknowledge the systematic perception through incremental change and upscaling as progression toward potential waste reduction.

2.1.2 PESTLE analysis

Research has identified factors in different viewpoints, such as legal, environmental, ethical and organisational considerations, for Industry 4.0 adoption [22], [33]. Sahu et al. [22] observe that the factors depend on the sector and location of interest. Nevertheless, the factors can be grouped into categories for evaluation and determining how these factors could impact the overall SC. For example, Siltaloppi and Jähi [26] identified obstacles for sustainability throughout the plastic value chain in market, SC, societal and technological aspects. The low recycled plastic supply for manufacturing is due to the need for advanced technologies and heterogeneous plastic waste complicating the mechanical recycling operations. Challenges for upscaling include demand uncertainty and investments for capacity development.

Paletta et al. [12] interpreted obstacles for plastic circularity from economic to socio-cultural concerns. CE initiatives would also need to consider the various factors for scalability [32]. Sahu et al. [22] analysed legal aspects, economic drivers, and obstacles in environmental perspectives. Therefore, factors can be categorised to group the information and acknowledge the technology applications in a holistic perception for solution development.

Chavez and Sharma [28] assessed a closed-loop SC in Mexico with respect to the PESTLE analysis to understand the conditions and evaluate each stage from legal to environmental concerns. This technique assisted in determining the SC performance and whether the system is applicable through different perspectives, such as frameworks in legal perceptions. Therefore, this technique is used to identify and group the main factors in adopting Industry 4.0 for any sector or country, thereby supporting and acknowledging the holistic perception for solution development and implementation.

2.1.3 Alternative solutions

Alternative solutions include chemical recycling, bioplastics and organisational culture as suggestions when the technology is not applicable or available for PWM [34], [35], [36]. This aspect is considered since Dijkstra et al. [20] have identified business models with different solutions to manage plastics sustainably. For example, business models may use additive manufacturing while the other models may refer to bioplastics or include communities in sustainable practices. Furthermore, Dijkstra et al. [20] assigned the waste management strategies to each business model case, indicating that models may consider different sustainable approaches, such as combining recycling with reuse or prevention.

Lisiecki et al. [32] evaluated various CE initiatives for plastic circularity, ranging from plastic bans to blockchain in waste sorting, bioplastics and chemical recycling. Bag et al. [24], citing Sung [37], found that companies may experience challenges regarding technology adoption since impacts could affect a SC's economic performance. Therefore, companies may consider different approaches besides Industry 4.0 for PWM and CE transition. These three alternative solutions are considered but not evaluated extensively since Industry 4.0 is the main topic for the research scope, meaning the alternatives are suggestions for further investigation.

2.1.4 Global Supply Chain Forum Model and Industry 4.0 Applications

Bag et al. [24] could not identify research regarding a framework providing a systematic perception of SC and Industry 4.0 for sustainability. However, the GSCF model includes eight core processes and various activities in each process that must be planned for the functions to operate accordingly and achieve SC objectives [29]. For example, manufacturing operations need information regarding product designs to determine the required capabilities and flexibility. Hazen et al. [30] and Rebelo et al. [38] used this model for CE motivation and IoT applications. Therefore, this research considers the GSCF model to illustrate Industry 4.0 applications throughout the SC network and demonstrate the conceptual framework's purpose for solution development. Figure 1 illustrates Industry 4.0 applications from the SLR according to the GSCF model's process descriptions and SC activities from Croxton et al. [29] and Hazen et al. [30].

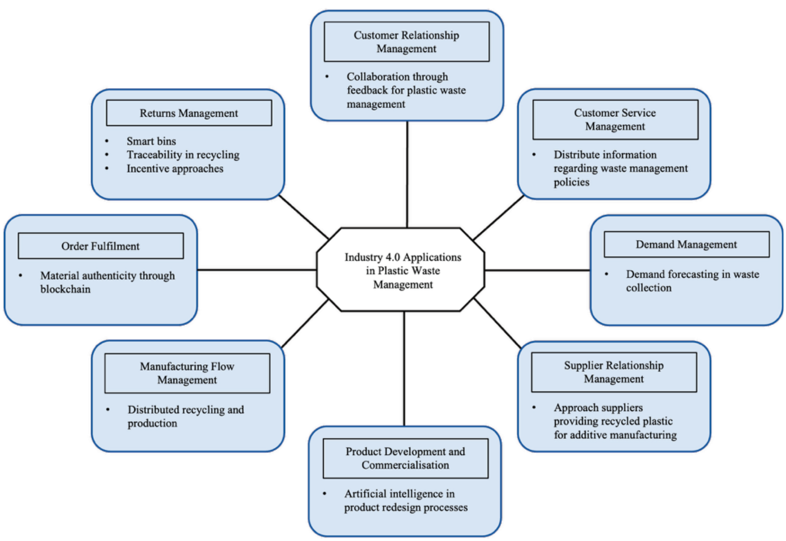

Figure 1: Examples of Industry 4.0 applications from the SLR according to each process in the GSCF model

IoT applications, for instance, can provide opportunities for governments to develop and distribute policies for waste management [39]. Residents can view the regulations and provide feedback for recycling improvement. Activities in returns management for CE involve collaboration and visibility enhancement throughout the SC [30]. Customer service management provides product information to the customers; relationship management needs to focus on customer involvement for CE transition [29], [30], [40]. Therefore, SC processes may consider IoT applications for these processes.

Lei et al. [23] identified essential technologies, such as IoT, artificial intelligence, big data and additive manufacturing for CE motivation. These technologies, as well as blockchain, have been analysed to promote plastic circularity [16], [17], [32]. While Lei et al. [23] appear to consider only one study, that of Nara et al. [25], regarding Industry 4.0 for sustainability with plastics, this research focuses on all five of these technologies for circular plastic flows.

2.2 Research methodology

This research follows the Double Diamond methodology of the Design Council [41], [42] to perform an SLR and design the conceptual framework. Clune and Lockrey [43] used the Double Diamond to identify sustainable strategies in the aged care sector. These authors considered divergent and convergent thinking to investigate the problem, promote collaboration, and to determine solutions for effective environmental performance in sustainability. The research adopts this framework to apply these thinking approaches during the SLR and conceptual framework construction phases.

The SLR was performed in the first two stages of the first diamond: "Discover" and "Define", to interpret literature regarding Industry 4.0 for PWM. The PESTLE analysis and waste hierarchy were used to assess the applications for adoption factors and waste management strategies. The SLR steps from Pollock and Berge [44] were conducted for the procedure, including the Critical Appraisal Skills Programme (CASP) checklist [45] as a quality assessment. Guidelines from Snyder [46] were used to address the required SLR elements.

The second diamond was then conducted for the conceptual framework design in the “Develop” stage. “Deliver” is the final stage where the solution is evaluated and implemented [42]. The framework is described and illustrated using the GSCF model for interpretation. Implementation is beyond the scope of this research.

3 SYSTEMATIC LITERATURE REVIEW

The first diamond involves two stages: “Discover” and “Define”, to interpret the problem comprehensively and determine areas for solution development [41], [42]. The SLR procedure began with the research objective and a search of articles to identify terms and databases for the “Define” stage [44].

3.1 Discover

Emerald, ScienceDirect and ProQuest were selected to search for resources. Table 1 displays search terms according to the research question and various sources to expand the search field, such as “circular plastic economy” and “digitalisation” [16], [47], [48]. The advanced search was included for the topic in plastics and waste management to focus on abstracts with these terms. The other topics did not have any specific requirements for the search string. Filters were used in ProQuest to list peer-reviewed studies in English. Filters were not applied in the other databases.

Table 1: Search terms for the SLR

Topics	Search Terms
Technologies	“industry 4.0”, “fourth industrial revolution”, “digitalisation”, “additive manufactur*”, digitalization”, “3D print*”, “digital*”, “knowledge-based system*”, “manufactur*”, “technolog*”, “smart”, “IoT”, “internet of things”, “industrial internet of things”, “industrial IoT”, “blockchain”, “machine learning”, “artificial intelligen*”, “AI”, “big data”
Plastics and Waste Management	“polymer*”, “plastic*”, “circular*”, “circular plastic economy”, “manag*”, “waste”, “municipal waste”
SCs	“supply chain*”
Organisations	“industr*”, “organisation*”, “compan*”, “organization*”

Figure 2 gives an overview of the criteria for article selection in each SLR phase. The screening phase, for instance, removed non-peer-reviewed resources and excluded inaccessible studies, except for three textbook chapters [49], [50], [51]. The eligibility phase included articles with any of the five Industry 4.0 technologies of interest [52], [53], [54]. Paras et al. [55] considered genetic algorithms for clothing. Textiles, trays consisting of polymer components, such as the inlay or coatings, as well as medical and packaging products, include plastics [2], [10], [52], [56]. The SLR process was documented in each phase with respective reasons for selection or exclusion on Microsoft Excel [47], [57], [58].

Sensitivity and specificity were applied in the screening and eligibility phases [47]. For example, abstracts were assessed in the screening process based on sensitivity to include potential studies applicable for the review after evaluation in the eligibility phase [47], [59]. The articles were analysed in the eligibility phase for relevance confirmation if the abstracts did not mention Industry 4.0 or PWM. Articles were added to the databases over time, meaning new articles were included until the end of the screening processes for each database. The new articles added after these dates were excluded.

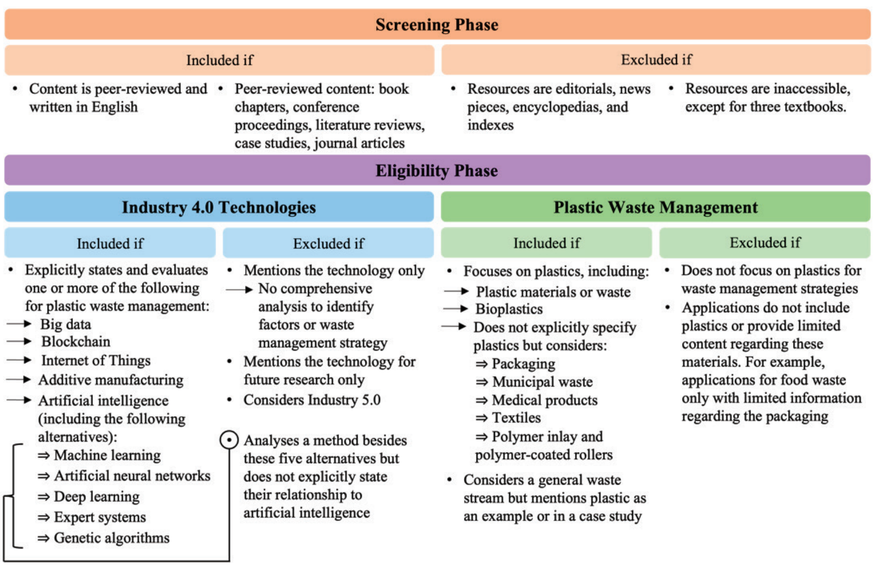

Figure 2: The screening phase and refined criteria for the eligibility phase

Figure 3 illustrates an adapted version of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart of the SLR [60].

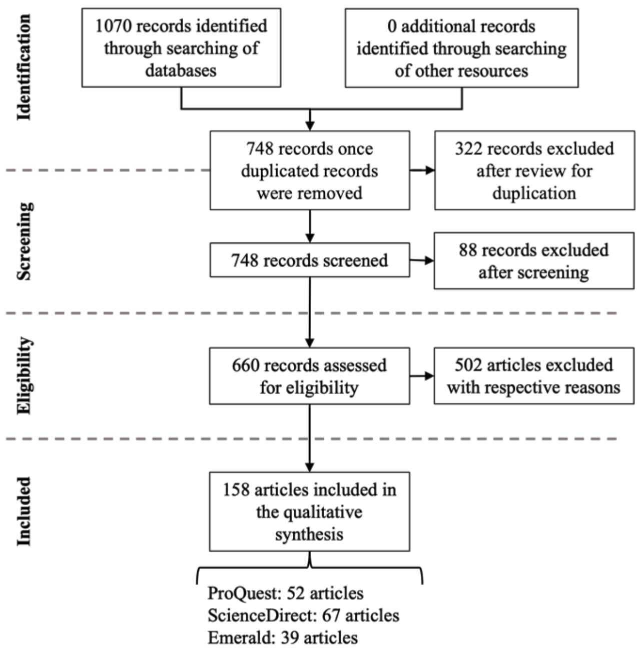

Figure 3: An adapted version of the PRISMA flowchart for the SLR [60]

Table 2 displays the timeframe for each database when the SLR was performed. Data collection and quality assessments were the next SLR steps performed in the "Define" stage of the Double Diamond [41], [42], [44].

Table 2: The SLR timeline from identification to eligibility

Database	Identification	Screening	Eligibility
ProQuest	13 July 2024	13-16 July 2024	23 September - 7 October 2024
ScienceDirect	17 July 2024	17-22 July 2024	17-22 October 2024
Emerald	2 September 2024	2-6 September 2024	7-17 October 2024

3.2 Define

The CASP checklist was used to interpret the selected articles' quality since research has referred to CASP for the quality assessment [45], [61]. The included articles were assessed to determine whether the research objective was clear, as well as to acknowledge the content and result interpretation. For instance, Gonçalves et al. [62] satisfied the criteria in Figure 2 since the study discussed Industry 4.0 applications and focused on plastic sectors for a roadmap towards sustainability. However, the study provided limited information regarding result precision or quality assessments of the respective resources. The authors indicated the study is in the initial stages and requires further analysis for the roadmap. Therefore, this research includes the study due to the eligibility criteria while identifying the potential limitations according to the checklist for the SLR. Beall's list of predatory publications was used to identify potential predatory journals [63]. These resources were removed but not recorded in the SLR since these publications are flagged as potential predatory journals. PESTLE and the waste hierarchy were then applied to gather data from the selected articles for analysis.

3.3 Waste hierarchy for Industry 4.0 classification

Table 3 summarises examples of Industry 4.0 applications based on recycling, waste prevention and reuse. A record indicating which strategy may be common [20], was not included since certain studies consider more than one strategy for reuse and recycling [55].

Table 3: Examples of Industry 4.0 applications in the SLR, from waste prevention to recycling

Waste Management Strategy	Technology Applications to Manage Plastics
Waste Prevention	Additive manufacturing utilising bioplastics or addressing material savings [64], [65] Blockchain or IoT for maintenance strategies [52], [66] Ul Haq and Franceschini [67] evaluated literature regarding distributed manufacturing with big data analytics, additive manufacturing, IoT and artificial intelligence.
Reuse	Artificial intelligence in processes to redesign products for reuse [55]
Recycling	Additive manufacturing in distributed recycling scenarios [68], [69], [70] Blockchain for incentive initiatives and tracking applications [71], [72] IoT and artificial intelligence in waste management applications [39], [73]

Waste prevention can imply the use of different materials or waste reduction through life cycle extensions [19], [20]. IoT and additive manufacturing for waste reduction may relate to maintenance and material utilisation enhancement [52], [64]. The use of materials can improve the associated expenses through the printers [64]. Maintenance could assist with value creation opportunities through preservation [8], [9], [11].

Reuse relates to product designs with durable characteristics, as well as activities in repair or re-assembly [19], [20]. Artificial intelligence could be approached in redesign operations to enhance reusability of clothing components [55]. Recycling can transform the waste into resources and additive manufacturing has been evaluated for distributed recycling operations [19], [68]-[70].

Big data analytics may provide potential opportunities to optimise the value chain for CE transition in terms of digitalisation and traceability. For instance, Ul Haq and Franceschini [67], citing Zaki et al. [74], state that digitalisation includes big data analytics technologies and that advancements are promoting distributed manufacturing. Recycling companies refer to big data to understand the plastic flow according to the product's barcode [75]. Digitalisation is also evaluated in the plastic packaging sector for CE [76]. However, regulations are needed to enhance traceability and these legal aspects are considered as factors influencing Industry 4.0 adoption for PWM, which is discussed in the following section [75], [77].

3.4 PESTLE analysis

Factors for technology adoption are arranged according to each perspective in the PESTLE analysis. The purpose of the PESTLE analysis was to determine key adoption factors for an organisation in any sector aiming to utilise the technology for PWM and CE transition. The Sankey diagram in Figure 4 displays examples of factors from 134 studies for Industry 4.0, along with a count of the factors identified in literature. This count includes the articles that may be from potential predatory resources [63]. However, the following sections refer to studies that did not relate to these potential predatory resources. Classification considers factors such as energy consumption for environmental concerns [28], [78]. However, this research interpreted the factors at a high level since the factors can relate to an organisation's location and sector of interest [22]. Therefore, the research considered key words, such as "energy consumption", for further evaluation, and included additional aspects, such as quality concerns, for additive manufacturing [53], [64].

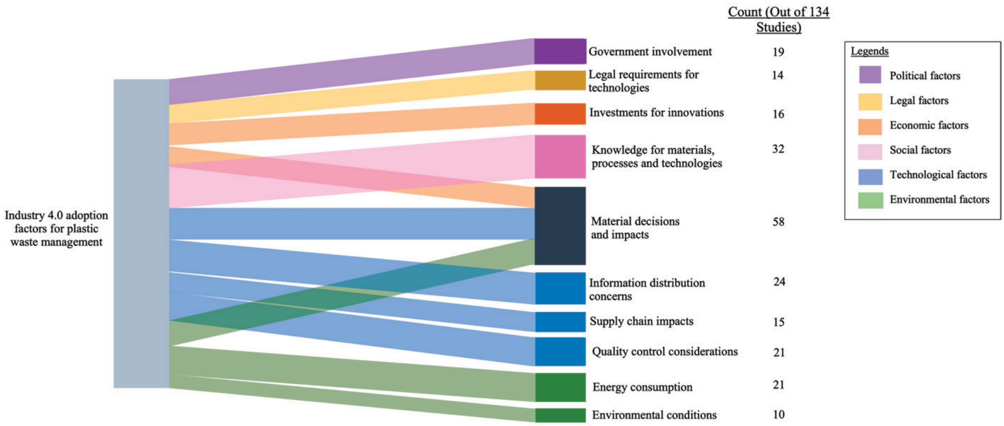

Figure 4: A Sankey diagram of possible factors for Industry 4.0 in PWM

The factors given in Figure 4 may imply challenges, requirements or impacts, depending on the study for PWM. For instance, additive manufacturing can affect SC flexibility performance and involve challenges related to the printed product's quality [64]. Tani et al. [53] and Chaudhuri et al. [79] suggest alternative approaches to address quality, such as competency or production enhancement. Biomedical sectors may also need to acknowledge legal aspects for utility due to health regulation concerns [53]. Nevertheless, this research has arranged the information according to each aspect in PESTLE to identify essential themes for adoption for any sector.

Factors in the Sankey diagram are discussed in the following sections. Dynamic aspects will refer to each factor category to illustrate how all these factors would need to be considered for the systematic perception and solution development.

3.4.1 Legal and political aspects

Companies may need to acknowledge potential legal concerns, such as regulatory restrictions for waste management, innovation, or health aspects [53], [54], [77]. Regulations in waste management may prevent a company's opportunity to conduct solutions for CE [77]. Biomedical sectors require certification to use the printers for valve production [53].

Intellectual property (IP) and standardisation may also require evaluation for the applications and PWM [53], [75], [80].

Organisations need to engage with stakeholders and enhance information exchange yet IP could imply collaboration challenges for CE transition [40], [75]. A potential approach to promote information exchange is the use of patents for value designs [53]. Policies could also be developed for information distribution concerns but these policies must also balance with opportunities for innovation [54], [75].

Standardisation is required for certain sectors, such as biomedical industries, since additive manufacturing implies different printers and associated performance for production [53]. The product design and quality would also need to acknowledge health regulations while using the printers for development. An example of potential standardisation is a combination of the printers with conventional manufacturing for product development [64], [79]. An interviewee in [53] explained that injection moulding is preferable for manufacturing products and reducing variation. Benthos Buttons used additive manufacturing to develop buttons from recycled plastic but the products' details required solutions [79]. This company then combined additive manufacturing with injection moulding where the printers create moulds and injection moulding manufactures the buttons from these moulds to control the variations.

Standardisation is also essential for recycling improvement [75]. The SLR identified existing standards related to additive manufacturing or waste management [39], [75], [79], [81]. Nevertheless, standardisation may require improvement to enhance plastic circularity and increase opportunities for utility in certain sectors [53], [75]. Furthermore, standards, as well as frameworks regarding legal aspects, are necessary for validating additive manufacturing in distributed recycling [68]. Therefore, government involvement is essential to develop policies for PWM improvement and Industry 4.0 adoption, as well as to assist in financial requirements for implementation [39], [54].

3.4.2 Economic aspects

Industry 4.0 applications may imply different economic performances, depending on the application and study. For instance, additive manufacturing in isolated locations could address logistics and manufacturing expenses [65]. Research has also analysed open-source approaches for economic considerations and distributed recycling [65], [68], [69]. IoT for maintenance strategies can reduce repair costs but decisions for IoT in waste monitoring may require evaluation to acknowledge expenses for implementation [52], [82]. Algorithm complexity can also impact the economic performance of blockchain applications [72].

Research would discuss investments for the applications, such as the use of the current hardware or open-source methodologies to address expenses [52], [65], [69]. However, financial requirements may imply challenges for certain sectors or companies aiming to implement innovative strategies for plastic circularity [54]. Governments may be required to assist organisations with this aspect.

Decisions regarding materials would incur expenses since costs between primary or secondary plastic may differ depending on oil prices and recycling operations [10], [34]. Material decisions can be considered for additive manufacturing in distributed recycling scenarios as the prices of these materials can be compared to determine the economic performance [69]. Market aspects may also need to be considered for recycled plastics and bioplastics, such as polylactic acid [34], [83]. These economic aspects, as well as environmental concerns regarding material decisions are illustrated in Figure 4. The market for recycled plastics and additive manufacturing may improve if distributed recycling development is concentrated [69]. Nevertheless, an organisation must learn how the secondary plastics should be utilised for additive manufacturing [79].

3.4.3 Social aspects

Knowledge of the materials, Industry 4.0 technologies and processes have been emphasised for the applications and plastic circularity [55], [75], [79]. For example, knowledge regarding recycled plastics could be essential in additive manufacturing applications for CE transition [79]. Training is necessary to implement the technologies [84]. Cultural aspects, such as lifestyles or behaviour, may also need to be considered for Industry 4.0 in PWM [54], [65].

Additive manufacturing applications must acknowledge values in cultural perceptions for utility in certain industries, such as reindeer husbandry sectors [65]. Behaviour regarding plastic waste may imply challenges for improving waste management [54], [85]. Waste management practices require customer participation to distribute the waste to collection centres for recovery, meaning behaviours may need to be considered for these practices [20]. Education and data aspects are also obstacles in Africa since stakeholders must understand the context of plastic waste for CE practices [54], [75]. Blockchain and IoT could be approached to encourage participation and collaboration through incentive initiatives and information exchange regarding waste management practices, respectively [39], [71], [72]. Blockchain could also assist with these obstacles through traceability to acknowledge and manage the product life cycle [54]. Therefore, stakeholder collaboration is a critical factor to be addressed for effective transition and digital applications could be approached for this requirement in terms of networks [86].

The informal sectors play essential roles in Africa for waste management and engagement with these stakeholders through the technologies could promote job creation opportunities [86]. However, companies may need to encourage stakeholders to adopt the Industry 4.0 technologies for their operations [79]. Tseng et al. [87], citing Kumar et al. [84], argue that employment concerns can imply hesitation in Industry 4.0 adoption. This concern for Industry 4.0 adoption is also considered in Africa and Korea [24], [37]. Organisations may need to determine strategies for encouragement, as well as to concentrate on training and improving awareness [84], [87]. Waste2Wear suggests adaptive approaches to address these concerns and implements education initiatives for blockchain in plastic recycling transparency [79]. Therefore, stakeholder collaboration, as well as training, is essential to ensure CE transition and utilise the technologies effectively for CE practices.

Health concerns were mentioned where emissions are released during production operations with additive manufacturing, meaning ventilation may be necessary while using the printers for product development [80], [88], [89]. In this regard, Kumar et al. [90] has constructed a framework for blockchain technologies to monitor the performance in additive manufacturing. This study provided limited information regarding the framework monitoring emissions impacting health, even though the performance considered age of employees and carbon emissions. Product designs may need to acknowledge safety and health aspects for waste monitoring [82]. Recycled plastics would also require sufficient quality for use in additive manufacturing markets [79].

3.4.4 Technological aspects

Technology performance for additive manufacturing can relate to the printer type and printing parameters [53], [81]. For instance, three different printers were analysed in the biomedical sector to compare the variations in the product's features [53]. Additive manufacturing should also be evaluated to acknowledge its impact on SC performance [64]. For example, Chiu and Lin [64] analysed additive manufacturing in a lamp production sector to determine its impact on SC flexibility. The study performed simulations to interpret scenarios with standard machines and additive manufacturing for product development and capacity was indicated as an essential aspect to balance the SC performance [64]. Benthos Buttons experienced quality variations and altered the production processes so that the printer develops product moulds, and injection moulding is used for manufacturing [79]. These aspects indicate that one may determine the required flexibility to utilise additive manufacturing for PWM and manufacturing. The level of flexibility is mentioned in one of the GSCF model's core processes for manufacturing [29]. SC designs could also relate to centralised or decentralised scenarios [53], [67], [69], [80]. For instance, the latter scenario implies that recycling facilities are nearer to waste sources than the former recycling scenario, meaning that the latter scenario can reduce energy requirements and emissions [91].

Open-source methodologies may assist in exchanging product designs yet companies must acknowledge IP, as well as privacy [39], [53], [71], [82]. IoT and blockchain applications may refer to these aspects for waste monitoring or participation in recycling [71], [82]. Information distribution concerns are categorised as a technological factor in this research due to the use of technologies and devices for information exchange [92]. Quality control is also included as a technological factor since this aspect relates to inspections, as well as to monitoring [80]. Quality assessments were analysed for distributed recycling but indicators may be needed to evaluate the waste for the operations from recycling to product development [68].

Organisations may also need to evaluate infrastructure and networks for applications [54], [82], [88]. Infrastructural aspects can imply recycling facilities to process materials for additive manufacturing [69], [79]. Koenig et al. [52] utilised the current hardware for IoT applications to evaluate tray conditions at airports. Energy may be needed for infrastructural requirements where organisations may consider alternative sources, such as solar, for additive manufacturing in PWM [88].

3.4.5 Environmental aspects

Environmental benefits of the applications include emissions in waste management, product life cycle extensions and waste reduction [54], [55], [73]. Energy has been evaluated in distributed recycling, as well as for additive manufacturing, blockchain and IoT [70], [72], [80], [82]. Malik et al. [80] mention that future research is needed regarding energy impacts for different materials in additive manufacturing. Environmental conditions must also be evaluated for these printers and plastic products [93].

Temperature is one of the environmental aspects impacting printing performance and plastic products' life cycle [88], [93]. Ultraviolet rays can also lead to degradation. These aspects may be essential to enhance recycling opportunities. Obydenkova et al. [65] suggest solar radiation as a possible environmental condition for further evaluation. Controlled environments may provide opportunities to control temperature differences during printing [88].

Bioplastics are used for distributed recycling and additive manufacturing in isolated areas [65], [68], [69]. These materials can assist in addressing the environmental impacts of conventional plastic during production operations [34]. However, bioplastics can also imply complications for waste sorting due to contamination in the waste flows, as well as new SCs to receive these materials for production [20], [34].

Factors are moreover susceptible to change over time [22]. A possible example identified in the SLR may relate to policies addressing information exchange and opportunities for innovation [54], [75].

3.4.6 Dynamic aspects

This research considers potential dynamic factors and impacts according to PESTLE. Distributed recycling and production, for instance, may assist in reducing environmental concerns compared to centralised recycling [91]. Open-source methodologies were evaluated for additive manufacturing and distributed recycling, and patents could be considered for the designs and information distribution [53], [69]. However, IP aspects may influence collaboration and information distribution for CE [75]. Governments could develop policies to address these concerns but the policies should also provide organisations with opportunities to implement the solutions [54], [75]. Furthermore, one must acknowledge environmental conditions, such as temperature differences, and emissions impacting health while using additive manufacturing for production [80], [88], [89], [93].

The research indicates Industry 4.0 impacts yet these studies focus on a particular technology, sector or country, providing limited information to generalise the factors for all applications and scenarios [55], [65], [67], [71], [90]. Koenig et al. [52] argue that IoT applications for maintenance could be approached in any industry. Nevertheless, this research encourages further analysis to ensure the factors can be generalised across different sectors.

Studies in the SLR consider different purposes for the applications, such as maintenance, product authenticity, and recycling improvement, as well as respective approaches for evaluation [39], [52], [79]. These applications then indicate the respective factors regarding implementation and potential improvements to address limitations. For instance, blockchain applications for tokenisation require further evaluation in other locations to confirm their effectiveness in recycling [71]. Chiu and Lin [64] performed simulations to determine the capacity for additive manufacturing in the lamp production sector. Paras et al. [55] evaluated case studies to acknowledge the processes and develop the model for clothing redesigning. Therefore, organisations are encouraged to evaluate their operations in terms of these factors and strategise accordingly for effective implementation. This aspect is also considered regarding the availability and applicability of Industry 4.0 applications.

3.5 Technology availability and applicability

Dijkstra et al. [20] state that the studies indicating the respective business models use various methodologies to address research questions. This research identified a similar aspect as the studies in the SLR consider different methodologies for the technology applications in PWM. Organisations may need to determine whether the technologies are relevant or available for adoption in terms of their respective operations and environment. Biomedical and reindeer husbandry industries, for instance, would need to acknowledge health and cultural aspects regarding additive manufacturing [53], [65].

Bioplastics may be adopted to address regulations, demand for sustainable products or littering considerations [20], [34]. Chemical recycling can assist in managing contaminated plastics; organisational culture is a possible consideration that may be needed to motivate change for technology adoption or integrate with stakeholders for sustainability [35], [36], [94].

The SLR has identified research including Industry 4.0 and one of the alternative solutions, such as bioplastics [65], [95]. Cruz Sanchez et al. [68] analysed literature on distributed recycling and acknowledged [96] to explain that chemical recycling could assist with contaminated plastics. Organisations may need to acknowledge essential considerations related to culture and change management for encouraging Industry 4.0 adoption in manufacturing to achieve sustainability [36]. Furthermore, training is required to motivate involvement and ensure the technologies can be utilised effectively [79], [84].

Table 4 provides an overview of the articles analysing Industry 4.0 technologies with respect to each factor as an extension of the Sankey diagram in Figure 4, as well as illustrating potential opportunities for the applications with respect to each factor. For example, potential opportunities for government involvement could imply monitoring the recycling operations for policy development [39]. These examples, however, do not reflect the count in the Sankey diagram as certain factors and opportunities are only identified after the themes have been finalised for the conceptual framework. The opportunity to use solar energy for additive manufacturing, for example, was not included in the count as this factor was identified after the themes have been finalised for framework development [88].

Table 4: An overview of factors with respective technology applications and opportunities

Factor	Industry 4.0 Technology	Potential Opportunities
Government involvement	Blockchain, IoT, additive manufacturing [39], [54], [72], [90]	Governments can use the technologies to monitor recycling performance and register stakeholders [39], [72].
Policies, regulations and standards	Additive manufacturing, IoT, blockchain and big data [39], [54], [68], [75], [77]	Regulations could assist in enhancing traceability and standards for quality evaluation in distributed recycling [68], [75].
Investments	Additive manufacturing, artificial intelligence, IoT and blockchain [52], [54], [65], [69], [73], [77]	Organisations may have challenges regarding investments for the solutions [54]. However, an opportunity could relate to the use of open-sourcing or current hardware to address expenses [52], [69]. This aspect requires further evaluation for confirmation.
Market aspects	Blockchain and additive manufacturing [68], [69], [71], [79], [83]	Distributing manufacturing could promote market growth for additive manufacturing and secondary plastics [69]. Marketing may also imply potential adoption diffusion for blockchain technologies [71].

Factor	Industry 4.0 Technology	Potential Opportunities
Stakeholder collaboration	Additive manufacturing, blockchain and IoT [39], [54], [86]	The technologies could assist in promoting collaboration for waste management improvement [39], [54].
Cultural and social values	Additive manufacturing, blockchain and IoT [39], [54], [65], [71]	Blockchain could provide tokens for participation in waste management and enhance recycling [71]. Organisational culture may also be a potential topic for Industry 4.0 adoption in PWM [36].
Safety and health	Additive manufacturing and IoT [80], [82], [88]	Ventilation may need to be evaluated for potential use in additive manufacturing [89].
Knowledge of technology, processes and materials	Additive manufacturing, blockchain, big data, IoT and artificial intelligence [39], [54], [55], [75], [79], [87]	Blockchain could assist in monitoring plastics and address obstacles regarding education and the lack of data for CE [54].
Technology design	Artificial intelligence, big data, IoT, blockchain and additive manufacturing [39], [53], [55], [71], [72], [75], [76], [80], [82]	Technology development can enhance monitoring capabilities [75]. Algorithms could be addressed to improve the blockchain's performance in recycling systems [72].
SC design	Additive manufacturing, artificial intelligence, IoT, blockchain and big data [64], [67], [69], [71], [80]	Centralised and decentralised scenarios, such as distributed recycling and manufacturing, as well as balancing the SC performance [64], [67], [91]
Information distribution	Additive manufacturing, blockchain, IoT and big data [71], [75], [80], [82]	Blockchain applications could assist in monitoring the plastic life cycle and exchange information for CE [54].
Infrastructure	Additive manufacturing, blockchain, IoT and big data [52], [54], [67], [82], [88]	Blockchain could monitor the plastic life cycle while considering waste management infrastructural challenges [54].

Factor	Industry 4.0 Technology	Potential Opportunities
Quality control	Additive manufacturing [53], [64], [68], [79], [80]	A combination of additive manufacturing with injection moulding could assist with quality control of the final product [79].
Decisions for materials and product design	Artificial intelligence, IoT, blockchain, additive manufacturing [53], [55], [71], [76], [82]	Product designs could be evaluated to include features for waste monitoring [71], [72], [82].
Energy usage	Additive manufacturing, blockchain and IoT [80], [82], [88], [90]	Solar energy can be considered as energy sources for additive manufacturing and distributed recycling [70], [88].
Environmental conditions	Additive manufacturing and IoT [65], [82], [93]	Acknowledgement of the environmental conditions on the plastic life cycle could assist to improve recycling [93].

The conceptual framework considers the identified factors as themes, as well as the plastic value chain and CE strategies for solution development [13], [76].

4 CONCEPTUAL FRAMEWORK

Figure 5 represents an overview of the conceptual framework for Industry 4.0 to enhance PWM and promote CE. The components include the themes discussed above, as well as solution upscaling, the holistic perception and CE objectives [11], [18], [76]. The GSCF model is acknowledged to discuss the conceptual framework and its components for Industry 4.0 applications in PWM improvement [29].

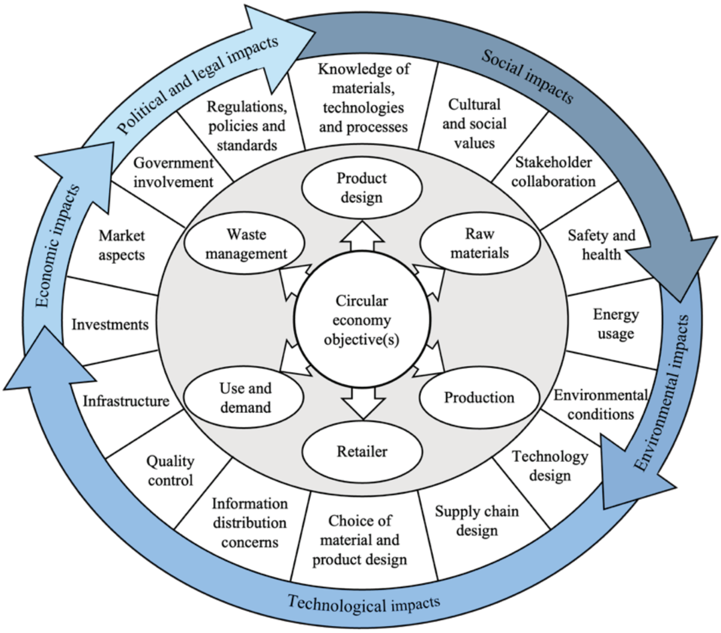

Figure 5: An overview of the conceptual framework for Industry 4.0 in PWM

4.1 Circular economy objectives and systematic perception

Levels in the GSCF model are identified as strategic, as well as operational considerations, for SC processes [29]. The former level plans each SC process while the latter level considers activities, such as determining metrics for performance evaluation. The conceptual framework addresses a similar aspect requiring organisations to find strategic solutions, using Industry 4.0 according to the CE objectives and respective adoption factors. Solutions are then analysed at the operational level for improvements and implementation. CE objectives are positioned in the center since clarity promotes alignment and individuals to be effective in decision-making, ensuring product delivery [97].

Organisations may begin the planning stage of the Industry 4.0 application by evaluating and selecting CE objectives throughout the plastic value chain for CE transition. The value chain in Figure 5 is an adapted version from Johansen et al. [13] and the objectives with arrows pointing at each phase indicating the systematic process, as well as the essence of waste hierarchies from Kirchherr et al. [18]. Organisations may plan for recycling, for instance, but the solutions must consider the overall objective to reduce waste and ensure a systematic approach for effective transition. Therefore, organisations can begin with recycling and take incremental steps to improve and upscale the solution for optimal sustainable performance and waste reduction [11], [31]. Organisations can also combine waste management strategies, such as recycling and reuse, to extend the product's life cycle [55].

Organisations can select any Industry 4.0 technology for the CE objective, such as IoT in maintenance strategies for waste reduction or additive manufacturing in a distributed recycling system [52], [68]. Companies can also select any position in the value chain or across the overall network for the technology application. For example, additive manufacturing can develop the products in the production phase using recycled plastics, whereas digitalisation and traceability may provide potential opportunities to enhance circular flows throughout the SC [75], [76], [79]. However, companies must understand the factors influencing technology adoption with respect to the selected CE objectives since SC designs rely on the chosen CE strategies [76]. This aspect is essential since the solution approach may indicate different concerns for the applications, such as material selection for additive manufacturing.

Decisions between bioplastics or recycled plastics may lead to different implications for recycling, such as infrastructural requirements to process recycled plastics and degrade bioplastics, as well as concerns for recycling performance since bioplastics can contaminate waste flows [26], [34]. Material decisions and product designs are included as technological aspects due to design attributes impacting recyclability and changes in production to use recycled plastics for product development [15], [34]. The themes in Figure 5 must be evaluated for the technology applications with respect to the overall value chain to ensure these solutions are effective for CE transition.

4.2 Factors and dynamic aspects

The GSCF model includes activities to plan the infrastructure, logistics and constraints for the flow management process in manufacturing [29]. These activities determine the manufacturing layout and operations with respect to the information from the other processes, such as product designs from product development, as well as possible metrics for measurement. The conceptual framework displays the themes for evaluation in each value chain phase to determine how the selected application could be implemented, as well as to enhance the systematic perception for potential requirements and impacts. For instance, additive manufacturing for production applications may need to consider environmental conditions impacting cooling rates and product degradation [88], [93]; legal requirements may involve certification; and technological aspects may furthermore relate to the product's quality due to the printing parameters [53], [81]. However, this framework is not strict in terms of factor classification and does not guarantee relationships between factors, aligning with research analysing factor interrelationships for Industry 4.0 adoption [33], [98].

Technological factors include material decisions yet this theme can also imply economic and environmental aspects, such as markets and environmental conditions, as indicated in the Sankey diagram in Figure 4 [69], [93]. The framework may indicate relationships between themes but cannot guarantee these relationships since factors depend on the location and sector [22]. The technology applications for PWM also imply different concerns, such as privacy for waste monitoring and recycling participation [71], [82]. Therefore, the framework cannot ensure how the themes would relate to each other for every application and industry sector due to the various considerations for solution development, as well as the need for further research on the applications and factors for all sectors.

Quality control is evaluated to understand why these themes must be interpreted throughout the value chain for the technology application. Distributed recycling, for example, requires measurements to determine the quality of the plastic during recycling and printing operations, which may refer to the melt flow index or investigations in the product's mechanical characteristics [68]. Quality is essential to ensure the plastics are sufficient for the printer market and that quality variations may need to be managed depending on the regulations for certain sectors [53], [79]. Companies may also need to determine how quality challenges could be addressed, such as combining the printers with injection moulding to standardise production. Therefore, the subcomponents for quality control relate to standards and inspections for organisations to perform their respective evaluations and determine applicable methodologies, potential solution adaptations and measurements for performance [53], [68], [80].

Organisations develop the solutions based on the evaluated themes and interpret the results for improvements. Arrows circulating the themes in Figure 5 indicate that these themes can also indicate potential dynamic aspects and impacts of the solution approach. For example, ventilation may be approached to address health concerns while using additive manufacturing during production [89]. Organisations are encouraged to assess the technology application's impacts according to each aspect, from economic to legal perceptions, to ensure the solution is effective and promotes scalability [32].

4.3 Upscaling

Upscaling is an enabler for CE transition [11]. The SLR has identified research performing simulations or pilot tests to assess the solution's performance [64], [71], [82]. For example, Chiu and Lin [64] conducted simulations to assess additive manufacturing impacts on the SC performance, acknowledging how capacity can affect SC flexibility.

One should note that if the organisation is planning to implement a solution on a small scale and then approach upscaling, the organisation must consider factors that could hinder upscaling, as mentioned in [32]. This aspect is considered since research is limited in its ability to generalise all the factors for the technology applications, meaning the themes require further investigation to ensure applicability for specific industries, as well as to identify potentially unidentified themes for evaluation. Nevertheless, organisations are encouraged to assess the themes in Figure 5 as a starting point for solution development and then assess the impacts to address limitations and promote scalability.

5 CONCLUSION

Plastics are identified in various products but a systematic perception of the overall value chain is essential for CE transition. Industry 4.0 technologies may be enablers for CE but factors for adoption vary between countries and industries. This research evaluated these technologies for PWM in SCs to construct a conceptual framework for solution development.

The framework acknowledges the CE objectives, plastic value chain and adoption factors to enhance the holistic perception for Industry 4.0 applications. Companies need to evaluate their operations to determine CE objectives, technology applications and associated factors for solution development. The solutions should then be assessed to acknowledge the impacts and opportunities for improvement, as well as to promote scalability. A case study will be performed in future research to refine the framework and determine which factors should be prioritised for solution development and evaluation.

Industry 4.0 technologies offer various opportunities to enhance plastic waste circulation for CE. Applications identified in the SLR are diverse but future research must ensure that the applications and respective factors can be generalised for each sector. Waste reduction and reuse should consider maintenance strategies and processes for product designs. Examples of these applications are also displayed according to the core processes in the GSCF model, indicating potential utility throughout the SC for PWM.

Solution alternatives that relate to bioplastics, organisational culture and chemical recycling may be used to address challenges such as littering, waste contamination and to motivate change. Nevertheless, these alternatives were not evaluated extensively compared to the technologies. Future research could investigate these alternatives for CE motivation.

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Development of a technical service work order system for a South African private hospital

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ABSTRACT

Private hospitals in South Africa's bilateral public/private healthcare system are known to provide clinical care on par with global standards. To maintain and improve this level of care, effective technical maintenance is required to manage risks and ensure patient safety. A large private hospital in South Africa consists of 16 operating theatres and 469 beds. The facility operates from several buildings of varying ages and interconnected levels. The technical team responsible for maintenance at this hospital faces challenges with unresolved work orders and labour utilisation. This research demonstrates how a work order system is developed to consolidate maintenance data and alert technicians to open work orders.

The requirements for the technical services work order system are derived from a thorough analysis of the shortcomings in the existing system, complemented by insights from industry best practices as identified in the literature. Statistical process control charts are used as a foundational mechanism for the decision support system architecture, resulting in efficient flagging mechanisms and reporting features that collectively promote timely work order closures and proactive maintenance practices. Qualitative results and scenario testing of the system confirm reduced maintenance requests backlog and enhanced operational efficiency.

Keywords: hospital maintenance, technical services, statistical process control, system architecture

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1 INTRODUCTION

The highest standard of healthcare in Africa is found in South Africa [1]. The healthcare system in South Africa is bilateral – it comprises a public and private sector. Approximately 20% of the country's population seeks private healthcare, which operates on a for-profit business model, whereas the other 80% of the population seeks public, government-funded healthcare [2]. Although the private healthcare sector in South Africa is much smaller than the public sector, it accounts for about half of the sector's expenditure [3].

One of the biggest private hospital facilities in South Africa is located in Berea, Durban. It is a 469-bedded hospital, consisting of 16 operating theatres and two cardiac catheterisation laboratories (cath labs). There are 140 highly skilled and experienced specialists practising at the facility. The buildings situated on the facility's premises range in age and level. Renovations are underway at the facility, including the upgrade of theatres to make them more modern and efficient. Maintenance management of this large hospital is consequently a considerable undertaking.

Additionally, maintenance management is closely linked to patient safety and forms an integral part of risk management. Since patient safety is also essential for the emotional well-being of nursing staff [4], the critical importance of effective maintenance management extends to stakeholders throughout the hospital. Attending to patient safety through effective risk management and a technical maintenance approach not only promotes greater resource efficiency and cost savings but also elevates patient satisfaction by ensuring the delivery of higher-quality and more reliable services [5].

The technical services department of this hospital is the custodian of all engineering-related activities at the facility. The disciplines covered by the technical team include electrical engineering, mechanical engineering, civil engineering, and clinical engineering.

The technical services department is responsible for ensuring the timely maintenance of all critical and non-critical equipment, encompassing preventative and reactive maintenance. This includes routine tasks as part of preventive maintenance and responding to equipment breakdowns through reactive maintenance. The technical team's primary objective is to identify and mitigate risks, ensuring a safe environment for patients, staff and visitors throughout the facility.

The technical team at this specific hospital faces challenges with unresolved work orders and fluctuating labour utilisation. Notably, these challenges pertain only to technical work orders, which include engineering-related maintenance tasks such as preventative and corrective activities. This does not include clinical or operating theatre equipment, nor outsourced work, thereby ensuring that the focus remains solely on the department's core technical operations.

Figure 1 provides a high-level overview of the existing work order process, illustrating how maintenance requests are received, assigned, executed, and recorded. The process flow highlights inefficiencies within the current system, including reliance on manual notifications, use of paper-based job cards, and delays in updating the records. Collectively, these factors contribute to prolonged turnaround times and unresolved work orders, emphasising areas where targeted interventions could enhance operational efficiency and reduce delays.

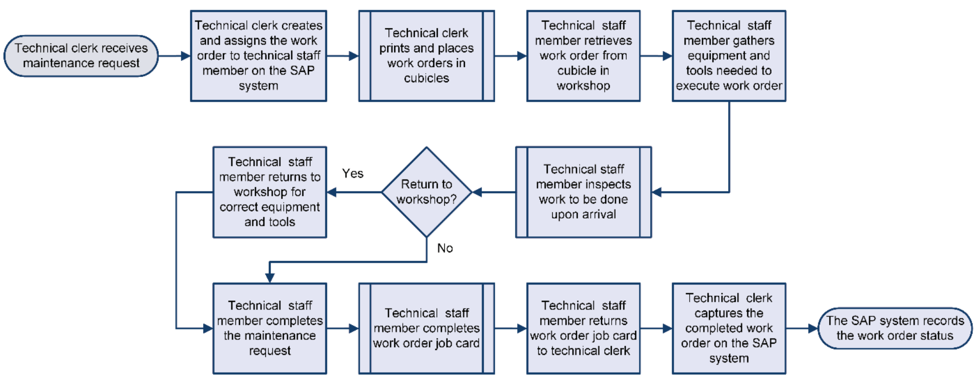

Figure 1: Work order process flow diagram

Compliance levels reveal a concerning trend of an exponential drop in closed work orders and a concurrent increase in both technically closed and open work orders, particularly in the final quarter of the year, with an average of 654 unresolved work orders per month, as shown in Figure 2.

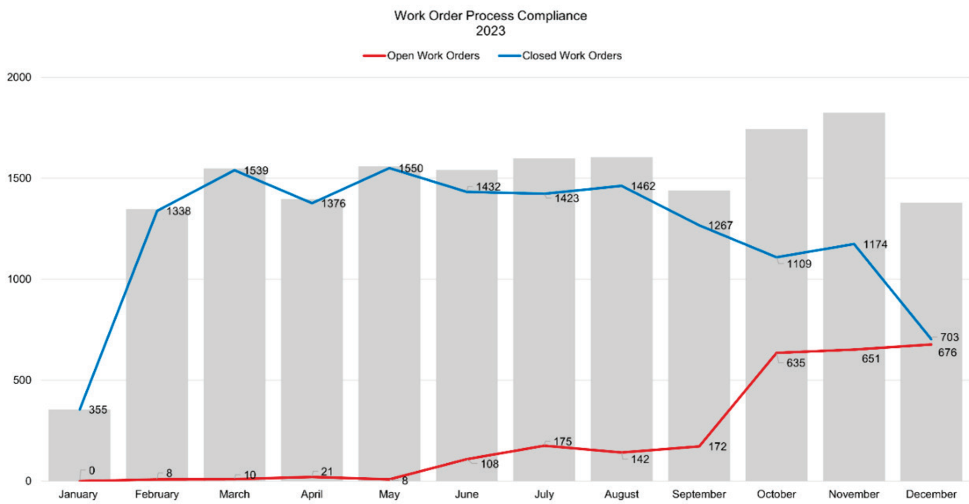

Figure 2: Work order process compliance for 2023

The objective of this research is to address this challenge by developing a system to allow the work orders in the technical services department to be closed sooner, ensuring that labour utilisation is more uniform. This study addresses a specific solution to the case study by applying established theoretical concepts to the maintenance management challenges faced by the technical services department of a private hospital. Our paper aims to explain the theory behind the solution for the specific case study and demonstrate the development of a practical solution. Section 2 of this paper provides an overview of the literature on developing a technical work order system. Section 3 expands on the methodology, architecture and design of the system. This paper concludes in Section 4, where the technical management work order system is demonstrated, and scenario testing results are discussed.

2 LITERATURE OVERVIEW

This literature review aims to provide a comprehensive understanding of maintenance management theories and practices within the context of a private hospital setting in South Africa, informing the design of our solution. The study explores the application of maintenance theories, such as asset management, to optimise the efficiency and effectiveness of maintenance operations, with a specific focus on work order management. It investigates potential strategies for improving work order generation, tracking, and analysis by examining the role of database design and the Internet of Things (IoT). Additionally, the study assesses the utility of Statistical Process Control (SPC) and advanced tools such as Computerised Maintenance Management Systems (CMMS), Power BI, and Microsoft Access in enhancing work order management processes. Through a thorough analysis of existing literature and relevant case studies, this review seeks to identify best practices and potential areas for improvement in work order management within the South African private hospital context.

2.1 Asset and Maintenance Management

Maintenance is the process of preserving equipment, facilities, and systems to ensure continuous and effective operations [6]. It also involves coordinating activities to ensure optimal asset performance and longevity [7].

Maintenance management is a critical function in various industries, ensuring that assets are adequately maintained to prevent unexpected breakdowns and to extend their operational lifespan. In the healthcare sector, efficient maintenance management is essential for ensuring everyone's safety when utilising the premises and the reliability of various types of equipment [8]. Delays in processing maintenance work orders can lead to equipment failures, which in turn impact the quality of the service provided.

Maintenance involves preserving equipment, systems, and facilities to ensure continuous and reliable operation. It includes preventative actions to avoid breakdowns, corrective actions to fix issues, and predictive actions to anticipate potential failures [9]. Asset management is a systematic approach to managing assets throughout their lifecycle, from acquisition to disposal, to maximise value, reliability, and cost-effectiveness [7].

Maintenance management coordinates these activities to optimise asset performance, extend operational life, and support patient safety [10]. It encompasses maintenance planning, scheduling, and performance evaluation, using key performance indicators such as uptime, mean time between failures (MTBF), and maintenance costs to ensure efficient and effective operations [11]. These concepts form the foundation for effective work order management in hospital maintenance systems.

2.2 Quality Management and Statistical Process Control

Quality management in maintenance ensures that activities meet predefined standards and support organisational goals and patient safety [12]. Tools such as Statistical Process Control (SPC), Shewart control charts, and Failure Mode and Effects Analysis (FMEA) are used to monitor processes, detect deviations, and identify areas for improvement [12], [13]. Although resource-intensive, these tools enable timely interventions and prevent equipment failures that could compromise patient care.

Quality improvement methodologies, including Six-Sigma and Lean, enhance efficiency by reducing defects and eliminating non-value-added activities, providing a structured approach for continuous improvement in hospital maintenance operations [12]. Applying quality management and SPC tools supports consistent maintenance standards and high-quality operational outcomes.

2.3 Data Analytics and Business Intelligence for Maintenance

Data analytics and business intelligence support the optimisation of maintenance activities and informed decision-making [10]. Predictive analytics utilises historical and real-time data to forecast equipment failures and schedule timely interventions, thereby reducing unplanned downtime and enhancing asset reliability [5]. Prescriptive analytics extends this by recommending specific actions to mitigate potential issues, enhancing asset performance and resource allocation [5].

Business intelligence tools, such as Power BI and Microsoft Access dashboards, transform raw data into actionable insights. These tools enable the monitoring of key performance indicators (KPIs), such as equipment uptime, mean time between failures (MTBF), and maintenance costs, helping to identify inefficiencies and support data-driven decisions.

Big data analytics further enhances maintenance management by processing large volumes of data from IoT sensors, maintenance logs, and operational systems [10]. This enables comprehensive asset performance analysis and facilitates a shift from reactive to proactive maintenance strategies, improving overall operational efficiency and decision-making.

2.4 Ergonomics

Ergonomics, the study of interactions between humans and other system elements, is critical in hospital maintenance management [14]. Applying ergonomic principles helps reduce physical strain, fatigue, and cognitive overload among maintenance personnel, enhancing efficiency, safety, and job satisfaction [15]. Properly designed tools, organised workspaces, and intuitive interfaces enable maintenance staff to perform tasks more effectively and respond rapidly to equipment needs [14]. Integrating ergonomics supports worker well-being and improves maintenance quality, reduces errors, and optimises operational performance, ultimately contributing to reliable healthcare service delivery. Literature positions ergonomics as a factor influencing the efficiency of work order processing. For instance, proper workstation design can minimise fatigue and improve the efficiency of maintenance staff, leading to better care for assets.

2.5 Database Design for Maintenance

Effective database design is essential for efficient maintenance management, enabling timely access to asset histories, work orders, maintenance schedules, and resource allocation [10], [16]. Basic database systems can handle transactional data, while relational databases and data warehouses, supporting comprehensive analysis, performance evaluation, and improved planning, are more suitable for hospitals. Advanced database structures facilitate the identification of maintenance patterns, optimise scheduling, and enhance resource allocation, thus ultimately contributing to operational efficiency and patient care.

3 METHODOLOGY

The project was executed in alignment with the V-Model methodology, a structured framework that integrates system development with corresponding verification and validation activities [17]. This approach allowed each system design phase – requirements gathering, system analysis, system architecture, model design, and final design – to be systematically tested through unit, integration, system, and acceptance evaluations. Applying the V-Model ensured that each phase was meticulously validated and verified, contributing to the successful development of the technical service work order system, which met stakeholder requirements, functioned correctly within the architecture, and supported efficient work order management.

3.1 Requirements gathering and system analysis

Requirements for the technical work order system were gathered from an analysis of the problems in the current system. The system analysis combined qualitative and quantitative methods, focusing on identifying the root causes contributing towards delayed maintenance work order processing in the private hospital of this case study.

An affinity diagram was used to visually organise and categorise related qualitative data, allowing patterns and relationships among contributing factors to emerge [18]. Analysis of the affinity diagram revealed several key factors contributing to delays in the work order process. Subsequent evaluation using the interrelationship diagram indicated that technical staff members, job cards, and technical clerks exhibited the highest levels of influence and dependency among the identified factors, highlighting them as the primary root causes within the system. These findings suggest that inefficiencies in work order management are primarily linked to the performance and interactions of these critical roles and processes, with delays arising from preparation, execution, or task handovers [19].

A Pareto chart was developed to analyse the frequency of different maintenance activities within the technical services department, following the 80/20 principle, which suggests that approximately 80% of effects stem from 20% of causes [20]. Work order data from October to December 2023 was examined to identify the most common maintenance activities, including repairs (REP), services (SER), inspections (INS), corrective work (CMO), replacements (RPL), and modifications (MOD). The chart allowed for prioritisation of the most significant activities, providing insight into critical areas requiring attention to improve efficiency and resource allocation within the department. Figure 3 illustrates that repair and service activities dominate the workload of the technical services department, accounting for approximately 77% of all maintenance tasks, with repairs contributing 54% and services 23%.

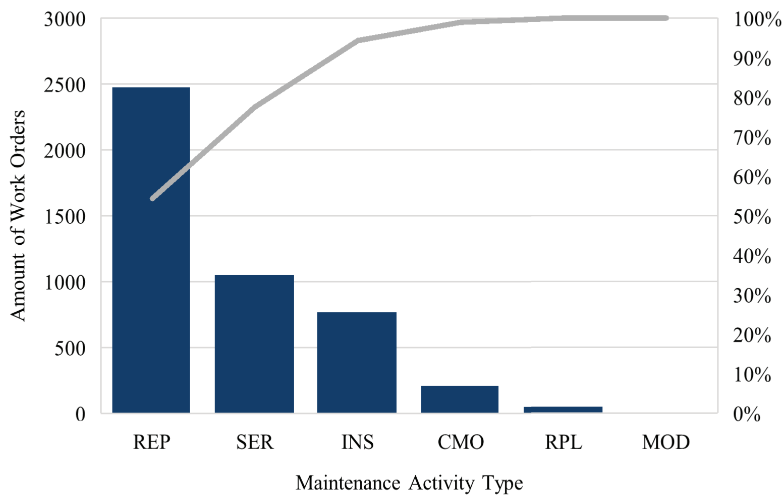

Figure 3: Pareto chart of maintenance activity types for work orders

To further analyse these high-frequency activities, SPC was applied using control charts to monitor process performance and variability over time [12]. Work order turnaround times for repair and service activities from October to December 2023 were extracted from the data, grouped by week, and sampled for analysis. xbar (average) and R (range) charts were generated in R using the Quality Control Charts (QCC) package to track the average completion time and variability, respectively. This approach enabled the identification of trends, anomalies, and potential delays, providing insight into process stability and areas for operational improvement within the department [13].

The quantitative analysis was extended by generating $\bar{x}$ and R control charts for repair and service work orders to assess process stability. The $\bar{x}$ chart (Figure 4) indicated that only one sample marginally violated the standard control limit of seven days for repair work orders, suggesting a potential non-random trend [12]. However, the corresponding R chart (Figure 5) revealed 12 points outside the upper and lower control limits, indicating excessive variability and necessitating corrective action. For service work orders, the $\bar{x}$ chart (Figure 6) identified two points beyond the 28-day control limit, while the R chart (Figure 7) showed 14 violating runs and several points outside the control limits, highlighting significant instability in the service process. It should be noted that the standard timeframes of seven days for repair work orders and 28 days for service work orders, as prescribed by the hospital and organisational performance standards, were incorporated in the control charts as reference benchmarks rather than statistically derived limits. Collectively, these control charts demonstrated that neither the repair nor the service processes were under statistical control, highlighting the underlying factors contributing to delays and variability in maintenance operations. This underscores the need for targeted interventions to reduce variability, improve turnaround times, and enhance overall operational efficiency within the technical services department. Such interventions could involve enhancements such as visual aids for monitoring key metrics, facilitating proactive management, enabling timely task completion, and providing actionable insights that directly address the identified inefficiencies.

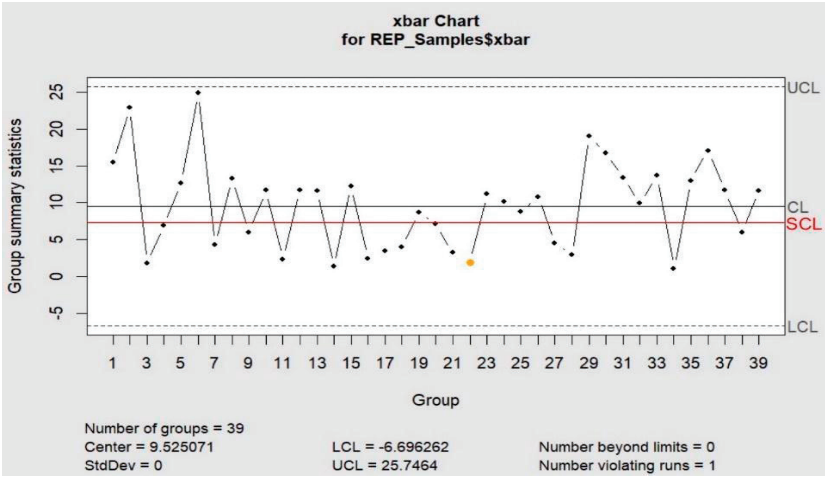

Figure 4: Repair work orders xbar Chart

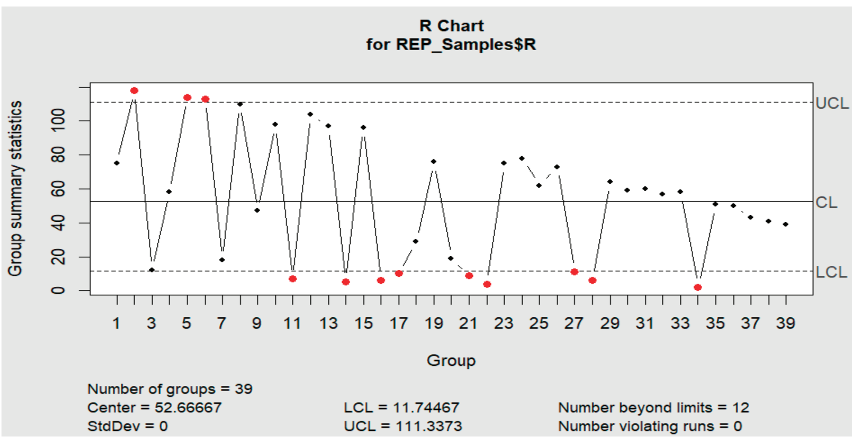

Figure 5: Repair work orders R chart

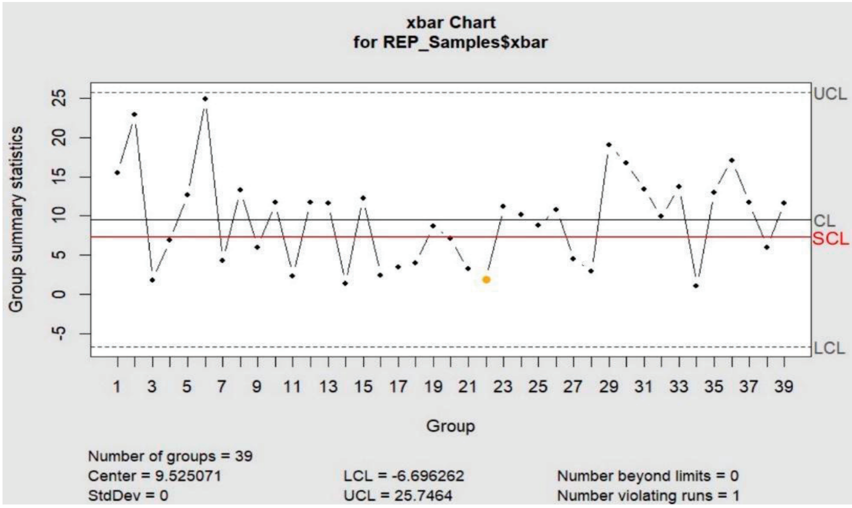

Figure 6: Service work orders xbar Chart

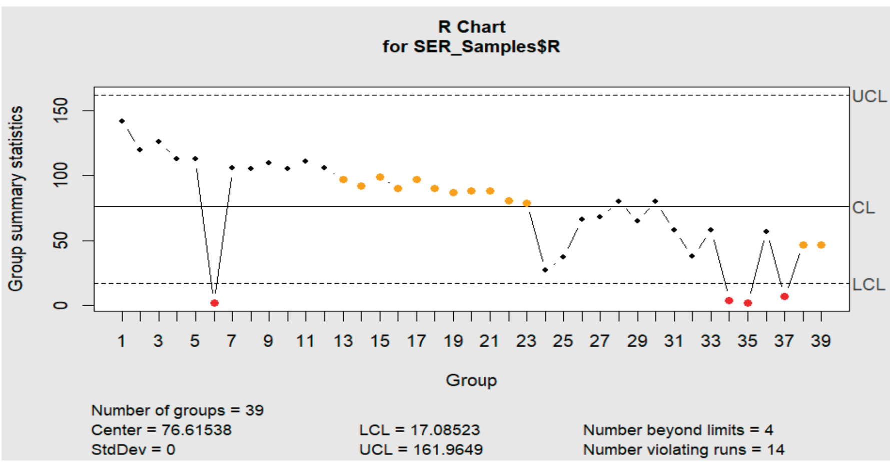

Figure 7: Service work orders R chart

In summary, the current system analysis identified the primary factors contributing to inefficiencies in the technical services department. Qualitative analysis using an affinity diagram highlighted technical staff members, technical clerks, and job cards as key contributors to delays. Quantitative analysis with Pareto charts showed that repair and service activities accounted for 77% of all maintenance tasks. At the same time, statistical process control revealed that turnaround times frequently exceeded the standard limits of seven days for repairs and 28 days for services, indicating process variability and inefficiencies.

The key findings of the root cause analysis are summarised in Table 1.

Table 1: Root cause analysis key findings

Category	Finding
Repair maintenance	The high frequency of repair work orders indicates underlying issues with preventative maintenance.
Service inefficiencies	Variation in service turnaround times suggests inefficiencies in routine maintenance processes.
Process variability	Statistical process control reveals process instability, particularly in turnaround times for repair and service maintenance activities.
Work order processing	Human error by technical clerks and staff in tracking work orders and the respective job cards significantly affects the turnover time for all work orders.

The insights gained from root cause analysis, combined with the structured phases of the V-Model, ensure that the system requirements are comprehensive, targeted, and aligned with operational needs.

3.2 System Architecture

The initial phase, requirements gathering, involved a comprehensive analysis of operational data and stakeholder consultations, as well as the integration of insights from root cause analysis and a literature review. The requirements identified for the technical service work order system intervention include:

- A flagging mechanism to indicate when preventative maintenance is necessary to avoid unexpected breakdowns and extend the operational life of equipment.
- An accurate reflection of current work order turnaround times based on actual operational data.

- A user-friendly interface that enables technical staff and clerks to easily enter, track, and manage work orders.
- Mechanisms to minimise human error in work order entry and job card management.
- Reporting features that allow users to generate reports on maintenance activities and work order turnaround times.
- Utilisation of SPC tools to monitor and control maintenance processes and work order turnaround times, ensuring they remain within acceptable limits.

Building on these requirements, the system architecture was developed with modularity, supporting seamless communication and data exchange between the web browser (client-side), web server (backend), and database server. Figure 8 illustrates the system components and interactions, providing a visual overview of the architecture and data flow. This modular structure enhances scalability and adaptability, facilitating future system enhancements or changes in operational requirements.

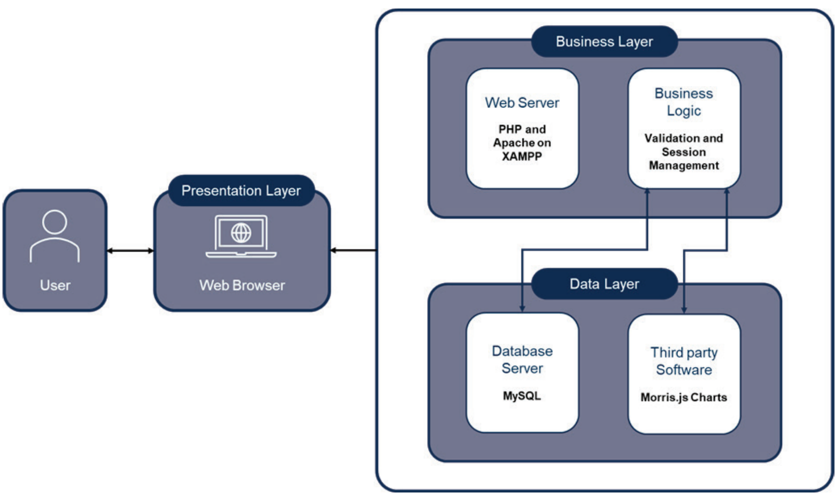

Figure 8: System architecture

The web browser is the presentation layer, validating inputs and displaying information in a user-friendly interface using HTML (Hypertext Markup

Language) and CSS (Cascading Style Sheets). The web server, implemented in PHP (Hypertext Preprocessor), processes user requests, applies business rules, and manages sessions. Through XAMPP (Cross-Platform), Apache provides a robust testing and deployment environment. The database server, powered by MySQL (My Structured Query Language), manages work orders and user data, supporting efficient data retrieval and the execution of business logic. Integration of Morris.js enables dynamic visualisation of key metrics, including SPC control charts, directly within the system.

The system architecture incorporates SPC as a core feature, allowing real-time monitoring of repair and service processes. The system can identify process instability and support proactive maintenance interventions by tracking deviations from control limits, ultimately reducing variability and improving operational efficiency.

3.3 Model design

The design of the technical service work order system is based on the foundations established during the system analysis and architecture design phases. These phases addressed the inefficiencies identified during the root cause analysis. They highlighted key features, including user-friendly interfaces, robust data management, and proactive maintenance strategies enabled by flagging mechanisms and SPC tools. These features, designed to enhance work order management and operational efficiency within the technical services department, were translated into distinct modules with clearly defined designs and functions to ensure compatibility and seamless interaction within the overall system architecture. This phase is crucial, as it outlines the integration of various components, as explained in the Entity-Relationship Diagram (ERD) for the database.

An ERD is a graphical representation used to model a system's data structure. It illustrates the entities (tables), attributes (columns), and relationships between those entities [23]. Establishing the ERD is critical before creating the database or system, as it provides a clear blueprint for data organisation and interaction. This ensures that subsequent development aligns with the intended structure and functionality. In the technical service work order system, the ERD plays a crucial role in organising and managing data, including work orders, administrators, and work order statuses.

The database captures all information regarding repair and service work orders and user actions, ensuring that each work order is tracked from creation to completion. The ERD facilitates the visualisation of this data flow, making it easier to understand how different parts of the system interact with the database. The ERD for the technical service work order system, as shown in Figure 9, demonstrates how each system component connects and interacts, reflecting the underlying structure that supports all system operations.

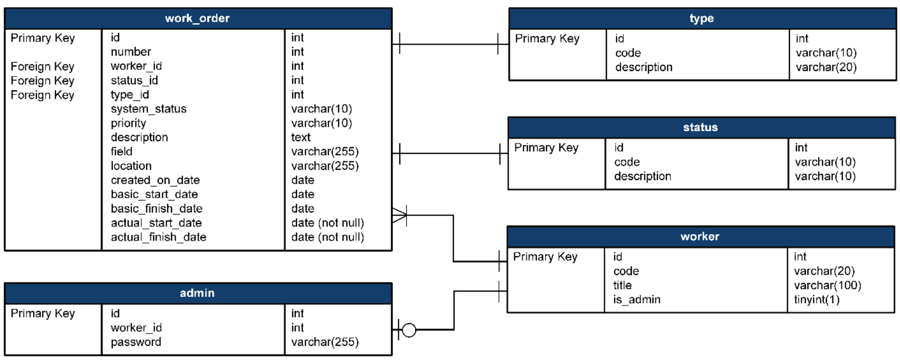

Figure 9: Entity relationship diagram

Each table in the database contains a primary key, which serves as a unique identifier for each record in that table. Primary keys enforce uniqueness, meaning no two records can share the same value for this key. Foreign keys are used to establish relationships between tables, with a foreign key in one table referencing a primary key in another table, thereby linking the two tables [23]. The "work_order" table captures all relevant information about work orders, including the responsible employee, the work order's status (part of the flagging mechanism with categories such as standard, warning, or overdue), the type of work order (repair or service), and the system status (indicating whether the work order is open or closed). The "worker" table stores information about all employees, including details on whether they are administrators with access to the system. The "admin" table stores the passwords of all administrators, ensuring secure access to the system. The "type" table differentiates between repair and service work orders, while the "status" table distinguishes among the various statuses of work orders (standard, warning, or overdue).

3.4 Final design

This subsection presents a walkthrough of the system's functionality, demonstrating how the modules integrate and how users interact with the system and its dashboard visualisation. The final design of the technical service work order system reflects the culmination of the methodology, building on the requirements gathering, system analysis, system architecture, and model design phases. It showcases the system's practical operation, emphasising key functionalities that improve work order management, process monitoring, and operational efficiency. The system delivers a straightforward, user-friendly interface for managing repair and service work orders.

The "Repair" tab, as illustrated in Figures 10 and 11, allows users to view and manage repair work orders. Users are presented with a detailed list of repair work orders, sorted in descending order by the "Created On" date. The status indicates how the work order is progressing relative to the turnaround times. For repair work orders, the control limit is set at seven days; therefore, the status is "Standard" (green) if the turnaround time is less than five days, "Warning" (yellow) if the turnaround time is between five and seven days, and "Overdue" (red) if the turnaround time exceeds seven days. The status updates automatically while the work order remains open and ceases once the work order is closed, functioning as the system's built-in flagging mechanism.

Home Repair Service Admin Log Out

Manage Repair Work Orders

Add Repair Work Order

No.	Employee	Status	System Status	Priority	Description	Field	Location	Created On	Turnaround Time	Actions
448	TS1AA07	Standard	Open	B	Plug points	Electrical	Caritas ICU	2024-10-21	1 days	Update Delete
453	TS01	Standard	Closed	C	Repair couches	Seating	Surgical Ward 2	2024-10-21	1 days	Update Delete
447	TS1AA04	Standard	Open	C	Check TV sound	Television	Cardio Thoracic	2024-10-21	1 days	Update Delete
454	TS1A01	Standard	Open	B	Room 3 is too hot	Air Conditioning	Surgical Ward 1	2024-10-21	1 days	Update Delete
445	TS1A02	Standard	Open	B	Lights repair	Electrical	Surgical Ward 4	2024-10-20	2 days	Update Delete
446	TS1H02	Standard	Open	A	Drains repair	Civil	Surgical ICU	2024-10-20	2 days	Update Delete
440	TS1H08	Standard	Closed	C	Lost key	Keys	Maternity Ward	2024-10-17	0 days	Update Delete
441	TS1H10	Warning	Open	C	Fix shelf	Shelving	Surgical Ward 4	2024-10-17	5 days	Update Delete
438	TS1H07	Warning	Open	B	Adjust aircon	Air Conditioning	Paediatric Ward	2024-10-16	6 days	Update Delete

Figure 10: Manage repair work orders part 1

440	TS1H08	Standard	Closed	C	Lost key	Keys	Maternity Ward	2024-10-17	0 days	Update Delete
441	TS1H10	Warning	Open	C	Fix shelf	Shelving	Surgical Ward 4	2024-10-17	5 days	Update Delete
438	TS1H07	Warning	Open	B	Adjust aircon	Air Conditioning	Paediatric Ward	2024-10-16	6 days	Update Delete
435	TS1A02	Standard	Closed	B	Bed not working	Electrical	Medical Ward 1	2024-10-15	3 days	Update Delete
437	TS1SA01	Standard	Closed	A	Ceiling is leaking	Ceiling	Surgical Ward 4	2024-10-15	1 days	Update Delete
432	TS1AA04	Standard	Closed	B	Repair bed	Electrical	Surgical Ward 1	2024-10-14	4 days	Update Delete
434	TS1AA07	Overdue	Open	B	Wall paint	Walls	Surgical Ward 4	2024-10-14	8 days	Update Delete
431	TS1A02	Overdue	Open	B	Lights repair	Lights	Coffee Shop	2024-10-13	9 days	Update Delete
430	TS1AA06	Warning	Closed	B	Install door	Doors	Surgical Ward 5	2024-10-12	5 days	Update Delete
429	TS1AA07	Overdue	Open	A	Fill generator diesel	Generator 6	Administration	2024-10-11	11 days	Update Delete
428	TS1SA01	Standard	Closed	B	Adjust aircon	Air Conditioning	Medical Ward 1	2024-10-10	1 days	Update Delete
426	TS1H06	Overdue	Closed	C	Toilet door	Doors	Emergency Room	2024-10-07	8 days	Update Delete
423	TS1SA01	Warning	Closed	A	Sink tap leaking	Civil	Medical ICU	2024-10-04	7 days	Update Delete
421	TS1AA07	Overdue	Closed	B	New light bulbs	Lights	Paediatric Ward	2024-10-03	12 days	Update Delete

Figure 11: Manage repair work orders part 2

The “Add Repair Work Order” button directs the user to the “Add Repair Work Order” page, illustrated in Figure 12. This page allows the user to input a new repair work order. The required information includes the work order number, the employee responsible for the work order, and the system status, which, in this case, is set to “Open”. Additional information includes priority, description, field, location of the work order, the date the work order is created (which is the current date), and the basic start and finish dates specified in the work order's requirements. These measures standardise key fields, reduce the likelihood of input errors, and enable users to provide all necessary details for each work order.

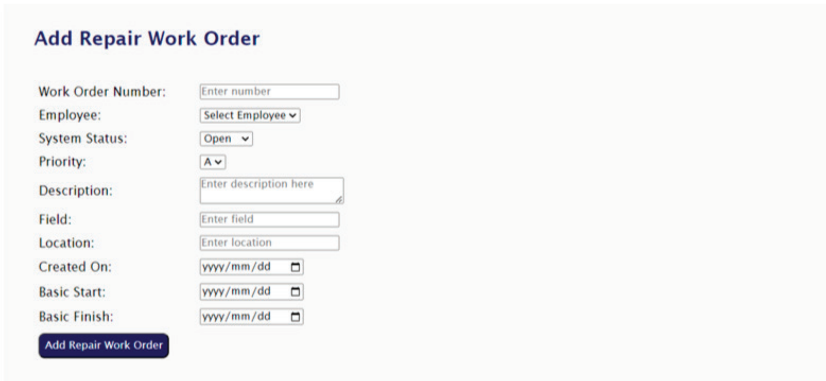

Figure 12: Add repair work order

The "Update" button directs the user to the "Update Repair Work Order" page, illustrated in Figure 13. This page lets the user close the repair work order by updating its status from "Open" to "Closed". Additionally, the user can select the actual start and finish dates for the repair work order.

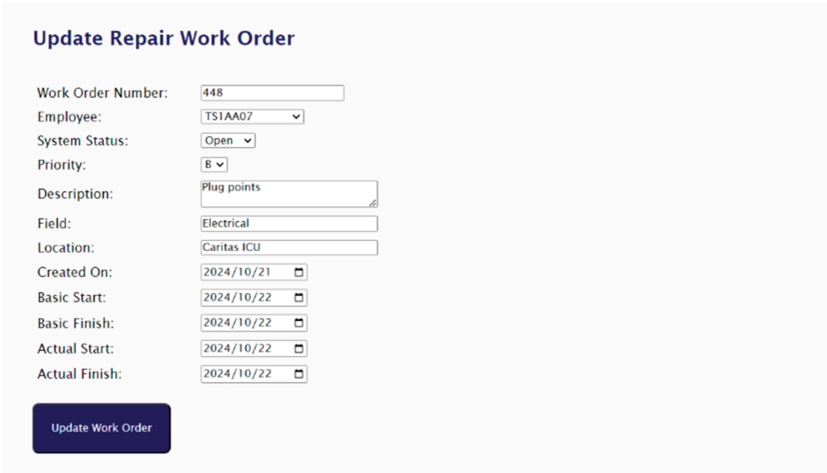

Figure 13: Update repair work order

The “Delete” button removes the repair work order from the database. The message stating “Repair work order successfully deleted” is displayed upon pressing the button. Similar confirmation messages are shown for adding and updating repair work orders.

Similar to the “Repair” tab, the “Service” tab enables users to view and manage service work orders. However, for service work orders, the control limit is set at 28 days; therefore, the status is “Standard” (green) if the turnaround time is less than 26 days, “Warning” (yellow) if the turnaround time is between 26 and 28 days, and “Overdue” (red) if the turnaround time exceeds 28 days.

The dashboard is the homepage and central hub for monitoring work order performance, providing an overview of repair and service tasks. It displays key metrics, including the total number of all work orders, the total number of open and closed work orders, the total number of overdue work orders, and the total number of open and closed overdue work orders, as illustrated in Figure 14. The dashboard also provides an overview of the repair and service tasks, displaying key metrics that mirror those in the overview of total work orders.

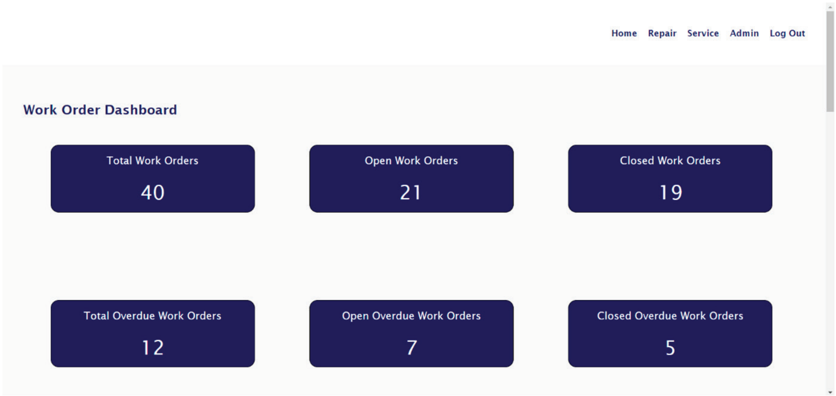

Figure 14: Dashboard of all work orders

All the information displayed on the dashboard comprises buttons that redirect the user to detailed reports. These reports contain a "Search" function, which allows users to search all work orders for specific terms. Users can search for terms such as work order numbers, employee codes, descriptions, fields, or locations, as well as work orders. This functionality enhances management's ability to view and interpret the reports on the technical service work order system dashboard.

The dashboard also features a section dedicated to control charts, incorporating SPC tools within the technical service work order system. The buttons provide access to the control charts for repair and service work orders. Six control charts cover total, open, and closed repair and service work orders.

Figure 15 illustrates the control chart for repair work orders, allowing users to visually monitor and track the status of these work orders. A red line indicates the control limit of seven days, while the warning limit set at five days is shown in yellow. Each work order is represented as a dot on the blue line. Any work order above the red line is deemed unacceptable, while those below it are considered acceptable. As the work orders approach or exceed the warning or control limit lines, the technical clerks and supervisors can easily identify situations requiring prompt attention, facilitating the timely closure of work orders. Thus, these control charts empower technical clerks and supervisors to effectively manage work orders and anticipate overdue cases. The control charts presented demonstrate the system's functionality and capability, illustrating how users can visualise and interpret work order performance data, rather than presenting actual operational outcomes.

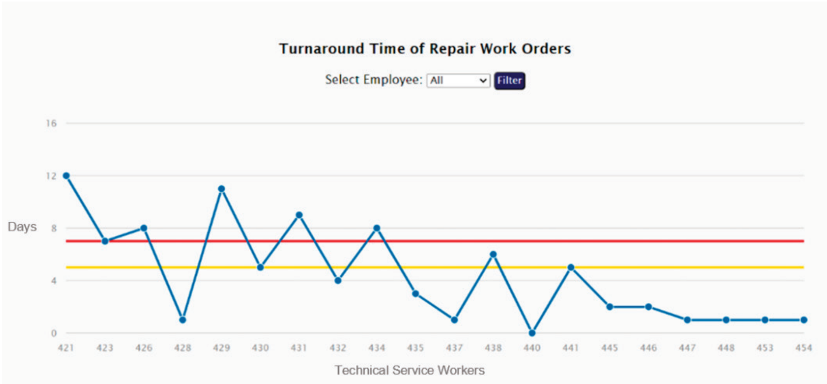

Figure 15: Control chart of repair work orders

Figure 16 illustrates the control chart for service work orders, which functions similarly to the control chart for repair work orders. The key difference lies in the control limits. For service work orders, the control limit is set at 28 days and displayed in red, while the warning limit is set at 26 days and shown in yellow. Each work order is represented as a dot on the blue line.

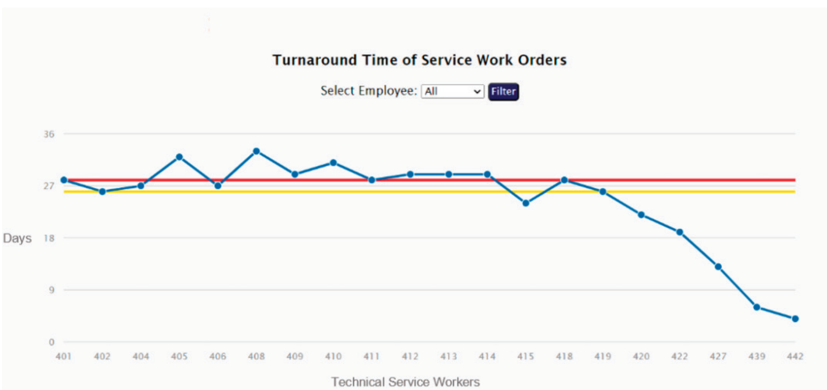

Figure 16: Control chart of service work orders

Each control chart can be filtered by employee (by selecting the desired employee from the dropdown list), allowing users to customise the display to show only a specific employee's work orders. This feature further enhances the performance management aspect of the control charts.

The final design showcases a user-friendly and efficient system for managing repair and service work orders, featuring integrated dashboards, flagging mechanisms, and SPC control charts. This design supports proactive monitoring, accurate record-keeping, and improved operational efficiency, providing a solid foundation for ongoing process improvements.

4 CONCLUSION AND VERIFICATION

This project successfully developed a technical service work order system, completing the full V-Model methodology from requirements gathering and system analysis through system architecture, model design, and final design, to verification and validation. The system integrates key functionalities, including flagging mechanisms, dashboards, and SPC control charts, supporting proactive monitoring, timely work order closure, and improved efficiency. These features provided supervisors and technical clerks with actionable insights, enabling task prioritisation, backlog reduction, and timely maintenance completion—confirming the study's aim through requirements testing, scenario testing, and industry feedback.

Verification and validation were conducted to ensure the system met its defined objectives and user requirements. Table 2 summarises the results of requirements testing, confirming that the system effectively implements critical features, including a flagging mechanism, accurate turnaround times, user-friendly interfaces, reduction of human error, comprehensive reporting capabilities, and the integration of SPC tools.

Table 2: Requirements testing

Requirement Description	Adhering to the Requirement
Flagging mechanism	A robust flagging mechanism was implemented to indicate when intervention on maintenance is necessary, aiming to avoid unexpected breakdowns and extend the operational life of equipment.
Turnaround time accuracy	The system was tested to ensure it accurately reflected current turnaround times for work orders based on actual operational data, thereby enabling more informed decision-making.
User-friendly interface	The interface was assessed for usability, ensuring that technical clerks, supervisors and management could easily enter, track, and manage work orders without extensive training.
Reduction of human error	Mechanisms were integrated in such a manner as to minimise human error in work order entry and job card management, thus enhancing data integrity.
Reporting features	The reporting capabilities were verified to ensure users could generate comprehensive reports on maintenance activities and work order turnaround times, especially on overdue work orders.
Utilisation of SPC tools	The system was tested for its ability to incorporate statistical process control (SPC) tools, using control charts, enabling effective monitoring and control of maintenance processes.

Scenario testing simulated real-world operational conditions, including urgent routine maintenance requests, and demonstrated that the system can handle multiple work orders simultaneously, with real-time updates. Industry feedback confirmed improved tracking, efficiency, and decision-making capabilities. These combined verification and validation processes demonstrate that the system aligns with its initial requirements and meets the end-user's needs.

The project faced several limitations. The system's effectiveness depends on the accuracy and completeness of input data; missing or incorrect data can reduce performance. Successful implementation also relies on staff adaptation and training, as resistance to change could affect utilisation. Additionally, the scope of the analysis was limited to the technical services department.

Several improvements are recommended to enhance system functionality and address limitations. Robust data validation mechanisms should be incorporated to improve reliability. Comprehensive training programmes are essential to support staff adoption of the system and optimise usage. Expanding the scope to include additional departments or integrating comprehensive asset management would enable a more holistic approach to maintenance operations. Implementing mobile-enabled interfaces for real-time work order tracking and digital job card submission would further streamline operations and improve accountability. Longitudinal studies could evaluate the system's impact over time, including part lifespans, task prioritisation, and asset management, supporting continuous refinement and ensuring sustained operational improvements. The study successfully delivered a validated work order system that improves efficiency, promotes proactive maintenance, and provides a foundation for future enhancements.

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IMPROVING INVENTORY MANAGEMENT OF A SOUTH AFRICAN HOSPITAL'S OPERATING THEATRE USING A MARKOV DECISION PROCESS

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ABSTRACT

South African healthcare is divided into public healthcare, which is available to all South Africans, and private healthcare, which is funded by healthcare insurance or private individuals. Operating theatres are the primary driver of revenue in private hospitals. The operating theatre complex of a private hospital in South Africa experiences challenges with the on-time availability of inventory for certain surgical procedures, leading to operational inefficiencies. This study addresses inefficiencies where inventory shortages occur at the point of use during elective surgeries. Our quantitative data analysis and qualitative investigation identify that orthopaedic elective surgeries occur most frequently, and inadequate inventory policies and demand variability are the primary drivers of inventory shortages. Furthermore, discrepancies occur between items that are prepared, picked and used for orthopaedic surgeries. In this research, a Markov Decision Process (MDP) is used for orthopaedic preference card optimisation to solve the problem. The proposed MDP framework utilises Contextual Multi-Armed Bandits (CMAB) algorithms to optimise surgical preference cards through continuous learning from current and future usage patterns. This approach offers a data-driven solution for dynamic preference card

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optimisation that adapts to surgeon preferences and procedural variations. Our results show improved efficiencies and availability of inventory at the point of use.

Keywords: inventory management, operating theatre, Markov Decision Process, private healthcare

1 INTRODUCTION AND PROBLEM STATEMENT

In the South African healthcare system, services are divided into two sectors: public and private. Public healthcare facilities are funded by the government, whereas private healthcare facilities operate as businesses, with patients either paying out of pocket or through medical insurance.

Hospital settings are sensitive in nature since human lives are at stake [1]. Operating theatres are a critical component of this setting, serving as the central point for both elective and non-elective surgical procedures. These environments are resource-intensive and inherently high-risk, thus necessitating exceptional levels of clinical precision, time sensitivity, adherence to safety protocols and inventory management. Efficient management of operating theatre consumables and medication is essential in supporting uninterrupted surgical workflows, minimising delays and safeguarding patient outcomes. Items must be accurately tracked and readily available to avoid cancellations or intraoperative complications due to missing or expired supplies. Inefficient inventory management in these critical settings can lead to significant challenges, including stock shortages, excessive waste and overstocking. These challenges not only increase operational costs but also compromise patient care. Additionally, many operating theatre items, especially medication and sterile supplies, require specific storage conditions and time-sensitive handling [2].

This study focuses on the operating theatre complex of a multidisciplinary private hospital located in an urban region. It is one of only two branches of the hospital group in the province and attracts private healthcare patients from across the region. Due to it being one of the only hospitals of its kind in the area, around 70 surgeries are done weekly across six operating rooms at the facility.

Similar to other operating complexes in hospitals, frequent logistical and communication problems lead to logistical challenges between surgeons, nurses, administrative personnel, medical representatives and pharmacists, and discrepancies in supply requests and availability. Manual, paper-based documentation systems are another concern, as they introduce opportunities for human error and inefficiencies, while poor traceability undermines accountability and compliance with medical standards. This can largely be attributed to poor information flow between surgeons and other clinical operating theatre staff pre-surgery and onwards to the operating theatre dispensary, continuing post-surgery with the restocking of items used. Information on stock requirements for elective surgeries flows between surgeons, nurses, the Unit Administrative Assistant (UAA) and medical representatives from outside the hospital.The process of preparing for elective surgeries, which is scheduled weekly by the UAA, currently relies heavily on the manual preference card system, which creates multiple points where errors and inefficiencies can occur. Surgeons are required to fill out a preference card indicating all consumables and medication needed for a procedure, which is then passed through nurses and the UAA before being used to source, stock, and prepare items for surgery. In practice, however, this process is often inconsistent: preference cards are not always completed or submitted on time, and verbal requests frequently replace formal documentation. This not only delays procurement, especially when medical representatives need to supply items not held in stock, but also results in poor information flow between stakeholders.

During and after surgeries, stock control is further challenged. While nurses document usage on billing sheets, the current system also requires that wrappers of consumables be collected in a bag for post-surgery review to capture missed items. Although this method helps recover some unrecorded usage, it remains error-prone and time-consuming, contributing to discrepancies in billing and restocking. Overall, the reliance on manual preference cards and wrapper collection highlights the inefficiency of the current system and underscores the need for an integrated, data-driven solution to improve accuracy, reduce delays, and ease the administrative burden on operating theatre staff.

The objective of this research is to enhance the availability and management of medication and consumables in the operating theatre complex of a multidisciplinary private hospital in support of elective surgeries. To achieve this, a decision support system that identifies the consumables required for the most frequently performed surgeries has been developed. Given that Markov Decision Processes (MDPs) provide a robust mathematical framework for modelling sequential decision-making under uncertainty [3], the system is built on the principles of an MDP. In addition, the system streamlines restocking and tracking processes, improving stock availability and reducing discrepancies.

In Section 2, literature that assists in elucidating the requirements for the decision support system is investigated. Section 3 explains the methodology followed to develop the system, and Section 4 briefly demonstrates the system and evaluates the system's performance. A conclusion is provided in Section 5, and recommendations are made for further development of and research into the decision support system.

2 LITERATURE OVERVIEW

This section presents the literature relevant to the control and flow of consumables and medication in operating theatres. The aim is to provide background on the operational challenges faced in surgical environments, particularly regarding inventory management and information flow. This section conducts further analysis while simultaneously gathering insights into the requirements necessary for the design phase.

A substantial body of research focuses on improving hospital operations efficiency, recognising its direct impact on patient care quality and cost containment. Recent studies highlight frameworks such as Lean Healthcare and Six Sigma as effective methodologies for streamlining hospital workflows and reducing waste [4]. Specific attention has been given to surgical suite management, where operating theatre scheduling, case cart preparation and turnover time optimisation are critical factors for overall performance.

The healthcare supply chain presents unique challenges due to demand uncertainty and critical service level requirements. Given the complexity of medical supply chains, integrated supply chain strategies that balance cost efficiency with service quality must be implemented. However, the constraints of different healthcare environments must be considered. Supply chains can be significantly supported and improved by implementing patient-oriented, agile and Lean perspectives and practices, while ensuring proper integration of patient needs [5].

Managing inventory in hospitals is characterised by several inherent complexities. Hospitals must contend with a broad variety of item types and usage patterns, constrained storage space within departments, uncertain demand influenced by both planned and emergency procedures, and strict service level expectations often exceeding ninety-nine percent for critical medical items [6]. Traditional inventory management approaches in hospitals often rely on experience-based ordering practices. While simple to implement, these practices have been shown to result in inconsistencies in inventory parameters, unnecessary holding costs and a frequent reliance on emergency orders. Research highlights these challenges and underscores the need for systematic, data-driven inventory control methods tailored to the specific demands of healthcare environments [7], [8].

The literature also underscores the critical relationship between stockout costs and patient safety. Studies demonstrate that stockouts in healthcare can lead to delayed procedures and increased patient risk, making inventory availability a direct patient safety concern. Vendor-managed inventory (VMI) systems have been proposed as a solution, improving stock availability while reducing administrative burden [9].

Furthermore, while operating rooms are considered a significant revenue source, they are also the main source of waste and cost within hospital departments [10]. This dual nature makes effective inventory policy development critical for healthcare organisations. The procurement and inventory management challenges within the healthcare sector have subsequently been the subject of ongoing debate [11].

Systematic inventory classification methods, such as ABC analysis for item value and VED (Vital, Essential, Desirable) classification for clinical criticality, provide a framework for developing inventory policies that consider both financial impact and clinical importance. The ABC-VED matrix approach ensures that high-value items receive appropriate attention while maintaining service levels for critical, low-cost items [12]. This dual classification system ensures that high-value items receive appropriate attention, whilst critical but low-cost items maintain adequate service levels.

Inventory policies typically employ either periodic or continuous review systems, each with distinct advantages depending on item characteristics and operational constraints. Continuous review systems provide immediate response to inventory depletion but require sophisticated monitoring infrastructure, making them optimal for high-turnover items where immediate replenishment is critical [13].

Operating theatre inventory policies must address unique challenges, including surgeon preferences, procedure variability and time-critical decision-making. Traditional inventory policies often prove inadequate for managing the complex interactions between scheduled procedures, emergency cases and individual surgeon requirements [7].

The development of procedure-specific inventory policies, supported by accurate preference cards and consumption tracking, represents a new way of healthcare inventory approaches. These policies must account for the sequential nature of surgical decisions, where intraoperative requirements may differ significantly from preoperative planning [7].

Effective surgical inventory policies require integration with scheduling systems, preference card management and real-time consumption tracking. Such policies must be sufficiently flexible to accommodate procedure variations whilst maintaining control over costs and service levels, necessitating sophisticated forecasting models that account for surgeon behaviour, procedure complexity and seasonal demand patterns [14].

Technological integration is increasingly crucial for driving operational efficiencies and particularly for more effective inventory management practices [1]. Systems capable of dynamic reorder points, automated exception reporting, and predictive demand analytics provide the responsiveness required in surgical environments. Case cart management, for example, plays a key role in perioperative efficiency and patient safety. Practical implementations illustrate measurable benefits: at Abbott Northwestern Hospital, case cart accuracy improved from 50% to 93%, labour-related additions decreased by 20%, and annual staff time savings exceeded USD 40,000, alongside improved interdepartmental cooperation [15]. Similarly, Lean Six Sigma interventions in Ireland streamlined case-cart preparation, reducing nurse preparation time by over 55% and cutting packaging waste through standardised preference cards [16].

Post-operative stock management is equally critical to maintaining surgical service continuity. Timely replenishment of instruments and consumables is essential in high-demand operating theatres [17]. Studies demonstrate that combining data-driven inventory models, Lean methodologies, and digital systems can optimise post-operative processes [16]. For instance, stochastic base-stock models adapted to sterilised surgical instruments using discrete-time Markov chains have enabled more accurate demand forecasting and reduced overstocking, while ensuring the availability of critical items [18].

Structured change management has also proven effective in adopting more efficient approaches to inventory management, as can be seen by the implementation of Kotter's Change Model at a tertiary academic hospital. This resulted in a 37.7% reduction in overall inventory levels, an 18% decrease in tray size, and over 1,300 annual reprocessing hours saved. Surgical cancellation rates due to instrument non-availability dropped from 3.9% to 0.2% [19].

Another notable approach employed by O'Mahony et al. [20] involves the use of Lean Six Sigma and 5S methodologies. In a private hospital setting, applying 5S principles led to a 17.7% reduction in operating theatre stock levels, a 45% decrease in pre-operative nurse preparation time and a dramatic reduction in expired stock, which dropped by more than 90% in value. These outcomes demonstrate that structured organisation and workflow redesign can have a direct impact on reducing waste and improving stock reliability following surgery.

Finally, the integration of supply chain principles into post-operative care environments can enhance overall responsiveness. Research in paediatric perioperative supply chains emphasises the need for value analysis, cross-functional collaboration and evidence-based product selection to avoid stockouts and reduce waste. These strategies ensure that the right products are available when needed and that post-operative care is not compromised by inefficiencies in supply replenishment [21].

The literature also identifies two primary categories of inventory control systems: periodic review systems and continuous review systems. Periodic review systems in inventory management operate by reviewing the stock level of the inventory at set times which occur sequentially with a fixed delay. These systems are generally more suited to items with lower turnover rates and longer lead times. In contrast, continuous review systems trigger replenishment as soon as inventory levels drop below a specific threshold and are typically applied to fast-moving, frequently used items. The application of Just-in-Time (JIT) inventory in hospitals has also gained traction, balancing potential cost savings against risks associated with stockouts of critical supplies [22].

A combined approach using two-bin Kanban systems for high-usage items and periodic review for low-frequency purchases has demonstrated improved availability, reduced overstocking, and fewer emergency orders [13]. Successful implementation requires careful classification, regular updates of ordering parameters, accurate data collection, and consideration of storage and packaging constraints.

Accurate data collection and tracking of actual demand and service levels enhance the reliability and effectiveness of inventory models and decision-making processes. Additionally, inventory management models must account for storage space constraints and package sizes to ensure the feasibility of practical implementation within the physical limitations of hospital facilities [23].

MDPs represent a powerful mathematical framework for modelling sequential decision-making problems under uncertainty. MDPs provide an appropriate technique for modelling and solving such stochastic and dynamic decisions [24]. The framework comprises states, actions, transition probabilities and rewards, enabling optimal policy determination through dynamic programming techniques.

Markov models prove useful when a decision problem involves risk that is continuous over time, when the timing of events is important, and when important events may happen more than once [25]. This characteristic makes MDPs particularly suited to healthcare environments where decisions are inherently sequential and uncertain.

The essential stochasticity of patients' response to treatment represents a major consideration for clinical decision-making in radiation therapy. Markov models serve as powerful tools to capture this stochasticity and render effective treatment decisions [26]. This demonstrates the framework's capacity to handle inherent uncertainty, making it relevant for inventory management applications where demand uncertainty exists.

Recent implementations have shown promise in personalised medicine. While MDP models enable the derivation of optimal treatment policies, they may incur long computational times and generate decision rules that are challenging for physicians to interpret [27], highlighting both opportunities and implementation challenges.

Healthcare inventory systems present unique characteristics well-suited for MDP modelling, including demand uncertainty, critical service requirements and the need for sequential decision-making under time constraints.

Despite their theoretical appeal, MDP implementations face practical challenges. Clinical decisions often have long-term implications, and difficulties can be encountered when employing conventional decision-analytic methods to model these scenarios. These complexities require sophisticated modelling approaches and may necessitate approximate solution methods [24].

The integration of machine learning techniques with MDP frameworks offers potential for adaptive systems that continuously improve performance. Multi-agent MDP approaches present opportunities for modelling complex healthcare supply chains involving multiple decision-makers and interdependent inventory systems [28].

In a case study done by Silva-Aravena et al. [29] a digital twin framework was integrated with a Reinforcement Learning (RL) model, formulated as an MDP, to support dynamic decision-making in surgical scheduling. The state space captured real-time system variables such as patient conditions, waiting lists and operating room availability, while actions represented scheduling and rescheduling decisions. The RL agent was trained through simulation to learn policies that maximise resource efficiency and equity in patient prioritisation. The study employed simulation-based validation using historical hospital data, showing that the MDP-RL hybrid model enhanced throughput by up to 15% and reduced surgical postponements compared to traditional priority-based scheduling. The digital twin component enabled continuous adaptation as new data became available, underscoring the potential of MDP-based RL in optimising surgical workflows.

In implementing an MDP, the choice of RL algorithms is critical to ensure the system can adapt to dynamic, uncertain demand while aligning with operational constraints. RL is thus implemented in this study to learn optimal policies through interaction with the environment. MDPs rely on solving sequential decision-making problems under uncertainty, which requires algorithms capable of efficiently learning optimal policies from historical and real-time data [30]. Given the constraints of healthcare environments, typically involving 50-300 surgical cases per algorithm training cycle, the selected algorithms must be data-efficient, interpretable and capable of learning from sparse feedback. The algorithm selection spans from traditional RL methods to specialised approaches designed for small-data scenarios with immediate reward feedback. By leveraging these algorithms, the MDP can continuously improve decision accuracy, reduce inventory waste and respond to variability in surgical demand [31].

The literature reveals a clear development from traditional experience-based inventory management toward sophisticated, data-driven approaches in operating theatre environments. While significant progress has been demonstrated through Lean methodologies, case cart optimisation and classification systems, the inherent complexity of surgical demand patterns and critical service requirements necessitates advanced modelling frameworks. The convergence of MDP theory with practical healthcare constraints presents a promising avenue for developing adaptive inventory policies that can simultaneously address cost efficiency, patient safety and operational flexibility. This foundation establishes the theoretical and practical basis for implementing intelligent inventory management systems capable of learning and adapting to the dynamic nature of surgical environments.

3 METHODOLOGY

The development of the decision support system was completed in three phases, which started with an analysis of the current practices for preparing consumables and medication for elective surgeries in the hospital's operating theatre complex. Requirements for a solution that will effectively support decisions in allocating consumables and medication for elective surgeries were then gathered and used as input into the system's design. Thereafter, the system was designed based on a similar methodology to that of the digital twin case study above.

3.1 Phase 1: Analysis

To understand the current system and ensure that the decision support system achieves the main objective of enhancing the availability and management of medication and consumables during surgery, an analysis is performed of the stock-keeping practices in place in the hospital's operating theatre complex. The first step is to develop an affinity diagram as a qualitative data analysis tool to identify categories of problems in the current medication and consumable system. Once the data is organised, relevant concepts can be constructed, and logical connections can be made [32]. These categories and a description of each can be seen in Table 1.

Table 1: Affinity diagram categories

Group	Description
Staff	Refers to the operating theatre personnel involved in surgical procedures, including scrub nurses, UAA, care workers and surgeons. This category examines their roles, responsibilities, workflow practices and how human factors such as training, workload and compliance affect consumable control and usage.
Inventory Policies	Encompasses the rules, procedures and standards that govern how surgical consumables and medication are ordered, stored, replenished and tracked.
Resource Planning	Focuses on how resources are allocated and scheduled for surgical procedures. It includes the planning of consumable needs based on case types and surgeon preferences and how well these plans align with actual usage.
Demand Variability	Addresses the unpredictability in surgical case types, volumes and intraoperative needs.
Stakeholders	Includes all individuals or groups affected by or involved in the surgical supply chain and their needs, influence and perspectives.
Communication	Examines the flow of information between departments and roles, such as from the consultation rooms to the operating theatres.

Interrelationships are drawn between categories in Table 1 to determine the main category from which most problems stem. These relationships are visually represented in Figure 1 below.

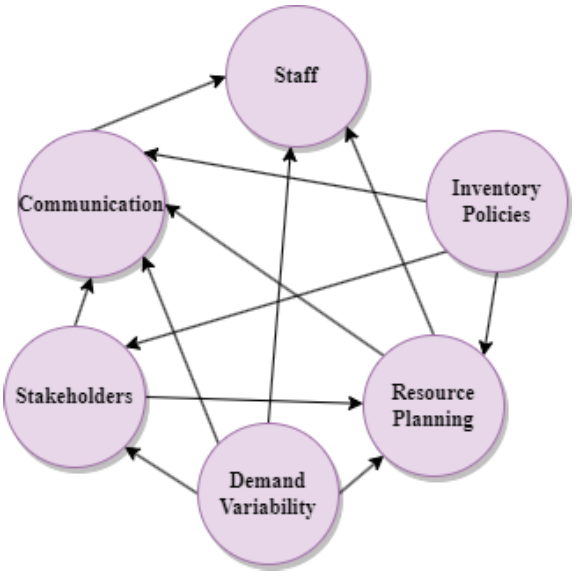

Figure 1: Interrelationship diagram

It is found that inventory policies and demand variability are the categories of problems that have the highest influence on the current system. These two factors can thus be identified as the key root causes. Staff and Communication are the most dependent on other factors and will thus most likely reflect the outcome or impact any changes might have on the system.

Poorly defined inventory policies often fail to account for the unique, high-stakes nature of surgical environments, leading to inaccurate stock levels, over-preparation of rarely used items or critical shortages of essential supplies. At the same time, demand variability, driven by differences in surgical procedures, surgeon preferences, emergency interventions and seasonal case fluctuations, makes it difficult to predict supply needs with accuracy. Without systems that can dynamically respond to these variations, operating theatres are forced into reactive modes of operation, often resulting in last-minute retrievals, delayed surgeries, inefficient resource use and increased stress on staff. Together, these factors undermine operational efficiency, increase costs and pose risks to patient outcomes.

To further enhance our understanding of the current system, quantitative analysis is done based on the Pareto Principle, which serves as a valuable tool to concentrate efforts on the few key sources that contribute to most of the challenges [33].

The Pareto Chart in Figure 2 is an analysis of the number of cases of different elective surgical disciplines. This chart helps to identify which category of elective surgical disciplines are most frequently performed and which specific elective surgeries are to be incorporated in our decision support tool for maximum impact. Data from surgical procedures over a two-month period is analysed, and the number of cases for each surgical category is converted to indicate the percentage of total elective surgeries performed over the two months. A total of 312 surgeries were performed over the two-month period and almost 80% of all elective surgeries performed occurred in three surgical categories, namely: Orthopaedic, Urology and General Surgery.

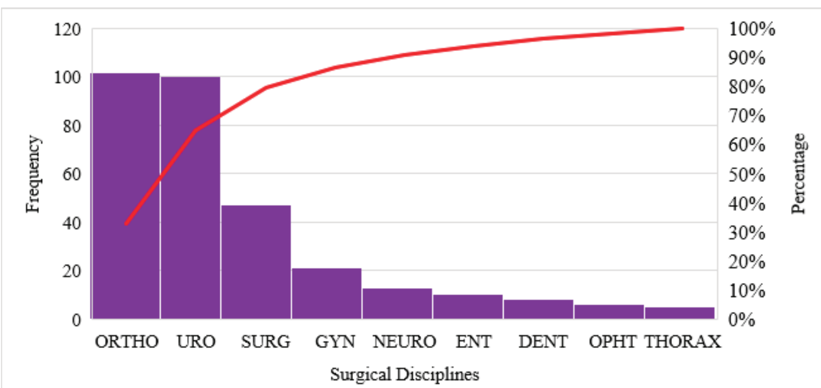

Figure 2: Pareto chart of surgical disciplines

Further analysis was done to investigate which of the orthopaedic elective surgeries contributed to 80% of the performed surgeries. A total of 16 surgeries were identified, and the stock flow and usage of these surgeries were examined.

Through this systematic qualitative and quantitative analysis, two key root causes were identified as driving the majority of medication and consumable stockout at the point of use. These are inadequate inventory policies and demand variability. Therefore, the inability to predict and prepare for these variations leads to emergency supply retrievals and operational disruptions.

3.2 Phase 2: System requirements

The analysis from Section 3.1 and the literature discussed in Section 2 are used as a basis to determine the requirements for the proposed solution. These requirements and an explanation of each can be seen in Table 2 below. These requirements provide the guidelines for the decision support system's design.

Table 2: Requirements for proposed solution

Requirement	Explanation
Identification of items used more than prepared for in elective surgeries	This refers to tracking and flagging when surgical procedures consume more supplies or instruments than originally anticipated in pre-operative planning. This helps identify patterns of under-preparation, improve future case planning accuracy and prevent related operational inefficiencies.
Possibility of future integration with the current AS400 system and the existing operating theatre workflows	This involves ensuring any new inventory or management system can seamlessly connect with the existing AS400 enterprise system and current operating room processes. This prevents workflow disruption and allows data to flow between systems without requiring staff to learn entirely new processes or duplicate data entry.

Real-time adaptability and responsiveness to changing demand	The system should automatically adjust inventory levels and supply allocation based on current usage patterns. This ensures adequate supplies are available when needed without excessive overstocking during quieter periods.
Ease of use	The interface and processes should be intuitive for clinical and administrative staff, requiring minimal training and reducing the likelihood of user errors. Simple navigation, clear displays and streamlined workflows are essential for busy healthcare environments.
Compliance with current inventory policies	The system must align with the existing hospital policies regarding stock rotation (FIFO), expiration date management, controlled substance tracking, vendor agreements and regulatory requirements.
Reduction of the impact of demand variability	This involves implementing strategies like safety stock optimisation or predictive analytics to minimise how fluctuations in surgical schedules or case complexity affect inventory availability and costs. The goal is to maintain service levels while controlling inventory investment.

3.3 Phase 3: System design

The decision support system design is based on an MDP that will be the foundation of preference cards for surgery types. The MDP consists of States (S), representing the different surgeons and procedures; Actions (A), such as adding, removing or modifying quantities and items on the preference cards; Transition Probabilities (P), which capture the likelihood that a change will lead to a new state based on observed usage patterns; and Rewards (R), which quantify outcomes such as cost savings, waste reduction and avoidance of delays.

For operating theatres, an MDP can be implemented by collecting historical data on actual versus requested supply usage, defining states that incorporate current card contents and contextual factors (for example, emergency item usage), modelling transitions based on usage probabilities and assigning rewards that balance efficiency gains with the risk of supply shortages. Optimisation techniques such as value iteration, policy iteration or RL can then be used to determine the optimal set of actions.

Over time, the MDP adapts as new data become available, allowing the preference cards to reflect evolving surgical techniques, changing supply availability and surgeon-specific preferences. This results in a dynamic, data-driven optimisation process that directly reduces waste, minimises costs and supports seamless surgical workflows while also addressing demand variability and inventory policies.

A structured plan for designing and implementing the MDP approach for preference card optimisation is followed as shown in Figure 3.

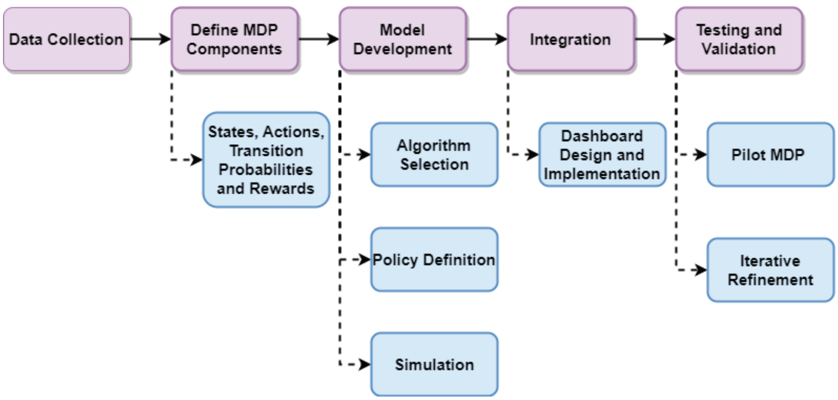

Figure 3: MDP design plan

The MDP is designed in five steps. The first step, completed in Phase 1, is to collect data on the usage patterns of inventory for elective orthopaedic surgeries. Steps two and three inform the different parts of the MDP framework, with step two defining the States, Actions, Rewards and Transitions and step three choosing the RL algorithms to be used as well as simulating the framework. Steps four and five are focused on the User Interface (UI) design and the refinement of the framework when tested on surgeon-procedure combinations.

The model is framed as an MDP with states, actions, rewards and transitions. States represent a surgeon–procedure pair, while actions are item–quantity recommendations. Confidence for each recommendation is calculated by averaging probabilities from supervised learning (logistic regression) and Thompson Sampling. Rewards capture both usage and quantity accuracy: a binary reward if the item was used, and a continuous reward measuring how close the suggested quantity was to actual usage. A weighted combination of these rewards guides learning. Transitions occur after each surgery, forming a contextual bandit setup.

In this study, the states consist of surgeon–procedure pairs, represented as $s = (surgeon, procedure)$, which inform the model about the surgical context. The actions correspond to item and quantity recommendations, expressed as $a = (select\ item\ i\ with\ quantity\ q)$. To generate these recommendations, probabilities from supervised learning and Thompson Sampling are averaged. The supervised learning probability is defined as

$$P_{SL} = P(R = 1 \mid surgeon, procedure, item)\#(1)$$

while the Thompson Sampling probability is drawn from a Beta distribution,

$$P_{TS} \sim Beta(1 + successes, 1 + failures)\#(2)$$

$$where\ successes = \sum \quad reward where\ failures = n - \sum \quad reward n$$
$$= number\ of\ times\ items\ were\ observed$$

The combined confidence score used for ranking recommendations is then given by

$$Confidence = \frac{P_{SL} + P_{TS}}{2}\#(3)$$

The reward function captures both usage and quantity accuracy. The usage reward assigns a value of one if the recommended item is used and zero otherwise,

$$R_{usage} = \{1 \quad if\ item\ is\ used\ 0 \qquad otherwise\ \#(4)$$

while the quantity reward measures how close the recommended quantity is to the actual quantity used.

$$R_{quantity} = 1 - \frac{|q_{rec} - q_{used}|}{q_{used} + 1}\#(5)$$

The overall reward is a weighted sum of these two components,

$$R = w_1 \times R_{usage} + w_2 \times R_{quantity}\#(6)$$

where the weights are currently set to 0.5 each but can be adjusted to prioritise either usage accuracy or quantity accuracy. After each surgery, the model transitions to a new case. Since future states are only weakly affected by current actions, the process can be simplified to a contextual bandit formulation that optimises expected rewards without explicitly modelling transition probabilities. The transition probability is thus represented as

$$T(s, a, s') = P(s, a)\#(7)$$

This formulation allows the system to continuously learn and refine recommendations by balancing historical usage patterns with adaptive decision-making.

A Contextual Multi-Armed Bandit (CMAB) framework underpins the system while the Thompson Sampling adapts to surgeons' preferences by sampling from Beta distributions of item usage as logistic regression predicts probabilities for new surgeon–procedure combinations. Averaging these produces a confidence score. Quantities are estimated from historical statistics and adjusted through the reward function. This hybrid of supervised learning and CMAB improves accuracy by balancing pattern recognition with adaptive exploration.

For the pilot study, data were collected and analysed in Excel, exported as CSV, and stored in SQLite for preprocessing and model training in Python. Streamlit provides the interface for recommendations. In the long term, direct integration with the hospital's AS400 system will automate data retrieval and ensure scalability.

Items are recommended if their confidence exceeds a threshold optimised using the F1 score, which balances precision and recall. This ensures that both correctly recommended and necessary items are prioritised. The UI in the form of a Streamlit app allows users to select a surgeon and procedure, then view ranked recommendations with suggested quantities. Items can be displayed above the threshold through the "Recommend Items" option, or all historical items through the "Show All Items" option. Tables are interactive and downloadable, supporting ease of use in the operating theatre.

4 SYSTEM DEMONSTRATION AND VALIDATION

This section will show a step-by-step run-through of the UI as well as explain the digital flow of the UI.

When the app is opened, you are welcomed to the landing page depicted below in Figure 4. No login page is necessary since users will already have had to log into their account on the AS400 system when opening the UI, if scaled and implemented in the future. On this landing page, instructions are given after which the user will select a surgeon and procedure type from the dropdown menu. Once the surgeon and procedure type are selected, the user can click on the "Recommend Items" button to show the list of items and respective quantities recommended for the surgery. The maximum number of items that are allowed in the dispensary according to inventory policies is also listed for each item.

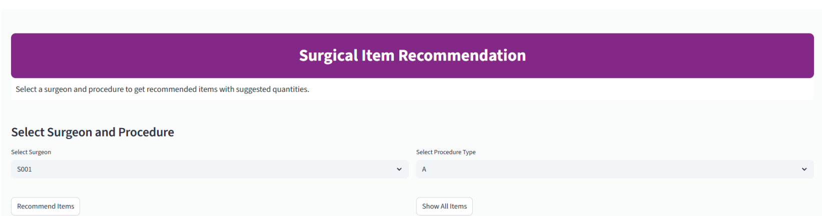

Figure 4: UI landing page

As can be seen in Figure 5 below, two tables will then be displayed, one indicating the surgeon-specific items and the other the procedure-specific items needed for the surgery. The items are ranked based on their confidence. The recommended items list consists of all items that have a confidence above the calculated confidence threshold.

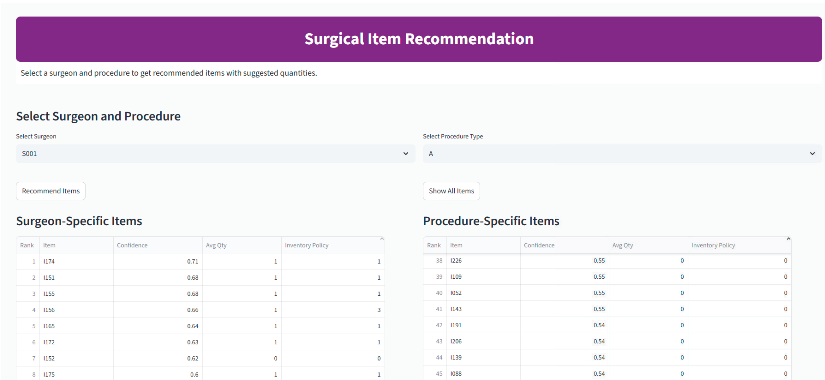

Figure 5: UI recommended item lists

The confidence threshold is indicated at the bottom of the page, as shown in Figure 6 below, and it is evident that all items displayed when clicking on “Recommend Items” either meet or exceed this confidence threshold. All tables also have the option, when hovered over, to be downloaded as a CSV file, or to be enlarged to full screen. When enlarged to full screen, items can be rearranged in ascending or descending order based on different criteria, such as alphabetical order. Furthermore, it is also possible to search a table for particular information.

Surgeon-Specific Items

Rank	Item	Confidence	Avg Qty	Inventory Policy
1	I174	0.71	1	1
2	I151	0.68	1	1
3	I155	0.68	1	1
4	I156	0.66	1	3
5	I165	0.64	1	1
6	I172	0.63	1	1
7	I152	0.62	0	0
8	I175	0.6	1	1
9	I170	0.6	1	2
10	I177	0.6	1	2
11	I169	0.57	1	1
12	I162	0.56	1	1
13	I178	0.56	2	2
14	I173	0.56	1	1
15	I163	0.55	0	0
16	I167	0.55	0	0
17	I161	0.54	0	0
18	I171	0.54	0	0
19	I160	0.47	1	2

Calculated best F1 threshold for your model: 0.33

Figure 6: UI table specific view

When clicking on the "Show All Items" button, the confidence threshold is disregarded and all items previously prepared, picked or used for the surgeon and/or procedure type are listed in a table in the same style and format as the "Recommend Items" tables.

Validation is an essential step in the development of decision-support systems, ensuring that the final solution not only complies with the specified requirements but also addresses the real-world challenges identified during the problem analysis. Various methods of validation are applied to ensure that all aspects of the MDP framework are implemented correctly.

The first method of validation is scenario testing. The aim of the scenario testing is to ensure that the recommended lists are comparable to the actual usage data available during this study. The UI is prompted to recommend items for known surgeon-procedure combinations, and this output is then compared to the data set available for this surgeon-procedure combination. An example of this is shown in Table 3 below, where a snippet of the recommended items for Surgeon S003 and Procedure I is compared to that of the actual usage data. An orange flag indicates where the recommendation differs from the actual usage.

Table 3: Scenario testing

Item	**Recommendation**	**Actual Usage**	**Flag**
I045	2	2	
I053	1	1	
I061	3	3	
I095	1	1	
I156	1	1	
I162	1	1	
I163	1	0	
I166	1	0	
I174	1	0	
I177	1	1	
I178	1	1	
I188	0	0	
I189	1	1	

In the above surgeon-procedure combination a total of 27 items are listed. Three of the 27 items' recommendations differ from the actual usage. Items I163, I166, and I174 are all surgeon-specific items, and the higher recommendation is due to surgeon S003 also using these items in many other cases and procedure types. These items were nevertheless not used for the particular case the scenario testing was done on. It is, however, better to be over-prepared for a few items than it is to be under-prepared, as over-prepared items are easier to account for post-surgery compared to under-prepared items.

To evaluate the predictive performance of the logistic regression model, k-fold cross-validation was applied to the dataset in Python. Specifically, the dataset was divided into five folds and the model was trained and tested five times, each time using a different fold as the test set while the remaining folds were used for training. This method ensured that all data points were used for both training and evaluation, providing a robust assessment of model generalisation. The cross-validation results were as follows:

Accuracy scores across folds: [0.736, 0.7435, 0.7467, 0.7139, 0.7182]
Mean accuracy: 0.7317
Variance of accuracy: 0.000177
F1-scores across folds: [0.7112, 0.7317, 0.7309, 0.6965, 0.7006]
Mean F1 score: 0.7142
Variance of F1 score: 0.000218

These metrics indicate that the model achieves moderately high predictive performance. With the F1-scores being close to the accuracy values, a balanced reflection of both precision and recall for predicting whether a surgical item will be used is shown.

The relatively low variance in both accuracy and F1 score suggests that the model's performance is stable across different subsets of the data. However, the scores are not perfect, indicating room for improvement, particularly in the handling of variability in item usage patterns across surgeons and procedures.

Increasing the dataset size is expected to enhance model performance in several ways. It should generalise predictions better as more training examples reduce overfitting and allow the model to capture a wider range of surgeon-procedure-item interactions. Higher stability of metrics should also be achieved with larger datasets, as it typically reduces variance in cross-validation scores, making predictions more reliable. If rare items or procedures are underrepresented, additional data can provide more examples, improving F1 scores, especially for less common cases. With more observations, dynamic thresholds for classifying item usage can also be better estimated per surgeon or procedure, further enhancing recommendation precision.

The current cross-validation metrics are thus acceptable when considering the smaller data set this study works on. This then subsequently indicates that the supervised learning model works effectively by utilising logistic regression.

To assess the performance of the whole surgical item recommendation model, a combination of global classification metrics and per surgeon-procedure regression metrics was used. These metrics provide a comprehensive view of both the model's ability to predict whether an item is used and how accurately it predicts the quantities needed.

The performance of the model was evaluated using four global metrics, each providing a different perspective on predictive quality. Accuracy measures the proportion of all predictions that were correct, offering a general view of performance. The F1-score combines precision and recall into a single measure, ensuring a balance between false positives and false negatives. The AUC/ROC captures the model's ability to distinguish between items that are likely to be used and those that are not, reflecting its ranking capability. Finally, Log Loss assesses how well the predicted probabilities match actual outcomes, penalising confident but incorrect predictions more heavily. Together, these metrics give a comprehensive view of both classification performance and probability calibration. To further clarify the AUC/ROC, it is visualised by means of a plot in Figure 7 below. The larger the area under the curve the better the model is able to discriminate between items that are used and not used.

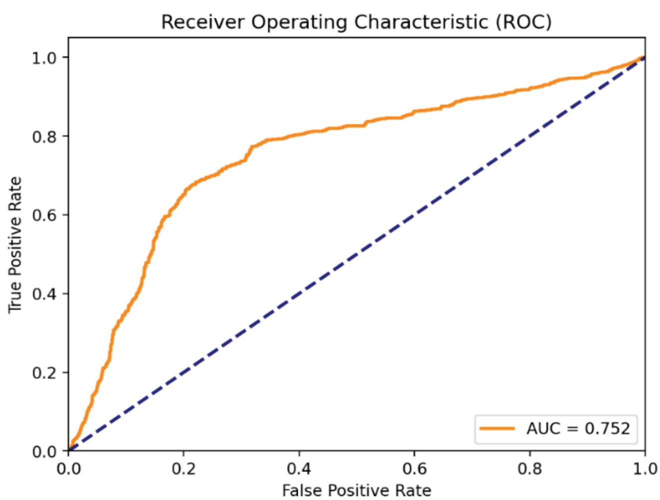

Figure 7: AUC/ROC

For predicting the quantity of items used per surgery, Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE) were calculated for each surgeon–procedure combination. MAE reflects the average size of the prediction error, while RMSE emphasises larger mistakes more strongly. Lower values indicate better prediction accuracy and consistency. Table 4 below shows different examples and interpretations of these results.

Table 4: Explanation of MAE and RMSE results

Example Cases	Interpretation
Low error (S001–A: 0.38 / 0.53)	Predictions are very close to actual quantities, with small deviations.
Moderate error (S001–H: 0.60 / 0.92)	Predictions are reasonably accurate but show some variability.
High error (S001–B: 1.16 / 1.19)	Predictions struggle due to high variability in usage or limited data.

Overall, accuracy is procedure-dependent: frequent and consistent procedures achieve low MAE/RMSE, while less common or more variable ones lead to higher errors.

5 CONCLUSION

This study effectively addressed the critical challenge of medication and consumable management inefficiencies in a private hospital's operating theatre through the development and validation of an MDP-based recommendation system. The findings demonstrate that systematic analysis of operational challenges, combined with data-driven solution development, can generate tangible improvements in healthcare supply chain management.

The research identified inadequate inventory policies and demand variability as primary drivers of operational inefficiencies within surgical environments. Through comprehensive root cause analysis employing both qualitative and quantitative methods, orthopaedic surgeries were highlighted as representing the greatest opportunity for improvement, accounting for 33% of all procedures performed during the study period.

The proposed system aims to address communication and inventory challenges by integrating adaptive, learning-based mechanisms that personalise surgical item recommendations for each surgeon and procedure. The system employs a hybrid prediction framework combining Contextual Multi-Armed Bandits, Thompson Sampling, and Supervised Learning. This approach enables continuous learning from historical data while dynamically adapting to new usage patterns, thereby improving both the accuracy of item selection and of the recommended quantities.

An intuitive Streamlit-based UI ensures accessibility for operating theatre staff without requiring technical expertise, addressing a critical barrier to technology adoption in clinical settings. The modular system architecture, designed with potential integration into enterprise systems such as AS400 in mind, reflects practical consideration of real-world implementation challenges.

Validation results indicate that the decision-support system is functional and aligned with the requirements defined during the design phase. Scenario-based testing confirmed that the system generates recommendations comparable to historical usage data, with minor deviations attributable to surgeon-specific preferences. Cross-validation demonstrated the model's generalisation capability, with stable accuracy and F1 scores across folds. Global evaluation metrics, including AUC and log loss, further highlighted the system's ability to distinguish between used and unused items and to generate well-calibrated probability predictions. Per surgeon-procedure MAE and RMSE values confirmed that the system provides reliable quantity recommendations, although performance varied with the availability of historical data and the variability of item usage.

The study faced certain limitations, including a relatively small dataset spanning two months (312 surgeries, including 102 orthopaedic cases), a focus limited to elective orthopaedic procedures at a single hospital, and moderate validation results (73% accuracy, F1 score 0.626). Simulated testing rather than live implementation also constrained confidence in real-world performance. Future research should expand data collection to at least one year, incorporate additional surgical disciplines such as urology and general surgery, integrate the system with enterprise platforms like AS400, and enhance predictive models by incorporating contextual factors. Despite these limitations, the study provides a robust foundation for transforming surgical supply chain management through intelligent decision-support systems.

The broader implications of this research extend to healthcare efficiency and patient safety, as improved inventory management supports uninterrupted surgical workflows and reduces the risk of procedure delays or complications due to supply shortages. Furthermore, potential cost savings from reduced waste and optimised inventory levels highlight the strategic value of data-driven supply chain management in healthcare.

Looking forward, this work establishes a framework for continued innovation in healthcare supply chain optimisation, with clear pathways for expansion across additional surgical disciplines, integration with emerging technologies, and scaling to larger healthcare systems.

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TOWARDS TOTAL DATA QUALITY MANAGEMENT THAT ENABLES FEASIBLE STATISTICAL MODELLING:
A CASE STUDY IN THE FINANCIAL SERVICES SECTOR

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ABSTRACT

Case studies play a valuable role when researchers want to understand why or how things work in real-life settings, which are often subject to complexity not always accounted for in theoretical work. This study contributes to the literature on data quality management by examining how data deficiencies can fundamentally alter the trajectory of applied research and business projects. Instead of advancing directly to statistical modelling, the project required a structured program of data profiling, quality assessment, and change management. Findings revealed that only 19.2% of the provided data set planned to be used for statistical modelling met the data quality criteria of being unique, up-to-date, accurate, consistent, complete, and valid. Reflective journalling documented the evolution and learnings of the data project and emphasised that improving data quality demands more than technical fixes—it requires iterative, collaborative processes that address issues at their source. Equally important is fostering a culture of problem-solving, supported by tools like checklists and *Poka Yoke*, to prevent recurring errors. By documenting these challenges and responses, the study offers a replicable framework for organisations and underscores the critical role of data quality in enabling reliable analytics.

Keywords: TDQM, data quality, financial services, data cleaning

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1 INTRODUCTION

In the financial services sector, the quality of data is crucial for operational efficiency, informed decision-making, and overall business success [1, 2]. With the increasing dependence on data-driven strategies, maintaining high standards of data quality has become imperative for organisations. The company of this case study, referred to as Company A, operates in the short term vehicle insurance sector in a low-middle-income country. In this industry, accurate and timely data processing—from customer policies to claims and financial transactions—is vital. This reliance highlights the necessity for robust data quality management practices.

Risk models play a crucial role in the financial sector, particularly within the insurance industry, by enabling companies to quantify and manage potential future financial losses [3]. The primary challenge in this domain is pricing premiums accurately to reflect the extent of future financial loss before it occurs. This challenge has driven the need for sophisticated statistical models that can quantify risk on a more granular level [4]. For instance, Company A aimed to redefine their vehicle insurance premium calculation framework using generalised linear modelling techniques. The initial goal was to develop models that estimate risk in terms of claim frequency and claim severity, thereby allowing for more risk-appropriate premium calculations. Such models are essential as they help in decreasing high loss ratios and improving the overall financial health of the company. However, the efficacy of these models is highly dependent on the quality of the underlying data. Discrepancies in the dataset and a lack of awareness about data quality issues can severely undermine the reliability of the resulting risk models. Consequently, addressing data quality is a critical step before any effective risk modelling can be performed.

Despite the evident importance of data quality, many companies still grapple with numerous data quality challenges. Especially where data is not automatically collected, and there is a lack of understanding and awareness of the importance of data quality, data sets can lead to missing, inconsistent and incorrect data entries. This phenomenon is demonstrated by the case study presented in this paper, which describes a project that was intended to focus on statistical modelling and data comparison, but had to take an important detour through a comprehensive data quality investigation, data profiling, change management, and the formulation of data quality maintenance steps. This paper provides a description on the state of the real-world data, as well as the results of a systematic data cleaning process.

As to their theoretical contribution, case studies play a valuable role when researchers want to understand why or how things work in real-life settings, which are often subject to complex relationships [5]. By studying various real-life cases, researchers can extract theory on why or how certain inputs succeed or fail to produce the desired outcomes [6]. This case study contributes to the literature on data quality management by illustrating how data quality challenges can fundamentally redirect the trajectory of applied research and business projects. Instead of proceeding directly to statistical modelling and data comparison, the study highlights the necessity of first undertaking a structured process of data profiling, quality assessment, and change management. By documenting both the deficiencies in real-world data and the systematic steps taken to improve data quality, the study demonstrates the practical value of integrating data quality investigations into project workflows.

The contribution lies in showing how comprehensive data quality maintenance strategies can transform flawed datasets into reliable inputs for advanced analytics, while also offering a replicable framework for organisations facing similar challenges in contexts where data is manually captured or poorly governed. Furthermore, it provides an honest case study of the state of data in some settings that are highly reliant on the data to make decisions that will affect business profitability directly, answering the research question of what real-world data may look like. By providing an in-depth look into one case where data is still manually captured, this paper provides the opportunity for similar case studies in other settings, which can be used to create a more realistic awareness regarding the state of real-world data. Knowing what data quality levels to expect and what issues to build into system designs, further paves the way for the use of Artificial Intelligence to expedite the preparation of data to avoid the phenomenon of 'garbage in, garbage out' where there is no human-in-the-loop.

The paper is structured as follows: section 2 provides some insights from literature on data quality and its management; section 3 describes the process followed for data quality assurance, followed by the results of the endeavor in section 4. Section 5 contains the recommended data quality assurance framework, with further research opportunities and the limitations of this study summarised in section 6.

2 LITERATURE REVIEW

2.1 The evolution of Total Data Quality Management

The concept of Total Quality Management (TQM) has its roots in the convergence of management theories and quality principles, drawing heavily on the foundational work of Deming's 14 points and Juran's quality trilogy. Over time, these ideas evolved into a holistic management philosophy aimed at embedding quality into every aspect of organisational practice [7]. TQM can be understood as a comprehensive system of practices, methodologies, and training initiatives designed to help organisations navigate dynamic environments while maintaining a clear focus on achieving and sustaining customer satisfaction [8]. TQM is thus a holistic continuous improvement approach focusing on building quality into the process to achieve customer satisfaction. It does this through employee involvement, teamwork – also with suppliers, and a long-term perspective [9]. In recent decades, the relationship between TQM and knowledge management has increasingly been strengthened leading to the adoption of many TQM principles into the sphere of knowledge and data management [10].

TQM was adapted to an information processing environment to form the Total Data Quality Management TDQM) framework [7, 11]. TDQM emphasises the accountability of all organisational members in maintaining high standards of data quality, thereby aligning data processing activities with customer expectations and operational goals. An advantage of treating an information processing system and a traditional manufacturing system in the same way is that many of the quality techniques used in TQM can be translated to suit the data environment.

Where TQM is a management approach where everyone in an organisation is accountable for maintaining high standards to produce quality products that meet customer expectations [7], TDQM views information manufacturing as a process that converts raw data into quality information products. In product manufacturing, a processing system converts raw materials into physical products. Similarly, information manufacturing can be viewed as a processing system which converts raw data into information products. TQM was consequently adapted to an information manufacturing environment to form the TDQM framework [8].

An advantage of treating an information manufacturing system and a traditional manufacturing system in the same way is that many of the quality techniques used in TQM can be translated to suit the data environment [12]. There are however some limitations that arise due to the nature of data when compared with a physical product which should be considered when adopting established frameworks. Where a physical product is consumed, a data unit or information unit is not depleted. In addition, the duplication of a data unit is trivial when compared with the expenses incurred to copy a physical product [12].

2.2 Understanding data quality

According to Sebastian-Coleman [7], the level of data quality in TDQM is the degree to which the data meets the expectations of the data users based on their user tasks. Data quality is therefore subjective to the perceived quality of the data user. Quality thinkers have identified several quality aspects, called dimensions, to measure data quality [7].These dimensions quantify data quality in relation to a scale or metric so that data quality can be compared between data objects and over different time periods to measure the impact of data driven business processes [7].

The following fundamental concepts form part of the early stages of any TQM implementation ([13, 14] and were the focus of this case study: Standardisation, which manifests as clear and communicated quality standards, as well as a strict view of what constitutes output, namely only output that complies to the set standards, Creating awareness amongst all employees that the next downstream process is an important customer, and that every employee has a role to play in assuring quality throughout the process, and Establishing an understanding, firstly amongst management, then amongst all employees, of what it means to proactively build quality into the process instead of reactively inspecting it in.

The six most relevant data quality dimensions identified for this case study have been compiled from the work of Wang [8], Shankaranarayanan and Cai [15], and Sebastian-Coleman [7] and were used to build a uniform awareness of what constitutes good data quality:

Uniqueness: evaluates the degree to which data cannot be mistaken for other entries,
Completeness: evaluates the extent to which all required data is present,
Consistency: evaluates whether data is uniform and reliable across different datasets,
Validity: evaluates whether data conforms to stated business rules,
Timeliness: assesses the relevance of data based on its age and the time it was captured,
Accuracy: evaluates the correctness of data in representing real-world values.

2.3 Building data quality into the process

Once these six data dimensions are being measured and monitored throughout the process, and ownership of data quality management has been established, team members should be educated on and empowered to look for and action opportunities to build quality into the process. A practical technique, highly applicable to the data environment, is that of error proofing. Poka Yoke or 'mistake proofing' is a concept originally coined by Shiego Shingo in the 1960s which has become applicable in many different environments [16, 17]. The practice aims to prevent defects from appearing in the first place by ensuring that mistakes are impossible. If this cannot be achieved then it can be used to detect and correct errors [18].

Poka Yoke consists of three sequential steps. The first step is to identify all possible errors, human and machine, that can occur in the process. The next step is to determine how the error can be detected when it occurs or when it is about to occur. The last step is to identify a specific action that can be taken to eliminate the error [19].

Poka Yoke can also be divided into three types of mistake-proofing categories namely, control, shutdown, and warning. Control is an action that corrects the error automatically. An example of a control would be auto-capitalisation at the start of a new paragraph in MSword. Shutdown occurs when the process is immediately halted upon the detection of an error. An example of a shutdown is a system that prevents submission of a data entry until all mandatory fields are filled in. Warnings inform people that an error has occurred. A drawback of warnings is that they are often ignored which is why controls and shutdowns are preferred [19].

Given the above description, it is evident that Poka Yoke can be used to reduce the reliance on people to operate free of error. One of the barriers to implementing Poka Yoke is the need for management support [20]. This is because people are set in their way of doing things and may resist changing, hence the importance of incorporating change management into the TDQM implementation. Another barrier of Poka Yoke is the lack of awareness of the concept [20]. This barrier can be remedied by creating awareness for the technique and getting employees involved in the process.

Checklists are a more common quality assurance tool used to ensure that all essential steps in the process are followed and to make it possible to confirm compliance in a standardised way [21]. It is however acknowledged that the implementation of checklists requires employee compliance and is time consuming [21], again highlighting the need for change management.

In a case study by Kalapurakal, et al. [22], the impact of checklists was evaluated in terms of the reduction of medical errors relating to dosage, patient identification and patient location. The case study highlights the use of checklists to improve the performance quality when human error needs to be addressed as opposed to system or machine error.

Although this paper focuses on the data cleaning and standardisation process that occurred at the beginning of the company's data quality management journey, the in-depth analysis of the state of the data automatically led to the further step of identifying opportunities for the implementation of Poka Yoke. The data analysis also made it clear to what extent the data quality improvement journey would rely on employees to assure quality, and thus change management was naturally an important part of the process from the start.

2.4 An overview of change management models

Kotter's 8-Step Change Model is an expansion of Lewin's three step change management model [9]. According to Galli [9], Kotter's model provides more direction on how to implement change and also incorporates more of the human component of change by delving deeper into preparing employees for change and supporting employees during change. The explicit steps in this model also make it easy to implement [9].

One major drawback of this model is that employees may experience a top-down approach [23]. Employees are only involved after the change vision has already been developed, which may create more resistance to change. If employees do not get on board with the newly developed strategic vision, then this may result in wasted effort. Kotter's model may be enhanced if used in conjunction with a model which is more people centric [9].

The ADKAR model consists of five sequential goals that focus on the acceptance of change. The acronym stands for Awareness, Desire, Knowledge, Ability and Reinforcement [9]. Awareness occurs when employees are informed of the need for change. Desire occurs when employees decide that they want to partake in the change. This is followed by the Knowledge of what the change demands and how to drive the change. Ability is what is required to implement the change. Lastly, Reinforcement is required to ensure that the change is sustained [24].

The ADKAR model is useful in identifying the relevant areas of resistance which are prohibiting change from happening [24]The goal-orientated structure of this model helps to facilitate change by working towards smaller, seemingly more attainable milestones as opposed to Lewin's model which focuses on the overall process. According to Galli [9], since this model focuses primarily on the human component of change, it is better suited to smaller environments and project teams as opposed to large scale organisations with complex business processes. Galli [9] postulates that in practice the ADKAR model should be paired with another model which deals with the human emotions that accompany change.

The Kubler-Ross change curve, also referred to as the grief curve or the five stages of grief, was introduced by psychiatrist Elisabeth Kubler-

Ross in 1969 as a product of her work with terminally ill patients. This model originally described how people handle grief when confronted with a terminal illness. The five stages of grief are defined as denial, anger, bargaining, depression and ultimately acceptance [25]. The change curve was subsequently translated to a business environment to describe how people experience disruptive change and how this influences their productivity levels.

The Kübler-Ross model is a people-centric model that focuses on the human experience to change and highlights the importance of considering an individual's experience to change as opposed to that of the team as a whole [25]. The framework allows team leaders to anticipate and understand their employees' reactions to change. Furthermore, team leaders are empowered to proactively support their employees so that the change is more likely to be successful. This model does however fail to provide an actionable framework for how the change should be implemented. It is therefore recommended that this model be paired with another change management model that addresses these shortcomings. However, by using this model, greater consideration can be given to how the information can be relayed so that employees feel supported during the change initiative. This model addresses the shortcomings of the ADKAR model and Kotter's 8-Step Model so that a holistic approach can be taken in creating a case for change.

Additionally, the McKinsey's 7S framework provides insight as to the seven interrelated key elements that companies should consider when implementing change in order to produce a synergistic outcome. These elements are further divided into hard and soft elements. The hard elements, namely strategy, structure and systems, can be controlled by management. Strategy is the proposed plan to transform the organisation from its current state to the desired state. Structure refers to the organisational structure such as the reporting hierarchy, roles and responsibilities and systems that are defined by the formal procedures and day-to-day activities [9, 26]. The soft elements are more often governed by intrinsic culture and include shared values, style, staff and skills. Shared values refer to the engrained organisational culture and company values. Style emphasises how the leadership style influences the resistance to change. Staff refers to the capabilities of the employees, and skills refers to the core competencies of those employees [27].

Unlike the other change management models, the McKinsey 7S model highlights the strengths and weaknesses that exist in different dimensions of an organisation, which allows managers to identify where there is a need for change. The McKinsey model does however not explore how employees experience change or how change should be implemented. Another disadvantage of this model is that proper implementation can be time consuming and therefore not cost effective for large organisations [9].

There are many other concepts within the TDQM framework that address various aspects of the quality assurance journey and only the ones relevant to the case study presented in this paper have been discussed here. How the reviewed concepts were integrated to address real-world quality issues is presented next.

3 THE CASE STUDY: REAL-WORLD DATA QUALITY

As mentioned in the introduction of this paper, the initial objective of this project was to utilise historical data to develop a statistical model to estimate the risk associated with a given policy. The existing premium framework would be replaced with the statistical model such that more risk appropriate premiums could be charged to clients on an individual basis as opposed to the existing fixed percentage approach. The project sponsor requested that generalised linear modelling be used to develop two statistical models in order to quantify the risk in terms of claim frequency and claim severity separately. Before implementation, the impact of the models would be evaluated by comparing the actual losses to the losses incurred if the statistical models were used to determine the premium charged. In addition, the available data was to be compared to other insurance models to identify if there is additional information that is currently not recorded by Company A which would benefit future risk models.

When a new policy is activated the policy information is stored on the system in the policy dataset. If a client submits a claim, the claim is entered and stored on the system in the claims dataset. Not all policies are expected to have corresponding claims as a client may have been claim free, but all claims are expected to correspond to a policy. These two datasets are then aggregated to calculate the loss ratio and evaluate the performance of the portfolio as well as the individual policies. The project sponsor provided the aggregated dataset containing both policy and claims information for the development of the statistical models.

After the application of generalised linear modelling was investigated in literature, the data was used to develop a frequency model with a Poisson distribution. The development of the frequency model had little success as the model's predictions were severely inaccurate and many of the variables available were not significant in predicting claim frequency. This raised the question whether the data being used for the model was of sufficient quality and contained sufficient variables to develop an accurate model. Upon inspection of the dataset, several discrepancies were identified. These discrepancies included:

- A significant number of empty data fields,
- Claims information for which there was no corresponding policy,
- Extreme vehicle values,
- Negative vehicle values,
- Negative vehicle ages, and
- Negative premiums.

Inquiries into these discrepancies were met with resistance from the individuals responsible for managing the data system, highlighting the need early on for change management and involving the team members in the data analysis to create awareness of the need for change. In addition, not only were there no relevant policyholder characteristics in the data but there were very few recorded vehicle characteristics. This was concerning as the data provided for this project was also used by Company A to calculate the loss ratio and to make business decisions. Since the quality of the data was observed to be inadequate, these internal evaluations may have motivated business decisions which were in fact not beneficial.

The reliability of any statistical model is directly related to the reliability of the data used to develop the model [28]. Due to the considerable prevalence of discrepancies in the data and the lack of available data, the modelling component of the project became secondary and the new problem that emerged was one concerning the quality of the data. It also became apparent that an appropriate change management framework would be required to motivate the project findings to the team and encourage productive change. After consultation with the project sponsor, the scope of the project was updated to address the data quality issues and include a change management component.

After the discrepancies were discovered in the dataset, the claims data and policy data were requested as stored in their raw form on Company A's system. A preliminary data analysis was carried out on the requested data to better understand the data environment and ultimately produce a clean dataset for modelling purposes.

The first task of this project was thus a comprehensive data quality investigation, which informed the data cleaning and preparation process. Once the data had been cleaned and prepared, it could be used for the originally planned statistical modelling. This paper will however focus on describing the data quality improvement journey, which consists of three phases: data collection, data cleaning and preparation, and data quality assurance initiation.

3.1 Data collection

Given the significant number of discrepancies found in the original merged dataset provided by the project sponsor, the raw claims dataset and policy dataset were requested. The policy data and the claims data were imported into RStudio for further analysis. There were 25 961 entries in the policy dataset and 2 381 entries in the claims dataset before analysis, covering three financial years. An important principle extracted from the experience was thus that data cleaning should start from the source data. This is similar to the concept of Genshi Genbutsu in lean management where problem solvers are encouraged to 'go to the floor' – 'the scene of the crime' – to start problem solving at the source.

3.2 Data preparation and cleaning

The data cleaning and preparation was done in sequential steps as follows:

Removal of duplicates: Firstly, the duplicates in the claims dataset and the policy dataset were removed. These were entries for which the values in the columns for a specific row were exactly the same as for another row. This means that data were entered into the system twice and the duplicate line-items should not have been included in the respective datasets. No duplicates were found in the policy data set, but the claims data set contained 59 (2.48%) duplicate entries. This provided the current state of one of the quality dimensions, namely uniqueness.

Removal of test run data: In both datasets there were entries which were clearly used for testing purposes since the word 'test' appeared once or more in a single line-item. In the claims data set, three (0.13%) test run entries were removed, and 134 (0.52%) were removed in the policy data set.

Aggregating of data within the data sets: The claims data contained a unique entry for every single claim incurred. However, some vehicles incurred more than one claim for the duration of the policy. Here a renewal of a policy is considered as a new vehicle entry so that the claim count can be assessed for every vehicle every year. Since more than one vehicle could belong to a specific policy number and the policy numbers are often carried over to the next year, the policy number could not be used as a unique identifier. The policy inception date, which is the date the policy was started, and the vehicle registration were combined to create a new variable that could be used to uniquely identify a claim for a specific vehicle in a specific year. Due to the lack of standardisation in how the data was entered, a further preparation step had to be included here: the vehicle registration numbers had to all first be capitalised and any spaces in the characters had to be removed. The claims data was then aggregated so that for every vehicle and every year the claim count and the total claim severity could be seen. This resulted in the removal of 177 (7.63%) entries from the claims data set.

Similarly, the same unique key was created for the policy data set. Some of the entries in the policy dataset were created to update existing entries. For example: say a vehicle was registered to a policy with a sum insured of USD15 000 and a premium of USD750. A week after the policy inception date, it was discovered that the true value of the vehicle was actually USD20 000. An adjustment entry was then made with a sum insured value of +USD5 000. Several of these adjustments also existed for the premium variable. The updated entries were aggregated with the original entries such that the new entries reflected the total sum insured and total premium for every vehicle in every year. During this step 5308 (20.55%) of the policy entries were removed.

The waterfall charts in Figure 1 (claims data) and Figure 2 (policy data) visualise the effect of the removal of duplicates and test data, as well as the aggregation of fields relating to the same claim or policy. After this initial cleaning process, the policy and claims data sets were merged to ensure that each claim is associated with the correct policy and to further assess and correct data quality issues.

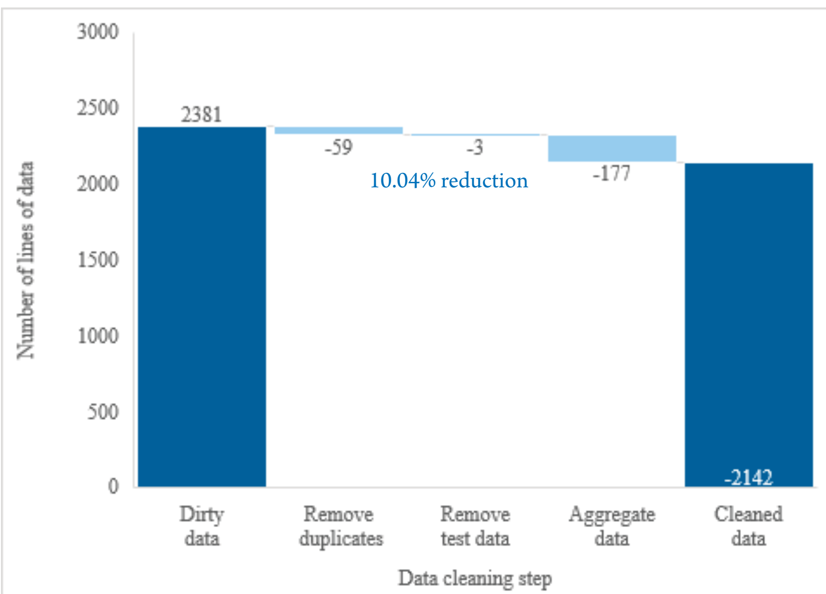

Figure 1: Claims data cleaning process results

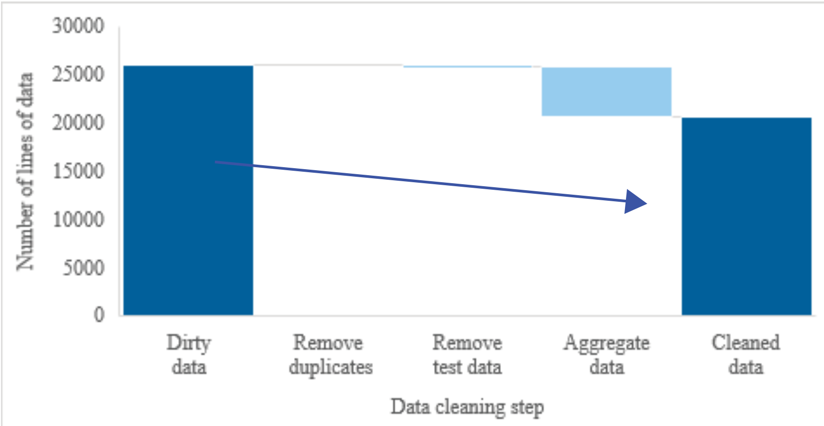

Figure 2: Policy data cleaning process results

Merging data sets: The next step was to merge the policy data and the claims data so that for every year and every vehicle the total claim severity and claim count were known. The unique key created in both datasets was used to merge the corresponding entries.

Correction of data: Upon merger, it became evident that there were some claim entries that did not correspond to a policy. Since it is impossible to make a claim without a corresponding policy, this indicated that there may be data errors contained within the policy inception date and the vehicle registration number that formed the unique key used for merger. The data thus had to be screened for the 115 unmatched claims to correct the data errors that could be identified so that these entries could be included in the aggregated dataset.

Creation of essential input data: The vehicle age of each vehicle was calculated using the vehicle manufacture date and the policy inception data. The exposure of the policy was calculated using the policy inception date and the policy expiration date whilst also accounting for policies which ran over into the next financial year.

Removal of irrelevant information: Irrelevant columns were then excluded from the dataset so that the data contained only vehicle characteristics, driver characteristics and the metrics needed for the risk model, such as claim count, claim severity and policy exposure.

Assessment of missing values: the driver characteristics, as well as the vehicle characteristics, were checked for missing values. The sum insured, vehicle make, and age data sets were complete as a result of some of the corrective actions already mentioned. More than half of the entries were missing for the engine size, fuel type and body type and no driver characteristics had been captured at all.

Exploration of available data: the structure of each variable was explored further by observation and by calculating summary statistics such as mean, median, minimum and maximum.

All of the actions mentioned up to this point resulted in the line items being reduced from 28453 raw line-items to 20238 line-items, a 28.59% reduction in the data set (Figure 3).

Up until this point, the data preparation, cleaning and correction judgement calls were relatively obvious, for example, duplicates, test run data, missing values etc. However, further data cleaning steps required frequent consultation with various stakeholders, including the management team. No data were removed without confirmation from the team that there was indeed no other option to deal with the discrepancy. The data cleaning steps are described next.

Detail data cleaning: During this step, the data was screened for the following:

- Outliers in the different variables such as sum insured and vehicle age,
- Missing values,
- Inconsistent entries,
- Spelling errors,
- Ambiguous entries,
- Incorrect entries,
- Inconsistencies, and
- Sparsely populated rows or columns.

As mentioned, the relevant stakeholders were consulted throughout this process so that no corrections or removals were made without careful consideration. This cleaning process revealed the true state of the data and reduced the data set to only 3 881 line-items, 19.18% of the merged data sets, that were full and reliable enough to use in statistical modelling.

Data imputation: Using fields that had been populated allowed for other fields, such as vehicle models, to be deduced from the available data. Through this data imputation process an additional 2465 entries could be included in the modelling dataset. However, the data in some columns were so diversely different in terms of the type and level of data captured that even a pattern extractor was unable to salvage the data.

Data set finalisation: Finally, the final state of the clean data was presented to the management team, who then decided on the set of variables deemed fit for statistical analysis.

The data preparation and cleaning phase thus resulted in only 19.18% of the merged data set being usable for statistical analysis and modelling. The data imputation step increased this to 28.00%. Figure 3 summarises the results of the data cleaning.

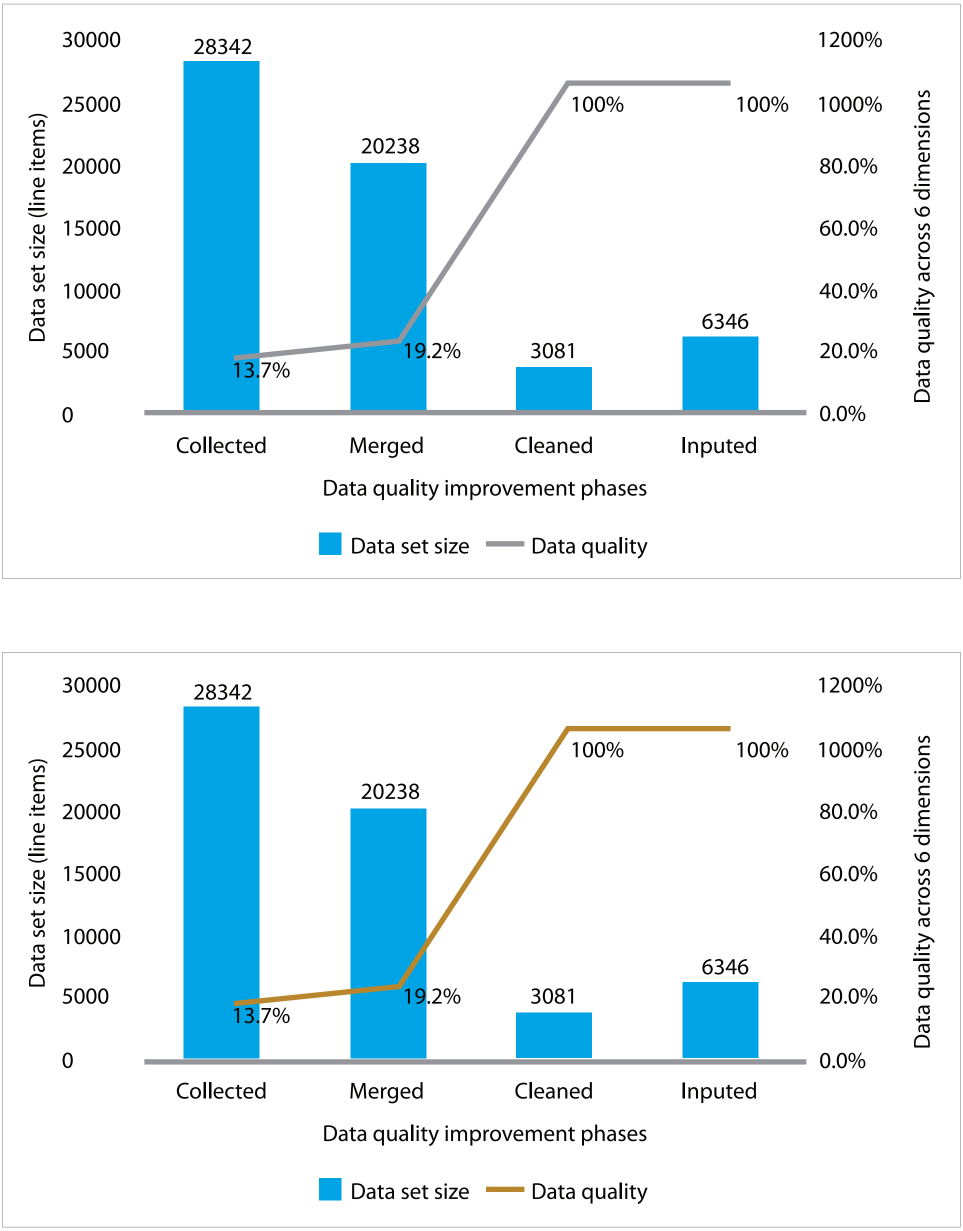

Figure 3: Results of data cleaning phases

To complete the current state investigation, the data analysis was summarised into the six data quality dimensions as follows:

- Uniqueness: The percentage of duplicates in the dataset was used as the metric for this dimension. Ideally, the percentage of duplicates should be 0%. The analysis revealed that the percentage of duplicate entries was 2.48% for the claims dataset and 0.52% for the policy dataset;
- Timeliness: The percentage of out-of-date entries was used as the metric for this dimension. Ideally, there should be no outdated data entries. However, the investigation found that 20.53% of the policy data was out-of-date, highlighting a significant issue in maintaining current data;
- Validity: The percentage of invalid data was used as the metric for this dimension, with an ideal value of 0%. The results showed that 1.72% of the data was invalid, indicating the presence of data entries that did not meet the required standards;
- Consistency: The actual-to-ideal ratio was used as the metric, with an ideal ratio of 1:1. The investigation revealed inconsistencies in various attributes: the vehicle registration had a 9:1 ratio, vehicle make had a 1.44:1 ratio, vehicle body type had a 1.43:1 ratio, and vehicle model had a 28.55:1 ratio;
- Completeness: The percentage of non-null data entries was used as the metric, with an ideal value of 100%. The investigation found that only 53.85% of the data was non-null, indicating substantial gaps in the data that needed to be filled to enhance its overall quality; and,
- Accuracy: The percentage of incorrect data was used as a metric, with an ideal value of 0%. The analysis showed that 5.37% of vehicle registration data and 8.24% of overall data were incorrect.

3.3 Data quality assurance initiation

The in-depth investigation into, and preparation and cleaning of, the data set raised awareness of the data quality issues amongst the stakeholders that had been involved during the process. However, improving the data quality in both the short and long term would require a holistic approach involving all employees.

Kotter's eight steps, infused with the learnings from the ADKAR and Kubler-Ross models, were used to guide the change management process to engage the team throughout the process. The goal of the first step of the change management initiative was to convince the data team of the urgency to implement change by highlighting the severity and impact of the data quality issues. A collaborative approach ensured that the team could raise questions and concerns regarding the findings and/or process and make suggestions on how quality could be built into the process going forward.

Change leaders who could be entrusted to inspire the desire to change and lead the change initiative were identified, after which the focus shifted to creating a shared vision on what constitutes data quality. For this the six data dimensions and their customised metrics were introduced to monitor data quality in future. To empower teams to attain the vision, the concept of proactively building quality into the process was introduced.

Poka Yoke solutions were developed to alleviate the cognitive load of the data team as well as to build quality into the process throughout. The following control and shutdown error-proofing opportunities existed:

- Auto-formatting fields to capitalise, exclude or reject spaces;
- Making filling of fields essential for analysis mandatory;
- Preventing users from submitting data which do not comply with the defined business rules, are invalid, duplicates or missing;
- Implementing drop-down lists to ensure the entry of only valid, correctly spelled data;
- Implementing specified ranges for continuous variables to immediately flag unrealistic and incorrect values;
- Formatting fields to only accept a certain character type or number of characters;
- Cross checking between categorical variables such as driver age and driver experience level to ensure validity;
- Auto-filling fields such as vehicle make and model used to prefill the body type; and,
- Creating checklists of required information to be collected during telephonic conversations with potential policy holders.

4 CLEANING REAL-WORLD DATA SETS: KEY STEPS AND PRINCIPLES

The preliminary data analysis and the data quality investigation successfully quantified the extent of the data quality issues and provided a strong case for change, and the initiation of a journey towards zero-defect when it comes to data quality. The process, as discovered through the experience of cleaning a real-world and very messy data set, and key learnings are discussed next.

4.1 Case study process flow

The steps followed during the data cleaning process were described in detail in section 3.2. The process can be summarised more generically as follows: the process begins with data gathering, followed by data preparation and cleaning, which includes removing duplicates, correcting errors, merging datasets, addressing missing values, and finalising inputs. Where needed, imputation and detailed cleaning ensure data completeness and reliability. The final step is building quality into the process, including embedding continuous checks and improvements for long-term accuracy. Figure 4 shows a comprehensive version of the process flow.

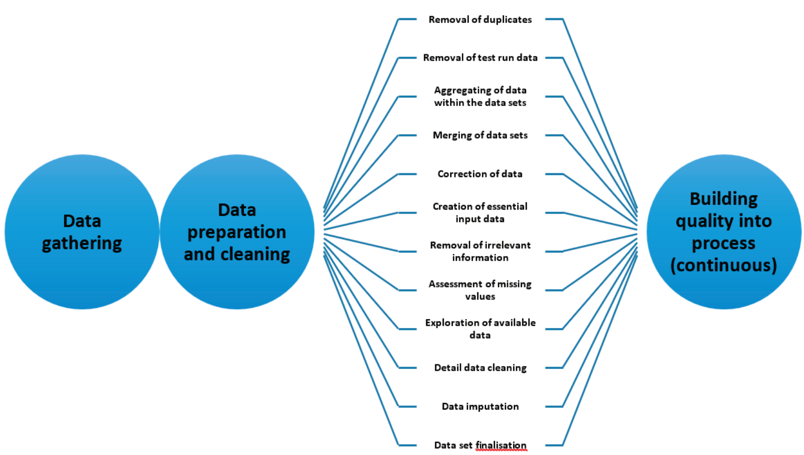

Figure 4: Data quality improvement process flow

4.2 Key learnings

Apart from working through a messy set of real-world data systematically, some key learnings can be extracted and are summarised here.

1. Start at the Source: Where possible, start by analysing the raw data instead of a derivative of the data set where errors might already be concealed or aggregated;
2. Assume the Worst: Adopting a cautious mindset helps ensure that all potential flaws are considered. Data should not be trusted at face value until it has been validated through structured checks;
3. Apply Validity and Logic Checks from Multiple Angles: Comprehensive reviews, for example, using statistical tools, logic tests, and business rules, help uncover inconsistencies. Techniques such as R programming and pattern recognition enhance this process. Typical checks include:

    - Duplicates
    - Test-run or trial data
    - Outdated or obsolete records
    - Outliers
    - Invalid entries (for example, negative vehicle ages)

4. Consider Data Imputation: Where feasible, imputation can supplement existing valid data and prevent unnecessary data loss;
5. Embrace Continuous Improvement: Data quality is not a one-off task. The process must be iterative, with regular monitoring and adaptation to meet evolving business needs [29];
6. Build Awareness Early: Communicating findings as they emerge ensures transparency and helps establish momentum for change. Early engagement builds awareness of the need for cleaner data and drives behavioural change through early adopters as well as the Hawthorne Effect;
7. Foster Collaboration and Problem Solving: Since most data errors originate from human activity, the cleaning process must be

collaborative. Team members should be encouraged to identify and flag discrepancies without fear of blame. A constructive, problem-solving culture is essential;

8. Avoid Blame, Promote Accountability: The guiding coalition should lead by example—rewarding problem reporting, linking reported issues to visible problem solving, and engaging data owners in developing solutions; and,
9. Empower Employees through Practical Tools: Introducing employees to error-proofing methods such as Poka Yoke and checklists provides simple, effective mechanisms to prevent recurring errors. These tools give staff a 'way out' of persistent issues, reducing resistance and building ownership of the process.

5 CONCLUSION

The data quality investigation emerged as the pivotal focus of this project, highlighting the critical importance of data integrity for subsequent statistical modelling efforts. Significant discrepancies within the data necessitated a comprehensive approach to identify and rectify these issues.

Utilising the TDQM framework, the six key dimensions of data quality were evaluated: uniqueness, completeness, consistency, validity, timeliness, and accuracy. This rigorous assessment revealed substantial deficiencies, prompting an expanded project scope to include targeted data quality recommendations and a change management initiative. Quantitative metrics provided clear insights into the extent of the problems. Only 19.2% of the original data set met the six data quality dimension criteria.

The project's findings indicated that data cleaning and preparation were crucial steps. The process involved removing duplicates, handling missing values, and correcting inconsistencies in order to ensure that the data met the defined quality metrics. For instance, the uniqueness dimension revealed a 2.48% duplication rate in the claims dataset, necessitating further cleaning to meet the ideal standard of 0%. Timeliness was another critical dimension, with 20.53% of the policy data found to be out-of-date, indicating the need for more timely data updates. A high incompleteness of data, with more than 46% of data points being incomplete, meant that a risk model was infeasible.

The data cleaning project demonstrated that improving data quality requires more than technical fixes—it demands a structured, collaborative, and iterative approach. Key principles include addressing issues at the source, applying rigorous validity checks, and considering methods such as imputation to preserve useful information. Continuous improvement is vital, with findings communicated early and often to build awareness. Most importantly, success depends on fostering a culture of problem solving rather than blame, empowering employees with practical tools like checklists and Poka Yoke to prevent recurring errors. Together, these practices form the foundation for sustainable progress toward zero-defect data quality.

The formation of a dedicated data quality improvement team was a direct outcome of this initiative, highlighting the project's success in fostering organisational change. Developed solutions focused on sustaining the data quality and were categorised into mistake-proofing actions, emphasizing prevention, detection, and correction. The iterative nature of data quality improvement was emphasised, advocating for continuous re-evaluation and adaptation to meet evolving business needs.

In conclusion, the project has laid a robust foundation for ongoing data quality improvement within Company A. By addressing the significant data quality issues, the project has ensured that future statistical models developed using this data will be more reliable and accurate. The methodologies and frameworks employed are generalisable to other researchers and organisations within the financial services sector, providing a structured approach to tackling similar data quality challenges. This comprehensive focus on data quality and change management has set the stage for more dependable data-driven decision making and enhanced business outcomes for Company A.

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USABILITY-CENTRED SELECTION OF PROCESS MODELLING TOOLS IN HIGHER EDUCATION: A MULTIVOCAL LITERATURE REVIEW

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ABSTRACT

Business process modelling underpins improvement, communication, and educative clarity in tertiary education. Selecting a usable, context-fit tool, particularly among free-to-use options, remains challenging and requires a consolidated evidence base. The purpose of this article is to review existing literature, searching for decision-making guidance when a tertiary educator has to select the most appropriate process modelling tool.

The review confirmed a gap in comparative, usability-centred evaluations of free-to-use Business Process Modelling and Notation (BPMN) tools for tertiary contexts. A systematic search of peer-reviewed and grey literature, with backward and forward snowballing, was conducted. A class of problems was validated through thematic analysis of problem instance analysis, with proposed solutions, highlighting persistent selection needs for free-to-use tools and recurring usability challenges in education. Tools identified in the grey literature were compared, based on their features and against minimum requirements for tertiary use, with feature importance weighted. Existing methodologies, used for tool selection, inform a solution artefact design.

Evidence shows few tertiary-specific comparisons, inconsistent and poorly reported usability metrics, and gaps in coverage of features important for teaching and learning. The review includes tertiary-specific

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requirements, a structured feature list, and a preliminary prioritisation scheme for decision support.
Keywords: BPMN, process-modelling, usability, tool selection, decision support, tertiary education, systematic review, grey literature

1 INTRODUCTION AND RESEARCH OBJECTIVES

According to Lytvyn, et al. [1], innovation and effective implementation of digitalised business processes play an important role in enhancing a company's competitiveness. Over the past decade, digital technologies have proven to be powerful tools that can improve efficiency and drive rapid enterprise development. These technologies not only improve productivity but also develop both the internal and external environments of businesses, impacting their competitiveness in the market. Within this context, Business Process Model and Notation (BPMN) provides a language for the graphical representation of existing operations in both production and service environments [2].

1.1 Problem context

Education of enterprise designers at tertiary level requires practical experience with process modelling tools and clear understanding of tool limitations across different contexts of use [3]. Modelling objectives include analysis of existing processes prior to digitisation and analysis of implementation deficiencies after deployment. The selection of an appropriate process modelling tool depends on alignment between objectives, feature needs, and non-functional requirements. Usability functions as a central nonfunctional requirement and is defined as ease, efficiency, and satisfaction of use as a software quality attribute [4], and the ISO 9241 11 standard describes it as achievement of specified goals with effectiveness, efficiency, and satisfaction in a specified context of use. *Satisfaction* refers to user happiness with task completion, *effectiveness* refers to task completeness, and *efficiency* refers to effort required for task completion [5]. Emphasis on usability within the software selection for process modelling artefacts aims to reduce dissatisfaction and inefficiencies in a tertiary education setting.

1.2 Problem instance analysis

This literature review indicates the absence of a comparative study that integrates feature offerings and usability for free-to-use process modelling tools. An incumbent desktop tool, Bizagi Modeler 4.2, is used at a Tertiary Education Enterprise (TEE), with observed usability concerns that initiated a search for an alternative, aligned with two stakeholder groups, lecturers and students. The primary measure for validation concerns the usability of the tool, where qualitative evidence from structured experimentation provides the basis for diagnosis.

1.2.1 Data gathering using experimentation

Experimental work, done by the main researcher, applied the tool to complete a compulsory undergraduate BPMN exercise using official instructions and supporting material given to the students. The documentation used to proceed with experimentation is shown in Table 1. Observations recorded areas of concern, perceived causes, and candidate remedies to inform validation of the problem instance.

Table 1: Documentation used for experimentation

Title	Author	Year	Description
Enterprise Implementation using BPMN: Introduction	Lecturer A	2023	Class notes introducing undergraduate students to the BPMN process model
Designing a BPMN diagram with the transaction pattern in mind	Lecturer A	2023	BPMN exercise required in the designated undergraduate module
Designing a BPMN diagram with the transaction pattern in mind Memorandum	Lecturer A	2023	Memorandum for the BPMN exercise in the designated undergraduate module

1.2.2 *Experimentation results*

A baseline usability appraisal of the Bizagi Modeler used the assessed BPMN exercise with learning outcomes that included: (1) Differentiation between Design and Engineering Methodology for Organizations (DEMO) and BPMN models; (2) Understanding the relationships among previous process related models and BPMN; (3) Distinguishing between core BPMN diagram types; (4) Application of BPMN 2.0.2 elements and examples; and (5) Construction of a diagram that incorporates coordination acts of the basic, standard, or complete transaction pattern. Initial observations were organised according to effectiveness, efficiency, and satisfaction, summarised as follows:

- **Ease of use:** Interface density, discoverability of specific BPMN elements, intermittent responsiveness during the control of elements, and repeated validation prompts affected ease and learnability. Also, hover tooltips and embedded help resources supported learning.
- **Efficiency:** Quick linking and partial auto connection improved speed, but mandatory drag and drop placement, inconsistent alignment behaviour, and prompts shown during saving interrupted workflow.
- **Satisfaction:** High-quality rendering and completion of the exercise supported satisfaction, while lack of real-time collaboration, absence of a spell checker, and label layout constraints reduced perceived quality for teaching and co-modelling use.

An example of one of these cases, namely the auto connection issues from the experimentation can be found in Figure 1.

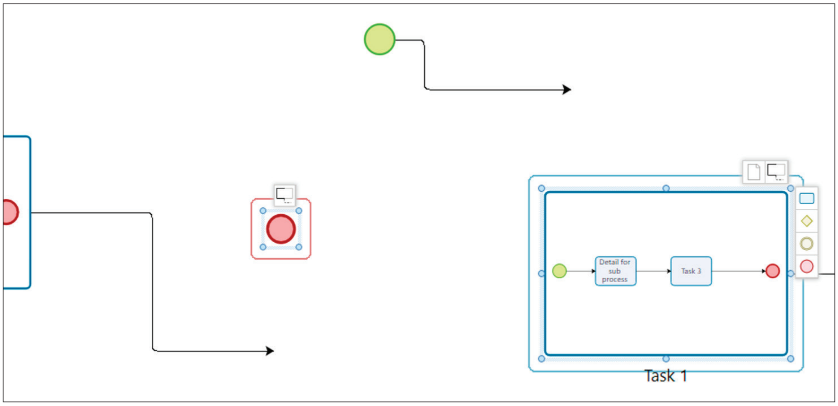

Figure 1: Sequence flow detachment observed when repositioning elements

These findings suggest that the Bizagi Modeller is generally usable within a tertiary context for students who receive adequate learning resources. However, its efficiency and ease-of-use limitations may present barriers to less experienced users. A summary of these findings is found in Table 2.

Table 2: Summary of experimentation observations

Framework	Observations
Ease	Mixed. Help resources aid learning. Interface appears cluttered. Several functions are difficult to locate or are unintuitive.
Efficiency	Moderate. Shortcuts enhance speed. Validation prompts and manual adjustments reduce workflow fluency.
Satisfaction	Generally positive. Task completion is achievable and rewarding. Minor frustrations detract from overall experience.

This study's stakeholders include lecturers responsible for teaching and assessment, and undergraduate students. Minimum entry requirements articulated by lecturers include BPMN 2.0 support, availability of a no-cost version, and rendering of high-quality images for document use. Preferred but non-mandatory requirements include participative modelling with a co-modeler and cloud-based access without operating system installation. A *fee-to-use* condition serves as an exclusion for possible tools in a tertiary education setting.

1.2.3 Problem statement

A comparative study on feature offerings and non-functional requirements affecting usability of free-to-use process modelling tools does not exist. Hence lecturers have to experiment with multiple process modelling tools prior to selecting the most suitable tool for their teaching context.

1.3 Research questions and structure

The study focuses on the explorative phase of a research study that includes the following discovery research questions:

DQ1: What are the problems experienced at an existing tertiary education enterprise regarding evaluation of an existing process modelling tool?

DQ2: What are the main concepts associated with process modelling, software tooling, and tool usability in a tertiary education setting?

DQ3: Does the presence of the problem instance feature as a *class of problems* in existing literature?

DQ4: What software selection solutions exist that address the *class of problems*, including existence of systematic literature reviews that compare free-to-use process modelling tools in a tertiary education setting, evidence of experimentation with software selection business process modelling tools in tertiary settings, and evidence of usability issues with business process modelling tools in other enterprises?

DQ5: What are the existing tools that comply with the free-to-use requirement of the tertiary education enterprise?

DQ6: What are the requirements of a solution that needs to be developed to address the *class of problems*?

The investigation addresses a documented gap concerning the comparative study of feature offerings and usability of free-to-use process modelling tools. Bizagi Modeller 4.2 is used as the current tool within a department at a tertiary education enterprise. Observed usability problems initiated a search for an alternative that better aligns with the needs of students and lecturers in a tertiary setting. This article uses a multivocal literature review, which is a form of Systematic Literature Review (SLR) which includes grey literature (for example, blog posts and white papers) in addition to published (formal) literature [6], to address the discovery questions.

The article is structured as follows. Section 1 provides an introduction to the problem context, answering DQ1. Section 2 provides a research protocol for a multivocal literature review, linked to discovery questions DQ2 to DQ6. Section 3 reports on the extracted themes, validates the class of problems, and consolidates selection requirements. Section 4 discusses the requirements from the themes present, explains their importance, and maps them to usability areas that are problematic, according to literature. Lastly, section 5 concludes and recommends requirements for tool selection, showing how they resolve problems and discovery questions.

2 LITERATURE REVIEW PROTOCOL

This section defines the protocol for a literature review to answer discovery questions DQ2 to DQ6. The review follows the eight-step traditional systematic literature review approach described by Okoli and Schabram [7]. New knowledge areas are additionally surveyed through a grey literature review conducted in line with guidelines by Garousi et al. [6]. The standard protocol structure for systematic reviews in software engineering is applied. In line with Okoli and Schabram [7], the review is arranged into the multi-step procedure, and the subsections reflect those steps, referenced as variation points at the relevant stages.

2.1 Keywords and digital repositories

Discovery question DQ4 informs keyword construction. Sub questions under DQ4 guide two complementary search strings. *The first string* combines terms for systematic reviews and mappings with terms for process modelling tools and software, comparison and decision making, higher education settings, and free-to-use or open-access licensing. *The second string* combines terms for usability and user experience, process modelling and BPMN, software selection and evaluation, free-to-use availability, comparison and decision procedures, and tertiary education. In these strings similar and closely related expressions for each theme are joined with the Boolean operator "OR", and the theme sets are joined with the Boolean operator "AND" to balance retrieval and precision while maintaining relevance to the study focus. The strict Boolean intersections increase precision but can lower results where licensing or education terms are absent, and restricted coverage may omit studies using alternative terminology.

Concepts related to usability in tertiary education (DQ2) were extracted from studies returned by both search strings. The initial academic search indicated limited evidence on process-modelling tool features. Therefore, a grey-literature review (GLR) was conducted to bridge these gaps by extracting from non-academic sources. The grey literature searches address DQ5 by focusing on software that satisfies requirements defined by the TEE in section 1.2.2.

Primary academic sources included SpringerLink, Scopus, and IEEE Xplore for comprehensive, high-quality coverage and authoritative peer-reviewed venues, combined with snowballing. Restriction to these databases provides reliable coverage of software engineering and information systems but may omit studies elsewhere that use alternative terminology, where backward and forward snowballing mitigated this constraint. Grey literature used a general web search engine to discover process modelling tools and supporting materials.

2.2 Snowballing procedure

Search efficiency is improved by combining database search with backward snowballing, followed by forward snowballing from the resultant set until saturation, as recommended by Wohlin et al. [8]. Backward snowballing identifies additional studies from reference lists of studies retrieved from Scopus and IEEE Xplore, where forward snowballing then identifies studies that cite the selected set. The snowballing procedure followed is seen in Figure 2.

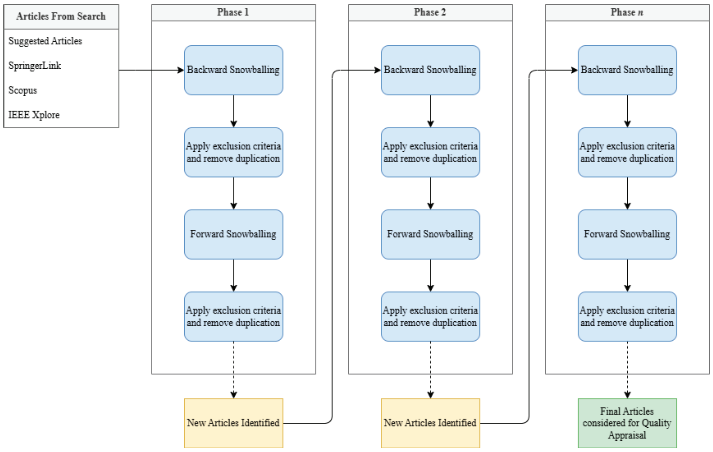

Figure 2: Snowballing procedure followed

2.3 Practical screening

Inclusion and exclusion criteria follow the guidelines provided by Okoli [9], with adaptation for the present topic. Titles and abstracts are screened first. Studies meeting exclusion criteria are removed with practical reasons recorded. The inclusion and exclusion criteria are included in Table 3.

Table 3: Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclusion
Content	Articles that emphasise or compare free-to-use process modelling tools. Articles that address usability needs of students and lecturers for process modelling tools. Any other studies relevant to the discovery questions.	Studies that predominantly discuss commercial tools unless a significant comparison or reference to free alternatives is present. Studies that focus on a single stakeholder group only or do not discuss usability. Studies that are not relevant to the topic.
Setting	Studies that discuss or evaluate software selection processes for business process modelling tools within tertiary education, with possible relaxation if the search proves too restrictive.	Studies focused on primary or secondary education.
Publication type	Peer-reviewed journals, conference papers, reputable books or book chapters.	Unpublished works, non-peer-reviewed sources, or unreliable publishers, with the exception that grey literature is considered *when identifying tools*.
Time frame	Studies published after public release of the BPMN specification in February 2006.	Studies outside the defined time frame.
Language and access	English language studies with full text availability.	Non-English studies or studies without full text access.

2.4 Quality appraisal

Peer-reviewed literature. Quality screening questions are adapted from the checklist by Kitchenham and Charters [10] for qualitative studies based on text or argumentation. The adaptation alters the questions to allow for a qualitative approach to answering the checklist by using the words, "to what extent" instead of "how", including the following questions in Table 4.

Table 4: Quality appraisal questions for peer-reviewed literature

No.	Updated Appraisal Questions
1	To what extent is the level of credibility of the findings?
1.1	To what extent are the findings important within the context of the study?
2	To what extent has knowledge or understanding been extended by the research?
3	To what extent does the evaluation address its original aims and purpose?
4	To what extent is the scope for drawing wider inference explained?
5	To what extent is the basis of evaluative appraisal made clear?
6	To what extent is the research design defensible?
7	To what extent are the sample design and target selection of cases/documents well defined?
8	To what extent are the eventual sample composition and coverage described?
9	To what extent was data collection carried out rigorously and as intended?
10	To what extent has the approach to, and formulation of, analysis been clearly conveyed?
11	To what extent are the contexts and data sources retained and accurately portrayed?
12	To what extent has diversity of perspective and context been explored?
13	To what extent has detail, depth, and complexity (richness) of the data been conveyed?
14	To what extent are links between data, interpretation, and conclusions made explicit and traceable?
15	To what extent is the reporting clear and coherent?
16	To what extent are the assumptions, theoretical perspectives, and values shaping the evaluation made explicit?
17	To what extent is attention to ethical issues evidenced?
18	To what extent has the research process been adequately documented?

Grey literature. Assessment follows criteria adapted from Garousi et al. [6], that is, validating the authority of the producer, methodology, objectivity, date, novelty, impact, and outlet control.

2.5 Data extraction

From included academic studies, the following items were extracted using observations in section 1.2.2 and the usability dimensions defined by ISO 9241 11:

i. General details: author (year) and method type (Conceptual / Review / Empirical).
ii. Usability definition as stated, including named themes aligned to effectiveness, efficiency, satisfaction, learnability, and context of use.
iii. Concept evidence mapped to code families: Process modelling, software tooling, usability in tertiary context, teaching assessment, and barriers and enablers.
iv. Tertiary context: Stakeholder group and any module or assessment context.
v. Modelling practice: Purposes before digitisation and after implementation, and how different modelling approaches relate to each other (for example, BPMN and DEMO).
vi. Barriers and enablers: Interface density, BPMN element discoverability, alignment/snap grid behaviour, auto-connection behaviour, validation prompts on save, help resources, export quality, collaboration support, spell checking, label layout, and learnability notes.
vii. Concept presence flags (presence per concept) to help with analysis and graphing across studies.
viii. Problem statements on the selection or use of free-to-use process-modelling tools in tertiary education, or usability issues reported in enterprises or education.
ix. Consequences linked to the problem: Examples include reduced task completion, increased effort, reduced satisfaction, diminished teaching effectiveness, and impaired assessment clarity.
x. Proposed solutions, with the following examples: Alternative tool adoption, configuration/workflow adjustments, training/guidance, and documented evaluation and comparison practices.
xi. Indicator for problem-to-solution linkage where both appear in the study narrative.

From grey literature, candidate business process modelling tools, and all attributes necessary to address discovery questions in synthesis, were extracted.

2.6 Application of the protocol

2.6.1 Peer-reviewed literature

This section provides more detail on the execution of the protocol to validate that a class of problems exists and to extract existing solution areas.

Searching for literature: An initial broad search on SpringerLink, Scopus, and IEEE Xplore applied no filters to find existing Systematic Literature Reviews (SLRs) comparing business process modelling tools across domains: SpringerLink = 17 results; Scopus = 118 results; IEEE Xplore = 92 results. The search was then refined using the protocol search strategy to target SLRs that compare free-to-use BPM tools in a tertiary education setting. The outcomes per database are as shown:

- **SpringerLink:** Five results after refinement, but none were kept after exclusion criteria. One candidate SLR from the loose search remained relevant.
- **Scopus:** Seven results were displayed but none were relevant. The scope was widened to SLRs on BPM tools outside a tertiary education setting; four SLRs were retained after relevance screening.
- **IEEE Xplore:** Four results were displayed with only one being relevant. The scope was then widened and three additional relevant SLRs were identified, one already captured via another database.

Final SLR inclusions after strategy application and exclusion criteria were as follows: SpringerLink = 1; Scopus = 4; IEEE Xplore = 3. The total SLRs included = 8.

This showed that the database search confirmed the absence of SLRs that specifically compare free-to-use process modelling tools within a tertiary education setting. However, broader SLRs offered useful comparative methods, evaluation frameworks, and tool-focused findings for synthesis. The search was then extended with the second protocol string to capture studies on process modelling, software tooling, and usability. The tertiary education criterion was relaxed to ensure adequate coverage while maintaining alignment with study objectives.

Practical screening: Titles and abstracts retrieved from SpringerLink, Scopus, and IEEE Xplore were screened against protocol inclusion and exclusion criteria. Restricting the search to free-to-use tools within a tertiary education setting proved too narrow and therefore constraints were relaxed as specified in the protocol. After applying the protocol search strategy, 649 articles were found across the three databases. Titles, abstracts, and full texts were then assessed for relevance as specified. This can be seen in Table 5.

Table 5: Practical screening of database search

Searching steps	SpringerLink	Scopus	IEEE Xplore
1. Loosely use the search string without many restrictions.	N = 3832	N = 1098	N = 391
2. Apply search strategy according to the protocol for keywords.	N = 431 Education and free-to-use restraints included	N = 183	N = 35
3. Apply exclusion / inclusion criteria	N = 207	N = 83	N = 20
4. Scan the titles manually for relevance.	N = 10	N = 16	N = 12 Low strictness applied
5. Scan the abstracts manually for relevance.	N = 5	N = 10	N = 4

From database searching, an initial set of 19 articles were retained (SpringerLink = 5; Scopus = 10; IEEE Xplore = 4). Three additional articles recommended by the lecturer were added for snowballing.

Snowballing: Backward and forward snowballing proceeded in two phases with predefined exclusion criteria applied at each stage. Phase 1 yielded 20 additional articles and Phase 2 yielded seven additional articles. A declining title and abstract relevance in Phase 2 indicated saturation, so snowballing concluded. As a result of this process, the total studies considered for the study was 50.

Quality appraisal: Quality appraisal followed the checklist as specified in the protocol. Each study received a score per item using 1 (fully met), 0.5 (partially met), or 0 (not met). Item scores were then summed, divided by the maximum possible, and expressed as a percentage. Inclusion required more than 60 percent, and applying this threshold then excluded five studies, leaving 45 studies for synthesis.

2.6.2 *Identifying existing tooling in grey literature*

Searching for literature: The search started by finding topics which provided considerations for identifying and selecting existing business process modelling tools. These discussions, summarised in Table 6, helped identify potential modelling tools that are considered at other stages.

Table 6: Knowledge areas relating to the selection of business process modelling tools

No.	Literature Type	Author	Title
1	Blog	Biskic [11]	How To Choose The Right BPM Tool with ADONIS
2	Blog	Mordy [12]	9 Best Free and Open Source Business Process Management Software
3	Blog	Jepma [13]	12 of the Top-Rated Free and Open-Source BPM Software Solutions
4	Blog	Zbigniew [14]	Free BPMN modelling tools – 2020 edition
5	Web Page	Wikipedia [15]	Comparison of Business Process Model and Notation modeling tools
6	Web Page	G2.com [16]	Business Software and Service Reviews

Practical screening: No sources were excluded for the grey literature review using the inclusion/exclusion criteria.

Quality appraisal: The appraisal technique is applied to the grey literature sources from one to six in Table 6. The scores from the appraisal questions equal a total of 20, where a threshold of 10 is used for this study, which means that the sources may be considered relevant if they conform to at least half of the questions from the checklist. All the sources conformed to at least half of the appraisal questions, and, therefore, none were excluded from the review.

2.7 Data synthesis plan

Extraction of main concepts (answers DQ2). Concepts related to process modelling, software tooling, and usability in tertiary education are derived through qualitative coding. A bubble plot visualises the frequency of concepts across studies.

Validation of a class of problems (answers DQ3 and DQ4). Thematic analysis as described by Guest et al. [17], is applied to studies that describe problem instances and proposed solutions. Evidence is assembled regarding the presence of a class of problems concerning the selection or use of free-to-use process modelling tools in tertiary education, and regarding usability challenges reported in other enterprises.

Identification of existing solution areas and tools (answers DQ5 and DQ6). Tools identified in the grey literature are analysed using feature-based comparison aligned with the minimum requirements defined in section 1.2.2. Feature importance is weighted by relevance to the TEE and supporting evidence in the literature.

3 PROBLEM CONTEXT RESULTS

The results provided here represent the findings from peer-reviewed and grey literature, according to the predefined protocol. Using the defined extraction items, main concepts are extracted and tallied, classes of problems are validated and existing tools with requirement alignment for tertiary education are identified. It should be noted that screening and extraction were performed by a single researcher using a fixed codebook and documented criteria. No intercoder agreement was calculated; therefore, a risk of selection and coding bias remains. On the other hand, synonym expansion, documented inclusion and exclusion criteria, and backward and forward snowballing improved recall and transparency. Findings should be interpreted as evidence of presence rather than complete coverage, with residual selection and coding bias acknowledged.

3.1 Peer-Reviewed Literature

3.1.1 Main concepts

Concepts related to process modelling, software tooling, and usability in tertiary education were derived through qualitative coding extractions from the studies, where a bubble plot of these concepts over time can be seen in Figure 3.

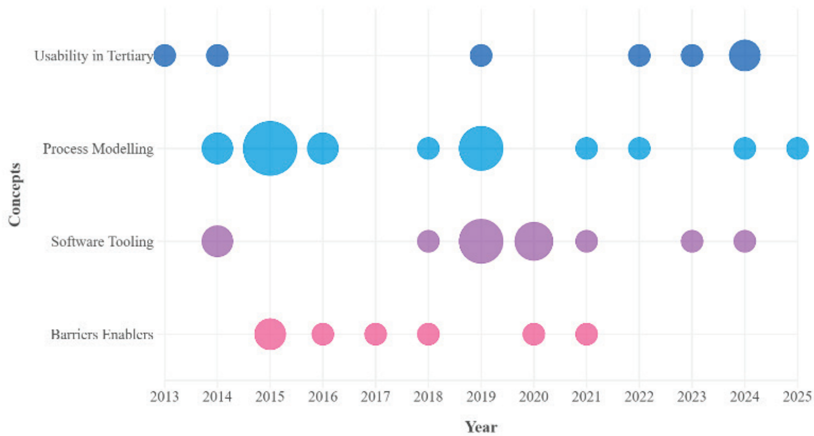

Figure 3: Rise of concepts over time

The extractions were then grouped under a common set of non-functional themes: Effectiveness, Efficiency, Satisfaction, Learnability, and Context of use. Additional items were recorded when present in the literature (such as Operability, Help resources, Collaboration support).

Dominant co-occurrences among themes

The most frequent pairs are Effectiveness/Efficiency and Efficiency/Satisfaction (each present in 20 studies). The most frequent triple is Effectiveness / Efficiency / Satisfaction (present in 18 studies). This pattern links outcome (Effectiveness) and experience (Satisfaction) with the effort and time it required (Efficiency), indicating that authors tend to link outcome and experience with the effort it required to get to that point.

Theme coverage at study level

Across the 45 studies, 22 have more than three themes, 23 have more than two themes, and five have exactly one theme each. This signals an integrative approach in which several usability-related themes are evaluated together within the same study, not treated as stand-alone attributes.

Presence of themes

To compare the relative salience of usability dimensions over time, themes were analysed individually and then summarised at study level. Efficiency appears in 25 studies, Effectiveness and Satisfaction in 20 each, Learnability in 14, and Context of use in 11. Additional themes appear less frequently: Operability (5), Help resources (2), and Collaboration support (1). These counts are presence tallies only and do not imply weighting beyond presence. A bubble plot was created with Year on the x-axis, the grouped themes on the y-axis, and bubble size equal to the number of studies that include the theme in that year. This plot is seen in Figure 4.

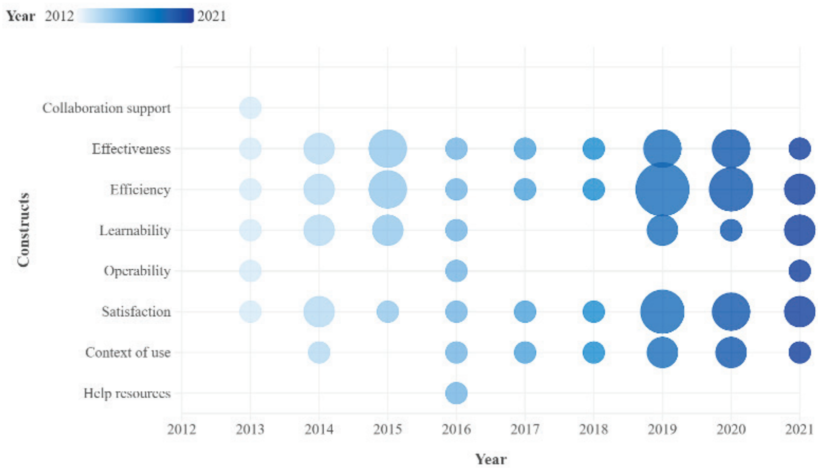

Figure 4: Rise of themes over time

It is seen that Efficiency is the most common theme overall (included in 25 studies), first appearing in 2013 and peaking in 2019. Effectiveness (included in 20 studies) and Satisfaction (included in 20 studies) are equally important, each first appearing in 2013, peaking in 2019. Learnability (included in 14 studies) first appeared in 2013, with a peak in 2014. Lastly, Context of use (Included in 11 studies) has been present since 2013, with a peak in 2019.

3.1.2 Validating a class of problems

Across 45 included studies, 16 explicitly paired a problem statement with a proposed solution, while 29 did not. This confirmed that some studies both described a problem instance and proposed solution within the same study. Problem statements were then mapped to categories based on the experimentation categories defined in section 1.2.2 (Ease of use, Efficiency, Satisfaction). A predefined list of keywords was developed for each category and used to analyse the problem statements, allowing studies to be assigned to one or more categories, as shown in Table 7.

Table 7: Findings about problem categories

Tooling Problem Categories	Findings
Operability and Manipulation	The most frequent category, which included difficulty with selection or movement of elements, disconnection of sequence flow during move operations, and unintuitive deletion or collapsing of sub-processes.
Workflow Interruptions and Validation	A frequent category, which included validation prompts on save and error message interruptions that broke the modelling flow.
Layout and Alignment	A frequent category, which included inconsistent snap-to-grid and alignment issues, label placement, and swimlane alignment concerns.
Learnability and Discoverability	A recurring category, which included difficulty discovering BPMN elements or their types, first-time use barriers, and reliance on tooltips or tutorials.
Interface Density and Clarity	A recurring category, which included dense or cluttered UI that hindered quick orientation.
Export and Documentation Quality	This was present but less frequent and concerned image quality for in-document use.
Collaboration and Co-modelling	This was present but less frequent and included lack of real-time co-modelling support.
Stability and Save Errors	This was present and referenced save errors or unstable behaviour.
Spell checking and Text Handling	This was present and referenced missing spell-check and label overlap.
Access and Authentication	Appeared occasionally and referenced login or connectivity prompts.
Assessment and Understandability	Appeared occasionally and referred to clarity and readability of models for assessment.

Consequences and proposed solutions

Using the same categories, it is evident that consequences most often accompany Workflow Interruptions and Validation, Layout and Alignment, and Operability and Manipulation, typically describing increased modelling time, reduced task completion, and reduced satisfaction.

Furthermore, proposed solutions most frequently cluster under Operability and Manipulation and Workflow Interruptions and Validation, including concrete workflow adjustments and evaluation practices, with a smaller group referencing Learnability and Discoverability by mentioning training or guidance.

3.2 Grey literature

From the grey literature sources, candidate business process modelling tools were shortlisted. The set included the current tooling in the TEE, Bizagi (desktop version), and an initial list for synthesis: Activiti, ADONIS Community Edition, ARIS Basic, BPMN Studio, BPMN.io (from Camunda), Cawemo (from Camunda), Camunda, HEFLO, Lucidchart, SAP Signavio Process Manager, Visio, and Draw.io.

Each tool was analysed against feature offerings aligned to the entry requirements in section 1.2.2, namely BPMN 2.0 support, availability at no cost, and export quality suitable for document inclusion, with preferred but non-mandatory attributes, co-modelling capability and cloud access without installation. Multi-Criteria Decision Analysis (MCDA) provided a ranking procedure for the tools. A one-point rating scale was applied to each feature, where 0 denotes no support, 0.5 denotes partial support, and 1 denotes full support. Tools were then scored feature by feature where the feature weights were assigned according to the importance defined by the TEE in focus. The resulting ratings on the existing tooling found can be seen in Table 8.

Table 8: Business process modelling tools rating

		Features			*Nice-to-haves*	
Weighting		0.3	0.3	0.2	0.15	0.05
Criteria		BPMN 2.0	Free-to-use	High quality image rendering	Participative modelling with a co-modeler	Cloud-based
1	Bizagi (Desktop Version)	1	0.5	1	0.5	0
2	Activiti	1	1	1	0.5	1
3	ADONIS: Community Edition	1	1	0.5	1	1
4	ARIS Basic	1	0.5	0.5	0.5	1
5	BPMN Studio	1	1	0.5	0.5	0.5
6	BPMN.io	1	0.5	1	0.5	0.5
7	Cawemo	1	0.5	1	1	1
8	Camunda	1	1	1	1	1
9	HEFLO	1	1	1	1	0.5
10	Lucidchart	1	0.5	1	0.5	1
11	SAP Signavio Process Manager	1	1	1	1	1
12	Draw.io	1	1	1	1	1
13	Visio	1	0	1	0.5	1

The ratings were next multiplied by the weight criterion of the features. These were then summed across all features, and a performance rating derived by dividing the sum by a hypothetical perfect tool. The resulting performance ratings, seen in Table 9, indicate the likelihood of the tools having the necessary features needed by the TEE.

Table 9: Performance scores of business process modelling tools

		Features			*Nice-to-haves*		
Weighting		0.3	0.3	0.2	0.15	0.05	
Criteria		BPMN 2.0	Free-to-use	High quality image rendering	Participative modelling with a co-modeler	Cloud-based	Performance Score
1	Bizagi (Desktop Version)	0.3	0.15	0.2	0.075	0	0.73
2	Activiti	0.3	0.3	0.2	0.075	0.05	0.93
3	ADONIS: Community Edition	0.3	0.3	0.1	0.15	0.05	0.90
4	ARIS Basic	0.3	0.15	0.1	0.075	0.05	0.68
5	BPMN Studio	0.3	0.3	0.1	0.075	0.025	0.80
6	BPMN.io	0.3	0.15	0.2	0.075	0.025	0.75
7	Cawemo	0.3	0.15	0.2	0.15	0.05	0.85
8	Camunda	0.3	0.3	0.2	0.15	0.05	1.00
9	HEFLO	0.3	0.3	0.2	0.15	0.025	0.98
10	Lucidchart	0.3	0.15	0.2	0.075	0.05	0.78
11	SAP Signavio Process Manager	0.3	0.3	0.2	0.15	0.05	1.00
12	Draw.io	0.3	0.3	0.2	0.15	0.05	1.00
13	Visio	0.3	0	0.2	0.075	0.05	0.63

4 REQUIREMENTS EXTRACTION RESULTS

This section elaborates on the themes that were extracted from the MLR, in answering DQ4 and DQ5.

4.1 Non-functional requirements for tooling

Efficiency: Reduce effort and time to complete standard modelling tasks in the tertiary context where evidence for Efficiency as a recurring concern appears across multiple studies [5], [18] - [21]. Requirements implied by this theme include minimisation of manual operations during element placement and connection, provision of reliable shortcuts, and removal of avoidable interruptions during save or validation operations. The theme, therefore, supports a requirement that typical undergraduate modelling tasks can be completed with minimal actions and without repetitious confirmation prompts or unstable behaviour.

Effectiveness: Support accurate and complete task attainment in accordance with prescribed modelling outcomes where evidence for Effectiveness is frequent [5], [19] - [21]. Requirements implied by this theme include clarity of element functions, dependable validation feedback that guides correction rather than interrupts flow, and coverage of the notation needed to achieve the intended exercise outcomes. The theme, therefore, supports a requirement that the tool afford correct use of notation elements with feedback on model completeness. This maps to Operability and Manipulation, and Assessment and Understandability, since ambiguous controls and fragile connections undermine model correctness and degrade grading clarity.

Satisfaction: Sustain a positive perceived experience during and after modelling tasks where evidence is present across the extraction [5], [18], [20] - [22]. Requirements implied by this theme include pleasant visual rendering of diagrams, smoothness of interaction, and absence of friction during routine save and export activities. The theme, therefore, supports a requirement that user experience quality not deteriorate under common classroom workloads. This targets Interface density and Clarity, and Export and Documentation quality, because visual clutter, label collisions, or low-resolution exports lower readability and perceived quality.

Learnability: Reduce initial time to proficiency for novice modellers and facilitate self-guided improvement [5], [20], [22] - [29]. Requirements implied by this theme include recognisable icons, informative tooltips, discoverable palettes, and in-product help resources that align with classroom tasks. The theme, therefore, supports a requirement that onboarding aids be available within the interface rather than through external materials only. This maps to Learnability and Discoverability, and Operability and Manipulation, since weak discoverability raises error rates during basic placement and connection and delays progression to higher order modelling.

Context of use: Fit for tertiary settings in terms of access, licensing, and assessment workflows, with evidence shown in multiple studies [21], [22], [25], [27], [30] - [33]. Requirements implied by this theme include zero-cost access for students, low-friction authentication, and export formats suitable for inclusion in assignments. The theme, therefore, supports a requirement that the tool operate reliably within a common space such as a lab, has remote access conditions and that outputs integrate into the assessment without additional steps. This maps to Access and Authentication, Stability and Save errors, and Assessment and Understandability, because login friction, unstable saves, and incompatible exports create avoidable barriers to completion.

See Table 10 for a synthesis that maps each non-functional requirement to a tooling problem category and usability dimensions.

Table 10: Non-functional and other requirements mapped to problem categories and usability dimensions

Non-functional requirement	**Description**	**Tooling Problem Category**	**Usability dimensions**
Efficiency	Reduced actions and time for modelling, minimal interruptions during save and validation.	Workflow interruptions and validation, Layout and alignment	Efficiency
Effectiveness	Dependable notation coverage, corrective rather than blocking feedback, support for task completion.	Operability and manipulation, Assessment and understandability	Effectiveness
Satisfaction	Smooth interaction and clear visuals during editing, saving, and exporting.	Interface density and clarity, Export and documentation quality	Satisfaction
Learnability	Discoverable palettes, recognisable icons, informative tooltips, and in-product guidance aligned to undergraduate tasks.	Learnability and discoverability, Operability and manipulation	Learnability
Context of use	Free-to-use access, reliable operation in laboratories and remote settings, document ready exports for assessment.	Access and authentication, Stability and save errors, Assessment and understandability	Context of use
Operability	Reliable selection, movement, grouping, and reconnection of elements.	Operability and manipulation	Efficiency, Effectiveness
Layout and alignment quality	Consistent snap to grid, swimlane alignment, and readable label placement.	Layout and alignment	Efficiency, Satisfaction
Low interruption workflow	Avoidance of repetitive confirmations and disruptive prompts.	Workflow interruptions and validation	Efficiency, Satisfaction
Stability and reliability	Protection from crashes, freezes, and save errors under classroom loads.	Stability and save errors	Satisfaction, Context of use

Non-functional requirement	Description	Tooling Problem Category	Usability dimensions
Interface clarity	Low visual density for rapid novice modeler orientation.	Interface density and clarity	Learnability, Satisfaction
Text handling	Clear labels, avoiding label overlapping, and including spell checking.	Text handling, Assessment and understandability	Satisfaction
Access and authentication	Minimal login friction and reliable connectivity.	Access and authentication	Context of use

4.2 Functional or other requirements for tooling

Tooling requirements implied by the themes include reliable alignment and placement through snap to grid and distribution to reduce manual layout effort and improve assessment readability; connection assistance through stable auto connect and low effort reconnection to maintain task flow; palette search and filtering to accelerate element discovery; integrated help and example templates aligned to undergraduate exercises; export to document-ready formats with adequate resolution; non-blocking validation to surface issues without halting progress; stable save and version behaviour to protect iterative work; low friction authentication for laboratory and remote access; and, optional collaboration for co-modelling and feedback where infrastructure exists. Each capability maps to the corresponding tooling problem category listed in Table 11.

Table 11: Functional and other requirements with problem categories

Functional or other requirement	Reason	Tooling Problem Category
BPMN 2.0	Entry condition for correctness and assessment alignment	Assessment and understandability, Operability and manipulation
Free-to-use	Availability for educational use	Access and authentication, Context of use
Export controls	Correct size and resolution for assignment submission	Export and documentation quality
Alignment and placement tools	Snap to grid, lane alignment, distribution to reduce layout effort	Layout and alignment
Element connection assistance	Stable auto connection and easy reconnection of elements	Operability and manipulation
Palette search and filtering	Quick element discovery and selection	Learnability and discoverability
Integrated help and templates	Guidance aligned to course tasks for first time users	Learnability and discoverability
Optional collaboration capability	Effective lecturer and student sessions for demonstration and feedback	Collaboration and co-modelling
Non-blocking validation	Issues flagged without halting progress	Workflow interruptions and validation
Stable save and version behaviour	Reliable saving during iterative work	Stability and save errors
Low friction authentication	Suitability for laboratories and remote access by students	Access and authentication

4.3 Alignment of study evidence with the experimentation-derived categories

Operability and Manipulation: Multiple studies report difficulties with selection and movement of elements, disconnection of sequence flow during editing, and unintuitive deletion or collapsing of sub-processes [19], [24], [34] - [37]. These studies directly support the experimental observation that operability during modelling is a recurrent source of friction.

Workflow interruptions and Validation: Two studies reference validation prompts and error messages that interrupt modelling flow, aligning with the experimentation finding that save time prompts and confirmations reduce fluency [5], [21].

Layout and Alignment: Some studies include inconsistent snap to grid, misalignment of elements and swimlanes, and label placement [5], [24], [38], [39]. These statements confirm the link between layout mechanics and modelling efficiency as identified in experimentation.

Interface density and Clarity: One study notes that dense or visually cluttered interfaces hinder rapid orientation [34]. Although less frequent than operability or layout items, this category confirms that visual burden contributes to perceived complexity in classroom use.

Stability and save errors: Some problem statements mention unstable behaviour, save errors, and crashes [26], [36], [40] - [43]. This category validates an experimental observation that reliability during saving or editing affects task progression and perceived experience.

Collaboration and Co-modelling: Three studies identify a lack of real-time co-modelling support or limited collaboration features [5], [42], [44]. This category confirms the role of collaboration in teaching activities when modelling tasks require synchronous guidance or feedback.

Export and Documentation quality: One study indicates insufficient export quality for in-document use [5]. This validates the experimentation observation that export functions influence assessment readiness in tertiary workflows.

Spell checking and Text handling: A study also mentions missing spell checking and label overlap [24]. Statements such as these support the experimental observation that text handling affects readability and assessment clarity.

Access and Authentication: One study refers to login prompts and connectivity friction [43]. The presence of this category also complements the context of use emphasis in the results and indicates that access constraints can become barriers in student laboratory or remote settings.

Assessment and Understandability: Some studies refer to clarity and readability of models for assessment purposes and to incomplete assessment of model quality [27], [39], [41], [45] - [47]. This category confirms that tool behaviour and produced artefacts have assessment consequences in tertiary modules.

Convergence between experimentation and literature shows problem categories apply beyond a single instance and supports targeted improvements prioritising operability, layout, and validation workflows to achieve the largest gains in learning and assessment.

4.4 Existing tooling

Identification of existing solution areas and tools proceeded through a feature-based comparison aligned with the minimum requirements in section 1.2.2. Each tool received a rating per feature, and a weighted sum was normalised by a hypothetical perfect score. Sorting by this rating showed three tools at the top tier, namely Camunda, Draw.io, and SAP Signavio Process Manager, with Bizagi Modeller positioned below these alternatives. The result is a clear shortlist that can reduce the confirmed problem categories without custom development, shift training effort from coping with tool friction to reinforcing modelling outcomes, and streamline assessment through better export quality and, where available, collaboration and sharing.

5 RECOMMENDATIONS AND CONCLUSIONS

The study delivers a comparative synthesis of requirements that affect the usability of free-to-use process modelling tools in tertiary education. Evidence from the literature and experimentation aligns with recurring classes of problems, indicating that tooling problems also exist within the body of knowledge, that is,. Operability, Layout and Alignment, Workflow interruptions, Stability, Access, and Assessment clarity. This is because they recur across the review and experimentation and directly degrade efficiency, effectiveness, satisfaction, and assessment clarity in tertiary modelling tasks.

The discovery questions were answered, where the problem instance was validated through structured experimentation using officially prescribed learning materials. Minimum and preferred requirements suitable for tertiary education were derived with emphasis on usability (effectiveness, efficiency, and satisfaction, supported by learnability and context of use). The original problem statement regarding the absence of a comparative focus on feature offerings and non-functional requirements has therefore been addressed through a clear set of minimum requirements in Table 10 and Table 11. The body of knowledge shows limited comparative work on feature offerings and non-functional requirements for free-to-use process modelling tools, yet includes document recurring categories of tooling problems that align with the experimentation results. The review, therefore, validates the class of problems while addressing the comparative gap by deriving minimum requirements for selection and evaluation in tertiary education. The synthesis provides a sufficient basis for requirement-driven comparison and for targeted improvement of teaching workflows, and recommends three tools as a basis for future evaluation of process modelling tools. Future work will develop a decision-making artefact that enables software selection of an appropriate process modelling tool.

Method constraints related to database coverage, query design, and single-researcher screening are documented in the body of the document. Additional limitations include English-only and recent sources, some sources missing full texts, mixed study types, simple counts that can mislabel items, unclear tool versions in sources, MCDA weights reflecting researcher judgement with little stress testing, findings tied to tertiary settings, and an experiment with one tool and one task.

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7 APPENDIX A: SEARCH STRINGS

The following appendix contains the search strings that were used in accordance with the relevant Discovery Questions.

7.1 Developed search strings targeting DQ2 and DQ4

Table 12 below presents the original search strings defined by the discovery questions where the subsequent subsections report repository specific implementations of the strings.

Table 12: DQ2 and DQ4 search strings

Original (“systematic literature review" OR “SLR” OR "systematic review" OR "systematic mapping") AND (“process model* tool" OR "business process model* tool" OR "BPM tool" OR "business process model* software" OR "process model*software" OR "workflow model*tool") AND (“compar*” OR “decision” OR “decision-making” OR “decision analysis” OR “choosing” OR “choice” OR “selecting” OR “select” OR “top” OR “best” OR “feasibility” OR “candidate matrix” OR “candidate screening” OR “alternative matrix” OR “alternative screening” OR “pairwise comparison” OR “analytic hierarchy” OR "ranking" OR "evaluation") AND ("tertiary education" OR "higher education" OR "university" OR "post-secondary" OR "college") AND ("free-to-use" OR "open-source" OR "freeware" OR "open access" OR "non-commercial use")
Relaxed ("systematic review" OR "SLR" OR "literature review") AND ("process modeling" OR "BPM" OR "workflow modeling") AND ("comparison" OR "evaluation" OR "selection" OR "decision") AND ("education" OR "university")

7.1.1 SpringerLink

Original string

("systematic literature review" OR "SLR" OR "systematic review" OR "systematic mapping")

AND ("process modeling tool" OR "business process modeling tool" OR "BPM tool" OR "business process modeling software" OR "workflow modeling tool")

AND ("comparison" OR "decision" OR "decision making" OR "decision analysis" OR "choosing" OR "choice" OR "selecting" OR "selection" OR "top" OR "best" OR "feasibility" OR "candidate matrix" OR "candidate screening" OR "alternative matrix" OR "alternative screening" OR "pairwise comparison" OR "analytic hierarchy" OR "ranking" OR "evaluation")

AND ("tertiary education" OR "higher education" OR "university" OR "post-secondary" OR "college")

AND ("free to use" OR "open source" OR "freeware" OR "open access" OR "non commercial use")

Relaxed string

("systematic literature review" OR "SLR" OR "systematic review")

AND ("process modeling tool" OR "business process modeling tool" OR "BPMN tool" OR "process modeling software" OR "business process modeling software")

AND ("comparison" OR "tool selection" OR "tool evaluation" OR "feature comparison" OR "usability analysis")

7.1.2 *Scopus*

Original string

TITLE-ABS-KEY("systematic literature review" OR SLR OR "systematic review")

AND TITLE-ABS-KEY("process model*" OR "business process model*" OR BPMN OR "workflow model*")

AND TITLE-ABS-KEY(compar* OR "tool selection" OR "tool evaluation" OR "feature comparison" OR usability)

AND TITLE-ABS-KEY(educat* OR university OR college)

AND TITLE-ABS-KEY(free OR "open-source" OR freeware OR "open access")

Relaxed string

TITLE-ABS-KEY("systematic literature review" OR SLR OR "systematic review")

AND TITLE-ABS-KEY("process model*" OR "business process model*" OR BPMN)

AND TITLE-ABS-KEY(compar* OR "tool selection" OR "tool evaluation" OR "feature comparison" OR "usability")

7.1.3 *IEEE Xplore*

Original string

("systematic literature review" OR "systematic review" OR SLR)

AND (“process model*” OR “business process model*” OR BPM OR “workflow model*”)

AND (compar* OR evaluat* OR select* OR decision)

AND (educat* OR university OR college)

AND (“open-source” OR freeware OR “open access” OR free)

Relaxed string

(“systematic review” OR SLR OR “literature review”)

AND (“process model*” OR BPM OR “workflow model*”)

AND (compar* OR evaluat* OR select* OR decision)

AND (educat* OR university)

7.2 Developed search strings targeting DQ4 sub questions

Table 13 below presents the original search strings defined by the discovery questions where the subsequent subsections report repository specific implementations of the strings.

Table 13: DQ4 sub questions search string

Original ("usability" OR "user experience" OR "UX" OR "user interface" OR "learnability" OR "ease of use" OR "human-computer interaction") AND ("process model* tool" OR "business process model* tool" OR "BPM tool" OR "business process model* software" OR "process modelling" OR "process model*" OR "business process model*" OR "BPMN" OR "workflow model*") AND ("software selection" OR "tool selection" OR "software evaluation" OR "software tools" OR "modelling tools" OR "process modelling software" OR "BPM tools" OR "educational software") AND ("compar" OR "decision" OR "decision-making" OR "decision analysis" OR "choosing" OR "choice" OR "selecting" OR "select" OR "top" OR "best" OR "feasibility" OR "candidate matrix" OR "candidate screening" OR "alternative matrix" OR "alternative screening" OR "pairwise comparison" OR "analytic hierarchy") AND ("free-to-use" OR "open-source" OR "freeware") AND ("tertiary education" OR "higher education" OR "university" OR "post-secondary" OR "college")
Relaxed ("usability" OR "user experience") AND ("process modeling tools" OR "BPM") AND ("software evaluation") AND ("free" OR "open-source") AND ("comparison" OR "selection" OR "decision") AND ("education")

7.2.1 SpringerLink

Original string

("usability" OR "user experience" OR "UX" OR "user interface" OR "learnability" OR "ease of use" OR "human-computer interaction" OR HCI)

AND ("process model* tool" OR "business process model* tool" OR "process modeling software" OR "process modelling software" OR "workflow model*" OR "BPMN" OR "BPMN tool*" OR "BPM tool*" OR "business process model* software")

AND ("software selection" OR "tool selection" OR "software evaluation" OR "software tools" OR "modelling tools" OR compar* OR "decision" OR "decision-making" OR "decision analysis" OR "choosing" OR "choice" OR "selecting" OR "select" OR "feasibility" OR "candidate matrix" OR "candidate screening" OR "alternative matrix" OR "alternative screening" OR "pairwise comparison" OR "analytic hierarchy" OR AHP)

AND ("free-to-use" OR "open-source" OR "freeware")

AND ("tertiary education" OR "higher education" OR "university" OR "post-secondary" OR "college")

Relaxed string

("usability" OR "user experience" OR UX)

AND (BPMN OR "process model*" OR "workflow model*" OR "process modeling software" OR "BPM tool*")

AND (comparison OR "tool selection" OR "software evaluation")

7.2.2 Scopus

Original string

TITLE-ABS-KEY(("usability" OR "user experience" OR UX OR "user interface" OR learnability OR "ease of use" OR "human-computer interaction" OR HCI) AND ("process model* tool" OR "business process model* tool" OR "process model* software" OR "workflow model*" OR BPMN OR "BPMN tool*" OR "business process model* software" OR (BPM W/3 (tool* OR software OR model* OR notation)))

AND ("software selection" OR "tool selection" OR "software evaluation" OR "software tools" OR "modelling tools" OR compar* OR decision OR "decision-making" OR "decision analysis" OR choosing OR choice OR selecting OR select OR feasibility OR "candidate matrix" OR "candidate screening" OR "alternative matrix" OR "alternative screening" OR "pairwise comparison" OR "analytic hierarchy" OR AHP))

Relaxed string

TITLE-ABS-KEY(("usability" OR "user experience" OR UX OR "ease of use" OR learnability OR readability OR understandability OR "human-computer interaction" OR HCI OR "visual notation" OR "cognitive load")

AND ("process model*" OR "business process model*" OR "workflow model*" OR BPMN OR "process diagram*" OR "process map*")

AND (compar* OR evaluat* OR assessment OR "case study" OR "empirical study" OR benchmark* OR select* OR "decision*"))

7.2.3 IEEE Xplore

Original string

(("usability" OR "user experience" OR "UX" OR "user interface" OR learnability OR "ease of use" OR "human-computer interaction" OR HCI)

AND ("process model* tool" OR "business process model* tool" OR "process modeling software" OR "workflow model*" OR "BPMN" OR "BPMN tool*" OR ("BPM" NEAR/3 (tool* OR software OR model* OR notation)))

AND ("software selection" OR "tool selection" OR "software evaluation"

OR “software tools” OR “modelling tools” OR compar* OR decision OR “decision-making” OR “decision analysis” OR choosing OR choice OR selecting OR select OR feasibility OR “pairwise comparison” OR “analytic hierarchy” OR AHP))

Relaxed string

((usability OR “user experience” OR UX OR “ease of use” OR learnability OR readability OR understandability OR HCI OR “quality in use”)

AND (BPMN OR “process model*” OR “workflow model*” OR “business process model*” OR BPM OR “process diagram*” OR “process map*”)

AND (compar* OR evaluat* OR assessment OR benchmark* OR select* OR “decision*” OR “case study”))

COST SAVINGS USING LOAD CONSOLIDATION AND MULTI-STOP ROUTING

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ABSTRACT

The research investigates opportunities for cost reduction in a secondary distribution for a fourth-party logistics provider operating in East London, South Africa. The logistics provider uses a transport management system that effectively minimises procurement costs through reverse auctions but does not fully optimise multi-stop routing and load utilisation. Historical shipment, loading, and vehicle data were analysed to solve this gap and evaluate different load consolidation and routing approaches. Among these viable solutions were clustering, load consolidation using a linear programming model, and a multi-stop vehicle routing problem using Open Door Logistics Studio software. The final design incorporated a multi-stop consolidation, allowing deliveries to multiple destinations per route while accounting for vehicle capacity and cost constraints. The results showed significant improvements by reducing the total number of trucks used by more than 50%. These findings highlight the value of vehicle routing-based approaches for logistics providers in complex distribution environments and how they can be applied in similar logistics networks.

Keywords: 4PL, vehicle routing, logistics, multi-stop routing

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1 INTRODUCTION

Efficient logistics have become increasingly critical as customers demand faster and more reliable deliveries. Traditional in-house logistics functions are no longer sufficient to meet modern demand, prompting many companies to outsource their logistics to third-party logistics (3PL) providers. These firms typically own their own fleets and distribution networks, allowing their client companies to focus on their core activities while outsourcing any transportation tasks [1].

More recently, fourth-party logistics providers (4PLs) have emerged, focusing on strategic coordination and optimisation rather than asset ownership. 4PLs integrate multiple 3PLs and supply chains and support the optimisation of 3PLs' logistics. Many well-known international companies have adopted this model, allowing businesses to benefit from streamlined operations without the complexity of managing their assets directly [2].

Central to the operations of 4PLs is the Transport Management System (TMS), which integrates data from multiple sources to plan, optimise, and execute logistics operations. A TMS provides significantly improved visibility across networks and enables collaboration among supply chain partners [3].

This study focuses on a 4PL company headquartered in Johannesburg, South Africa. The company provides logistics strategy, 3PL procurement, routing and execution services. The company heavily relies on its TMS, which allows visibility of distance travelled, costs, weight, utilisation and trip details. The system integrates with 3PLs' Economic Resource Planning (ERP) systems. A key feature of the company's TMS is the use of a reverse auction system, where 3PLs competitively bid for shipments offered by shippers, ensuring that transport is secured at near-minimum base rates [4].

Despite these advantages provided by the TMS, the company continues to face cost-related challenges in the East London region. Most importantly, a large variation in types of customers is seen in this area. These customers range from large retailers who order full truckloads of 34-36 tons, to small spaza shops in remote areas, which typically order small shipments of less than 500kg at once.

This variability in shipment sizes results in an increased volume of empty space within trucks and necessitates the deployment of a greater number of trucks required to fulfil all shipments. Consequently, this escalates operational costs. The combination of these factors within the company's current circumstances indicates significant potential for finding hidden cost savings within the TMS.

The overall aim of this research therefore is to investigate any untapped cost savings by improving how the TMS manages load consolidation and route planning. To complete this, the following deliverables are required by the end of this research:

1. Conduct a root cause analysis on historical TMS data;
2. Identify various solution approaches to solve the root causes; and
3. Compare the proposed solution approaches against historical data to determine the best approach.

It should be noted that statistical analysis (significance, sensitivity or runtimes) falls outside the scope of this project.

2 LITERATURE REVIEW

A comprehensive literature review was conducted to explore potential strategies for enhancing the current state of the TMS. The objective of this literature review was to underscore the significance of evaluating multiple solution approaches from external sources. The investigation included various methodologies, principles, and engineering tools that could be employed to further refine the TMS and address the current challenges.

2.1 Load consolidation strategies

Load consolidation fundamentally involves the combination of multiple smaller shipments into single loads for dispatch in a singular vehicle. This approach optimises any unutilised capacity, while balancing quality, cost, and transport time requirements [5], [6].

Hall [7] identified three primary consolidation forms: inventory consolidation, vehicle consolidation, and terminal consolidation, each addressing different operational challenges. The most relevant of the three for this research, vehicle consolidation, involves the loading and unloading of items at various origin and destination locations along a vehicle's route. Mutlu et al. [8] further categorised vehicle consolidation into three policies:

1. Time-based policies (consolidating shipments within predetermined intervals),
2. Quantity-based policies (holding orders until a target load accumulates), and
3. Hybrid time-quantity policies (a combination of the previous two approaches).

However, the effectiveness of consolidation depends significantly on contextual factors. Wu [9] demonstrated that cargo consolidation proves especially viable when incoming container utilisation is low, or when unit vehicle costs are high. Hernández et al. [10] further demonstrated that carrier collaboration through load consolidation under dynamic capacity conditions can significantly reduce empty miles and improve overall network efficiency, particularly in less-than-truckload operations. When utilisation falls below a certain threshold, opportunities emerge to combine partial loads and reduce costs. However, consolidation may lead to delayed deliveries and additional costs if not properly balanced against the timing requirements [11].

Within the specific context of auctioning by use of TMSs or other methods, Mesa-Arango and Ukkusuri investigated combinatorial auctions within less-than-truckload operations [4]. This method of auction allows shippers to bid on segments of a truckload, as opposed to bidding on an entire truck. This method of consolidated bidding substantially outperformed non-consolidated approaches by increasing profits for both shippers and carriers while reducing the overall costs.

Within the solution approach of this research, load consolidation effectively corresponds with the existing load planning challenges faced by the company. Combinatorial auctions also align well with the existing TMS platform in its use of reverse auctions but fell outside the scope of this investigation.

2.2 Multi-stop consolidation

Multi-stop truckload optimisation, also termed milk run logistics due to its origins in the dairy industry, represents a flexible approach to delivery consolidation [12]. Unlike traditional milk run models with repeating routes, multi-stop truckload optimisation allows for dynamic addition of pickups, deliveries, and stops based on operational requirements.

Stenger et al. identified key variables impacting transportation cost and carrier acceptance rates, including, but not limited to distance, number of stops, lead time, stop-off charges, and more [13]. While additional charges may apply for multi-stop deliveries, overall costs remain lower than dispatching multiple vehicles for individual shipments, particularly when sophisticated routing algorithms account for practical operational constraints.

But despite the drawback of possible carrier rejection, multi-stop truckload optimisation offers multiple benefits, as documented [14]. These include a 20-37% reduction in transportation cost, a 10-35% improvement in vehicle loading rates, shortened travel distances, enhanced flexibility, and significant inventory reductions. Further case studies also continue to show these significant improvements. In this study, the implementation of multi-stop routing, in conjunction with load consolidation, improved the current system's performance significantly.

2.3 Vehicle Routing Problem applications

The Vehicle Routing Problem (VRP) represents one of the most studied topics in operational research, addressing the challenge of determining optimal delivery routes for vehicle fleets [15]. Recent comprehensive reviews have documented substantial evolution of VRP methodologies, with over 30 distinct VRP variants identified that extend the classical formulation to address increasingly complex real-world operational constraints [16].

More recent advances in VRP formulations incorporate multiple criteria, including vehicle capacity constraints, time restrictions, multiple depot considerations, and 2-dimensional space requirements, among others [17], [18]. These VRP formulations are significantly more advanced than their original counterparts, with new variants continuously being developed to incorporate additional criteria and constraints to better model real-world operations. Of special interest to this study is the advances to incorporate vehicle capacity restrictions in the capacitated VRP (CVRP),and the inclusion of multiple vehicle types with varying capacities and costs in the Vehicle Fleet Mix Problem (VFMP) [17].

For large-scale problems, clustering approaches provide a computationally efficient way of grouping delivery locations before optimising. Various clustering algorithms each offer different advantages: K-means/K-medians performs well for equally sized clusters, Sweep/Sweep-Nearest naturally account for any capacity constraints (within CVRPs) and hybrid methods such as the DBSCAN clustering based on density and K-means with demand balancing provide a combined benefit [19], [20].

3 METHODOLOGY

3.1 Research design

The research employs a mixed-method approach combining a root cause analysis with quantitative optimisation modelling. This methodology comprises three distinct phases: diagnostic analysis to identify inefficiencies, solution development comparing various solution approaches and further testing of the final selected solution approach with historical data.

3.2 Data collection and preparation

This study utilised two primary datasets provided by the company, covering a 13-month period from January 2024 to February 2025. The load-level dataset contained 23 000 entries representing overall truck performance, while the shipment-level dataset comprises over 46 000 entries documenting individual shipments sent during this period. After applying data filtering focused on the operations in East London, it reduced the loadings dataset to approximately 2 000 load entries, and approximately 2 200 shipment entries.

3.3 Root cause analysis framework

Root cause analysis employed three different techniques to identify the main problems:

1. **Data analysis:** The systematic examination and thorough exploration of the data to identify potential issues and comprehend the feasible and infeasible approaches within the data.
2. **Fishbone diagram:** Systematic categorisation of potential causes across multiple domains.
3. **Pareto analysis:** Quantification of the defect frequencies as identified by the fishbone diagram to prioritise improvement opportunities.

3.4 Optimisation model development

The solution approach integrates insights from the root cause analysis alongside potential solutions identified in the literature review to define the design requirements and determine feasible implementation options. It is important to note that direct implementation is not possible due to the lack of access to the TMS's source code. Instead, various suggested solution approaches were tested as proof-of-concepts to demonstrate which solution would deliver the best results within the company's specific context.

3.4.1 Scalability considerations

While the direct multi-stop VRP approach demonstrated superior optimisation results, it is important to note the trade-off between solution quality and computational scalability. The clustered VRP approach, though somewhat less optimal, offers greater advantages for larger-scale implementations. By decomposing the routing problem into smaller, more manageable subproblems, the clustering significantly reduces the computational complexity, making it more suitable for large datasets. Conversely, the direct multi-stop VRP faces increasing computational time as the problem size grows. Organisations aiming to scale this framework across multiple regions (or on a general larger scale) should consider this trade-off.

4 ROOT CAUSE ANALYSIS

The root cause analysis presented below encompasses all relevant factors that inform the final design solution. The investigation covered various aspects, including the types of trucks used, their utilisation rates, the quantity of each truck type used within the datasets, shipping and loading costs (considering distance, weight, and volume), distance travelled dependant on truck type, and delivery frequency during singular trips. For the sake of conciseness, this study focused exclusively on highlighting the potential problems identified.

4.1 Data analysis

4.1.1 Fleet composition & utilisation analysis

Figure 1 indicates smaller vehicles (3-ton, 16-ton, 24-ton flatdecks) demonstrate consistently poor utilisation, with each operating below 80% utilisation (otherwise known as load factor) on average, compared to bigger vehicles (34-ton -36-ton tautliners).

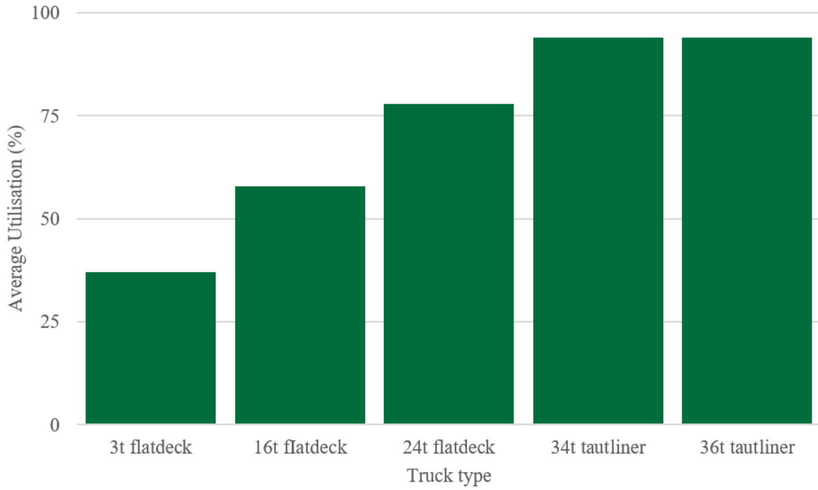

Figure 1: Average utilisation of each vehicle type

4.1.2 Delivery pattern analysis

The loadings dataset contained data on the number of shipments, number of deliveries, number of stops, and number of pickups during a particular trip. The analysis is shown in Figure 2. The investigation revealed a critical inefficiency: more than 85% of trucks involved single deliveries with one shipment per truck. This pattern indicated minimal to no exploitation of consolidation opportunities, with trucks consistently not being well utilised and returning empty after singular deliveries.

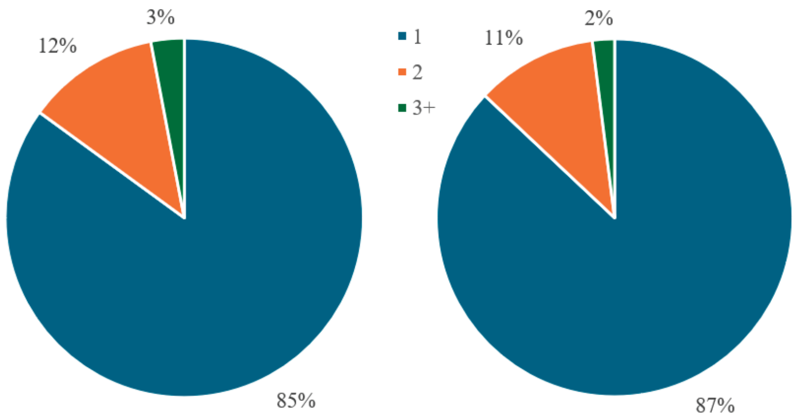

Figure 2a. Number of shipments per trip

Figure 2b. Number of deliveries per trip

Figure 2: Number of shipments (Fig 2.a) and deliveries (Fig 2.b) made during one truck trip

4.2 Fishbone diagram

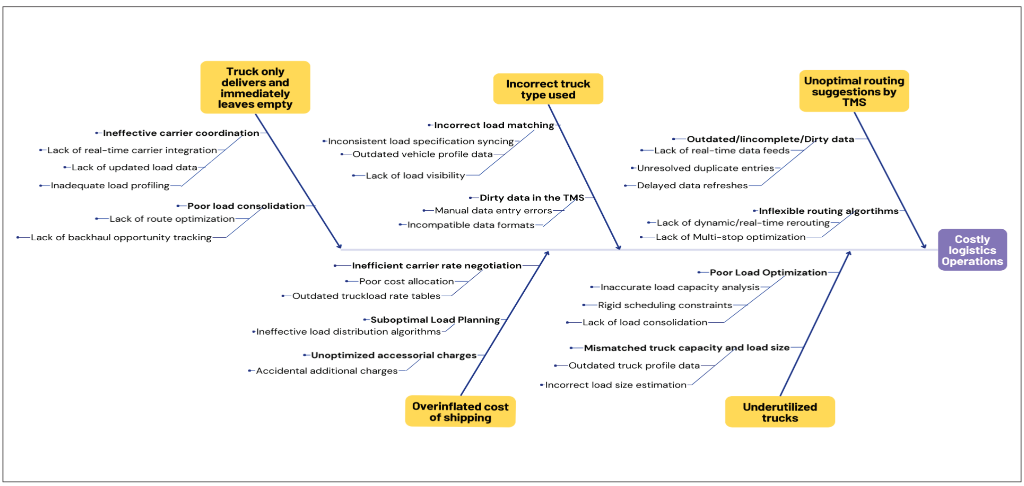

Figure 3: Fishbone diagram for the root cause analysis

Figure 3 presents a fishbone diagram illustrating five main areas that may contribute to costly logistics operations. Each area branches out to identify the underlying root causes of each of these issues. This tool was used to gain a comprehensive understanding of the problem, assess which root causes are addressable, which may be beyond control (within the scope of this research), and to verify whether historical data supports the existence of these root causes.

The historical data analysis, in conjunction with the fishbone diagram, revealed five key root causes that significantly impact the logistics efficiency:

1. **A lack of backhauling**
   The scarcity of backhaul trips – return journeys that carry cargo – leads to increased empty miles and higher operational costs;
2. **Mismatched truck capacity & load size**
   Inefficient pairing of truck sizes with shipment volume results in underutilised capacity, negatively affecting cost and performance;
3. **Ineffective load distribution algorithms**
   Current algorithms for allocating loads to trucks fail to optimise for cost and efficiency, causing suboptimal routing and resource use;
4. **Lack of multi-stop optimisation**
   The lack of route planning that consolidates multi-stops into a single trip diminishes delivery efficiency and increases travel time and expenses;
5. **Poor cost allocation**
   Poorly designed cost allocation practices obscure the true shipping expenses, leading to misinformed decisions and financial inefficiency.

4.3 Pareto Analysis

To effectively use a Pareto chart, the causes of defects were identified. The key issues were identified based on the fishbone diagram and data analysis. These are outlined below along with the criteria used to test their occurrence in the historical dataset:

1. **Lack of backhauling opportunity**
   A truck returning empty is flagged when the number of pick-ups equals zero.
2. **Low truck utilisation**
   Total utilisation per truck (load factor) is lower than the capacity of a vehicle with smaller capacity, indicating that a smaller truck could have been chosen with lower travelling costs to improve efficiency.
3. **Single shipments causing low utilisation**
   When a truck is less than 80% utilised, but only carries a single shipment, where shipments to the same delivery location could have been consolidated to improve efficiency.
4. **Single deliveries causing with low utilisation**
   When a truck is less than 80% utilised, but only carries items to a single delivery location, suggesting a missed opportunity to combining deliveries to improve efficiency.
5. **Cost-distance mismatch**
   A truck travelling a certain distance should incur costs within an expected range; deviations from this indicate possible inefficiencies or misallocations.

Figure 4 depicts the Pareto chart that was constructed from the available data. The figure highlights that 80% of the logistical issues stem from three main issues: low truck utilisation, single shipment with low utilisation, and single delivery with low utilisation. Therefore, the proposed solution should primarily focus on addressing these three problems.

Furthermore, the TMS did not record empty trips meaning the impact of the lack of backhauling could not be analysed effectively. Consequently, it was difficult to determine with certainty whether backhauling was actually taking place. However, the company indicated that carriers typically adjust pricing to offset empty return trips, effectively managing this concern in practice. As a result, backhauling was considered a lower priority that had zero number of defects and did not require further focus.

In summary, the root cause analysis suggested that the key problems to resolve were:

- Low utilisation of trucks, where vehicles with smaller load capacity were available,
- A single shipment occurred when truck utilisation was low and shipments to the same delivery point could have been combined, and
- A single delivery occurred when truck utilisation was low and multiple deliveries to locations in close proximity, for example, could have been combined.

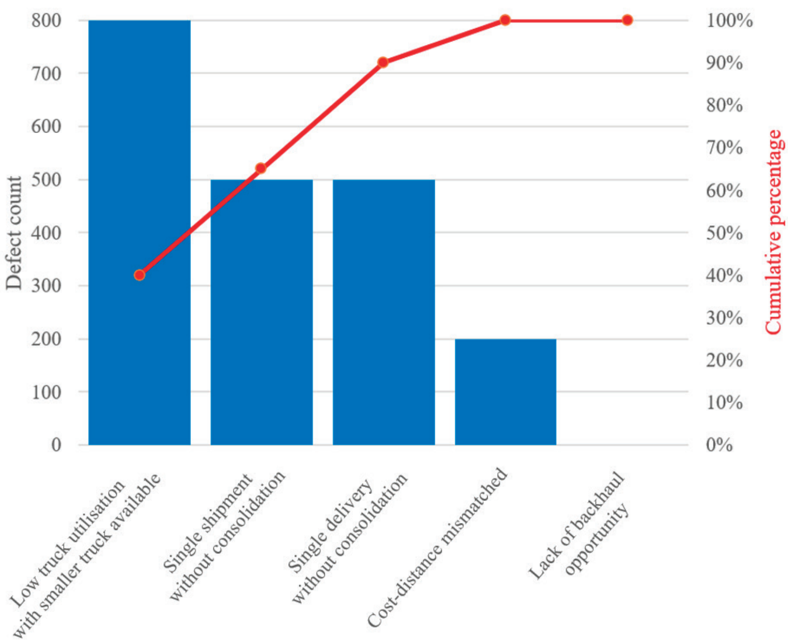

Figure 4: Pareto chart analysis showing different defects within historical data

5 FINAL DESIGN

The proposed solution approach identified inefficiencies through integrated multi-stop consolidation and routing optimisation. Unlike simple load consolidation targeting same-destination shipments, the design enabled deliveries along common routes, maximising utilisation while minimising total distance. Shipping and loading costs are highly variable, depending on season, market conditions (high or low volume movement), and truck availability. For these reasons, the costs in the historical datasets were not suitable for comparison with the solution results. Instead, distances and the number of vehicles used were provided to allow the reader to find the cost savings in comparison to the current market conditions.

Three load consolidation strategies were evaluated:

1. **A simplified Linear Programming Model (LP Model):** consolidating loads to the same delivery location without considering vehicle routing.
2. **Clustered multi-stop VRP:** grouping delivery locations followed by vehicle routing optimisation.
3. **Multi-stop VRP:** direct optimisation across all delivery points without upfront clustering.

The three consolidation strategies represent a progressive hierarchy of optimisation complexity. The simplified LP model did not consider any vehicle routing and served as the baseline benchmark, representing the most fundamental consolidation approach achievable without sophisticated routing algorithms. This delivery location consolidation strategy deliberately excluded routing considerations, consolidating only shipments destined for the same delivery location. It required minimal technical expertise to implement manually. A logistics coordinator could theoretically execute this strategy using basic spreadsheet tools by grouping shipments by destination location.

To enable consolidation across the dataset, it was essential to segment the data by capacity and time, as discussed in the literature review. Given the historical nature of the dataset, splitting by capacity or exact timing could produce impractical solutions, such as consolidating shipments that are months apart. Therefore, a practical approach was to divide the dataset into week-long intervals.

This approach assumed that shipments within the same week were eligible for consolidation, which simplified solution testing without handling over 2 000 shipments simultaneously. Additionally, for comparison purposes, the number of shipments in the historical dataset was assumed to be equal to the number of trucks used. This provided a straightforward benchmark to evaluate improvements from optimised vehicle assignments.

For both VRP-based approaches, Open Door Logistics (ODL) Studio software [21] was used as the optimisation routing platform. ODL Studio is a free and practical tool for VRP analysis that supports multiple vehicle types, considers vehicle capacity constraints, incorporates per-kilometre cost variations by vehicle type, and allows precise location mapping using latitude and longitude data. It also enables modelling of multi-stop deliveries along a single route, making it well-suited for evaluating historical data in the East London region.

ODL Studio was set to allow for an infinite fleet size (no data or information is available showing any limit on trucks), using the 'Great Circle' distance setting. Otherwise, the base vehicle routing algorithm was used, and any non-relevant columns were left empty.

5.1 Linear Programming Model

The simplified LP model assumed that two or more shipments travelling to the same delivery location were eligible for consolidation. This approach did not yet incorporate VRP routing but was used to test whether simple load consolidation could reduce costs before considering more advanced solutions.

The LP model used an exact method to find the most optimal answer, with the following objective function and constraints:

$$Minimise \sum_{i=1}^{m} \sum_{j=1}^{n} x_{ij} \tag{1}$$

subject to:

$$\sum_{j=1}^{n} x_{ij} \geq 0 \;\; \forall i = 1,2,\dots,m \tag{2}$$

$$\sum_{j=1}^{n} x_{ij} * c_j \geq W_i \;\; \forall\, i = 1,2, \ldots, m \qquad (3)$$

$$\sum_{i=1}^{m} x_{ij} \leq 1 \; \forall\, j = 1,2, \ldots, n \qquad (4)$$

$$x_{ij} \in (0\,,1) \; \forall\, i = 1,2, \ldots, m; \; \forall\, j = 1,2, \ldots, n \;\; (5)$$

where i represents the delivery locations, m the total number of locations, j the individual vehicles available and n the total number of trucks. x_{ij} represents the binary decision variable indicating if vehicle j was allocated to location i. Furthermore, c_j represents for the capacity of vehicle j – varying based on vehicle type for the 3–36-ton trucks that were available, and W_i the total weight required to be delivered to a specific location i.

The minimisation function in Eq. (1) aims to use the least number of trucks possible. Note that the LP model does not use latitude and longitude values; it consolidates loads based only on shipment weight and location name.

The constraint in Eq. (2) ensures that at least one truck was assigned to every delivery location i. Eq. (3) ensures the total weight to be delivered to a location i is limited to the sum of the total capacity of all vehicles allocated to the same location. Eq. (4) ensured that a vehicle j could only be allocated to a single delivery location and Eq. (5) restricted the x_{ij} decision variables to binary values.

As an example, the first week of the dataset was extracted. We refer to this as the first test set, containing 91 shipments requiring deliveries to various locations within the East London region. Table 1 provides a list of the model solution results based on this test set, as well as a sample of ten destinations from the test set. The LP model's results, as seen in Table 1, end up being a significant improvement over the original number of trucks used in the historical dataset, with an improvement from 91 trucks used and shipments sent, to only 36 trucks used to complete the deliveries. However, one may notice that a large majority of trucks were still only carrying one shipment to their given destination, and additionally the utilisation of these trucks was extremely low (only the first ten entries are shown).

A summary of the total number of vehicles per truck type for the solution is given in Table 2, indicating that only 3-ton and 36-ton trucks were used within the LP's solution. This is likely due to very few lone shipments being within the 3-ton to 34-ton range. This solution was likely to improve significantly during the following two solution approaches, where lone shipments could be combined based on delivery location groupings.

Table 1: The LP Model solution results for the first test set, listing the first ten destinations

Objective value: 36			
Total shipments: 91			
Delivery Location	**Total Weight**	**Number of Shipments**	**Assigned trucks**
Aliwal North	372	1	1
Amatola View	1 216	1	1
Amatoleville	1 223	5	1
Beacon Bay	361	2	1
Cambridge	2 293	3	1
East London	120 446	42	4
Flagstaff	64 512	2	2
Fort Beaufort	50	1	1
Gately	367	2	1
Grahamstown	32 256	1	1

Table 2: A summary of the total number of vehicles per truck type for the LP model solution for the first test set

Total trucks: 36	
Truck Type	**Total number per truck type**
3t flatdeck	13
16t flatdeck	0
24t flatdeck	0
34t tautliner	0
36t tautliner	23

5.2 Clustered multi-stop VRP

To reduce the computational complexity and improve the scalability of large-scale VRPs, clustering methods are often used as a preprocessing step to group delivery points prior to optimisation. Clustering creates geographically cohesive sets of delivery locations that can then be assigned to vehicles in a second stage or route planning. For more information on clustering and its effects please refer to Bührmann and Bruwer [22], where an in-depth explanation is given and exploration done of clustering and its effects.

Several clustering algorithms were initially tested in this study, including DBSCAN, Sweep, Sweep-Nearest, K-means and K-medians. Both K-means and K-medians performed relatively well in grouping delivery locations spatially. These are shown in Figures 7 and 8 respectively. However, these algorithms produced clusters that were highly imbalanced in terms of shipment weight. Such imbalance results in impractical or infeasible routing solutions, as overloaded clusters need to be serviced by multiple vehicles, while underloaded clusters lead to low utilisation and inefficiencies. This is a common limitation of purely distance-based clustering approaches, which tend to minimise spatial dispersion without accounting for logistical constraints such as vehicle capacity [19].

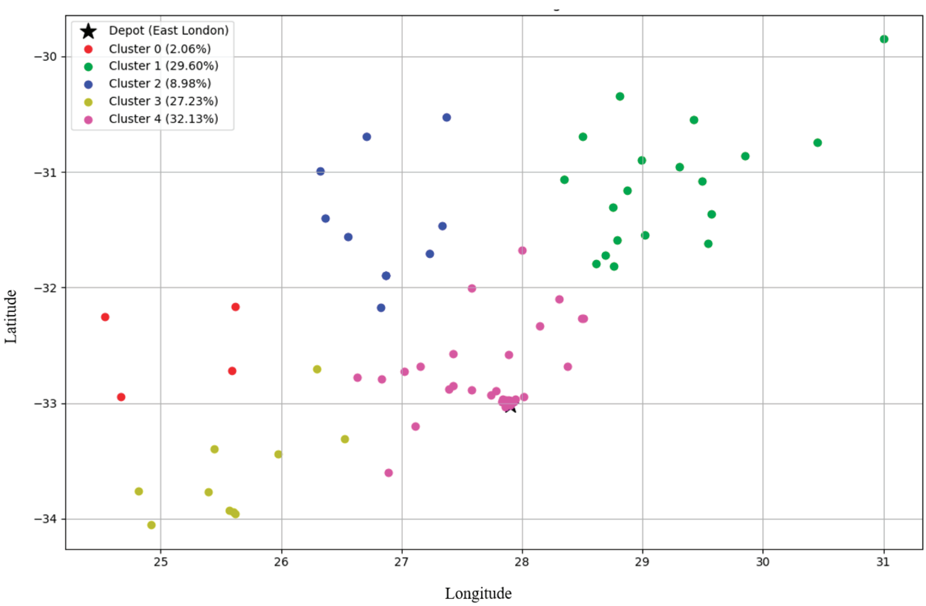

Figure 7: K-means clustering results the first test set, with destinations in the East London region

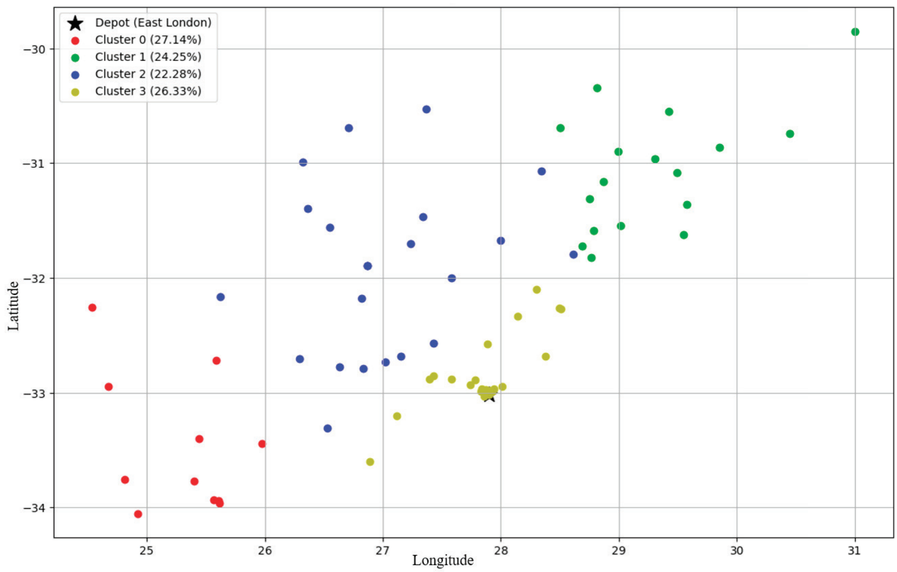

Figure 8: K-medians clustering results the first test set, with destinations in the East London region

To overcome this challenge, a demand-balanced variation of K-means clustering was implemented. This selection of demand-balanced K-means was driven by the specific operational constraints of the East London distribution network. Standard K-Means clustering, while computationally efficient, fails to account for the heterogeneous shipment weights characteristic of the company's customer base. The demand-balanced variant addressed this limitation by incorporating capacity constraints directly into the clustering algorithm. This modification maintained the spatial efficiency of traditional K-Means while producing clusters that were operationally feasible for assignment to the company's fleet. As shown in Figure 9, this method achieved a significantly more balanced allocation compared to standard K-means or K-medians. This clustering allocation to group delivery locations was then applied to ODL Studio to create a final routing solution, using the same initial test set with 91 shipments.

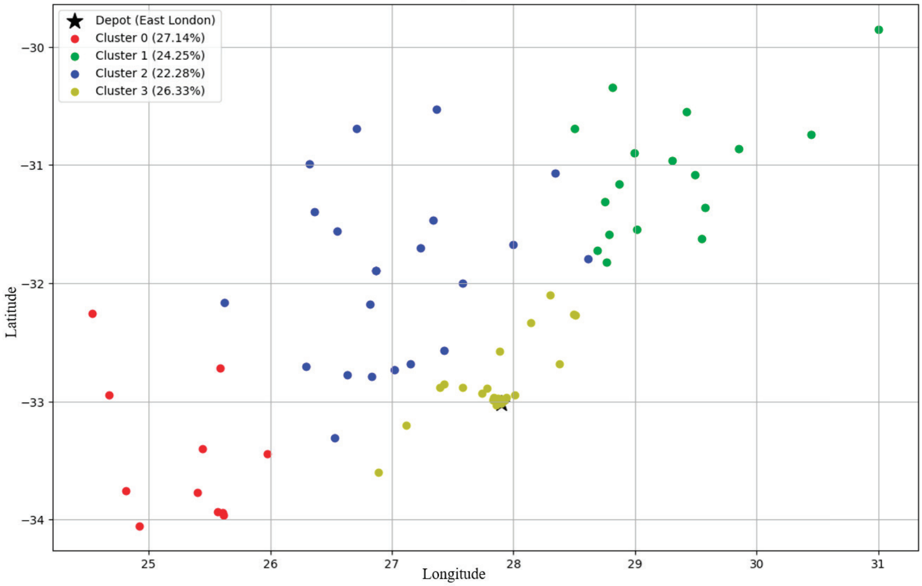

Figure 9: Demand-balanced clusters for the first test set, with destinations in the East London region

Table 3 presents the ODL Studio results for the demand-balanced clustered solution. Compared to the LP model, the clustered approach improved the vehicle utilisation and further reduced the total fleet size from 39 for the LP solution to only 29 for the clustered VRP solution. Nonetheless, clustering introduced some inefficiencies of its own. For example, one truck was assigned only a single 129 kg delivery. This motivated a direct comparison with a full multi-stop VRP approach, where clustering was omitted and ODL Studio assigned shipments more directly.

Table 3:ODL Studio solution for the demand balanced-clustered solution for the first test set

Vehicle name	Capacity (kg)	Deliveries count	Delivered quantity (kg)	Kilometres travelled
3t flatdeck	2700	1	129	294
3t flatdeck	2700	7	2551	536
3t flatdeck	2700	4	1641	7
3t flatdeck	2700	14	2627	32
16t flatdeck	14400	12	12211	302
16t flatdeck	14400	2	8434	215
16t flatdeck	14400	8	4541	12
16t flatdeck	14400	14	8549	20
16t flatdeck	14400	8	9701	9
24t flatdeck	21600	1	21579	152
34t tautliner	30600	1	28224	243
36t tautliner	32400	1	31940	233
36t tautliner	32400	1	32256	243

5.3 Multi-stop VRP

Building on the clustered approach, the multi-stop VRP solution was tested using ODL Studio without any prior clustering. In this setup, all shipments were directly assigned to routes while considering vehicle capacity, cost, and distance simultaneously. This eliminates the potential inefficiencies caused by rigid cluster boundaries, while still leveraging the computational power of ODL Studio to solve the problem at scale.

The results for the same 91 shipment initial test set, for the multi-stop VRP model, are listed in Table 4. Compared to both the LP model and the demand-balanced clustered VRP, the direct multi-stop VRP approach produced superior outcomes. The required fleet size was reduced to just 27 trucks - outperforming the demand-balanced clustered VRP (29 trucks) and the LP model (36 trucks). Smaller vehicles carried most shipments, while the largest trucks were allocated only to high-volume single deliveries. This is consistent with operational expectations. The progression from clustered VRP to direct VRP highlights a key finding: while clustering can provide balanced and computationally simplified subproblems, direct optimisation captures the full problem structure more effectively, leading to further reductions in fleet size and travel distance. The next section verifies these findings against multiple weekly test datasets.

Table 4: ODL Studio multi-stop VRP solution details for the first test set

Vehicle name	Capacity (kg)	Deliveries count	Delivered quantity (kg)	Kilometres travelled
3t flatdeck	2 700	8	2 603	714
3t flatdeck	2 700	6	2 600	9
16t flatdeck	14 400	9	11 887	300
16t flatdeck	14 400	18	11 360	16
16t flatdeck	14 400	24	13 099	39
16t flatdeck	14 400	5	8 835	150
24t flatdeck	21 600	1	21 579	152
34t tautliner	30 600	1	28 224	243
36t tautliner	32 400	1	32 256	152
36t tautliner	32 400	1	32 256	233

5.4 Comparison between different solutions

Table 3 gives a comparison of the three solutions for the initial test set, showing the important metrics as well as the improvements gained by each solution.

Table 5: Comparison between different solutions' results for the initial test set

Metric	Original	LP model	Clustered VRP	Multi-stop VRP
Number of trucks	91	36	29	26
Shipments consolidated	0	55	70	70
Average utilisation	~50%	~58%	~65%	~85%
Improvement in utilisation	N/A	8%	15%	35%

6 RESULTS

To verify that the various solution approaches consistently reduced costs, nine more random test datasets (each one week in size) were evaluated. These test sets were randomly chosen throughout the year and contain between 16 and 99 shipments during a particular week. A total of 525 shipments were investigated.

Three key metrics were used to validate the solution against the identified root causes:

1. Truck utilisation rates,
2. Frequency of single delivery/shipment trips, and
3. Total distance travelled.

Table 6 summarise the results of the ten test sets, including the initial and nine new test sets. The table demonstrates that the multi-stop consolidation approach achieved a 61.3% reduction in trucks used overall (from 525 to only 203), and a further 38.5% reduction in total distance travelled overall (from 55 982 km to only 34 396 km). All test sets furthermore showed both a reduction in the number of trucks and total distance travelled using the multi-stop consolidation VRP approach. These improvements translate directly to cost savings through reduced procurement needs and lower per-kilometre operational expenses.

The solution successfully transformed the delivery pattern from 87% single-delivery trips to a multi-stop approach where smaller vehicles averaged four to eight deliveries per route (depending on the number of shipments available to consolidate). The fundamental shift in operational approach directly addressed the second critical root cause of inefficient single-shipment dispatches.

Table 6: Multi-stop consolidation solution details for ten test datasets in comparison to the base case

	BASE CASE/BENCHMARK CASE		MULTI-STOP CONSOLIDATION SOLUTION	
Date	**No. of trucks used**	**Total distance travelled (km)**	**No. of trucks used**	**Total distance travelled(km)**
2024/01/05	91	6 850	27	4 383
2024/02/05	41	5 329	21	3 892
2024/03/11	35	3 488	7	1 304
2024/04/08	44	6 523	25	5 120
2024/05/06	99	10 743	37	5 904
2024/06/10	16	1 583	6	955
2024/10/07	85	9 782	34	5 754
2024/11/11	62	8 627	36	6 206
2025/01/27	25	2 175	6	687
2025/02/24	27	882	4	191
Total	**525**	**55 982**	**203**	**34 396**

While the multi-stop consolidation VRP solution demonstrated substantial improvements, several limitations should be noted:

- The model assumed static demand patterns based on historical data;
- Time windows and service duration constraints were not incorporated due to data limitations;

- As more destination locations are added to the problem, the computational complexity and time required to calculate the solution increase; and
- Backhauling opportunities could not be evaluated as the TMS did not record empty return trips.

7 CONCLUSION AND FUTURE RESEARCH

This research successfully demonstrates that implementing multi-stop consolidation through VRP optimisation can achieve substantial cost reductions for 4PL providers operating in complex distribution environments. The solution reduced vehicle requirements by over 60%, while improving utilisation rates and reducing total travel distance by nearly 40%.

The key contribution of this work lies in providing a practical framework for 4PLs to enhance their current TMS capabilities without requiring complete system overhauls. By focusing on multi-stop consolidation rather than simple same destination grouping, the approach unlocks previously hidden efficiency gains that are particularly valuable in markets with diverse customer profiles.

In the case of this company, implementation of this approach in the East London region alone could generate significant annual savings. The framework is scalable to other regions and adaptable to different market conditions, making it valuable for the broader 3PL and 4PL industry facing similar challenges with mixed customer bases.

Several opportunities exist to extend this research, including the development of dynamic, real-time optimisation systems capable of responding to incoming orders rather than relying on weekly batch processing. The recording of empty return trips in the TMS could further allow for the study of incorporating backhaul consolidation opportunities that could lead to further cost savings. Integration with the existing TMS through an API function also represents a valuable path, enabling seamless adoption without replacing the core platform. Testing the approach in other South African regions where there are varying customer densities and infrastructure would provide insights into further scalability and adaptability.

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DEVELOPMENT OF A LEAN LEADERSHIP FRAMEWORK FOR THE TECHNOLOGY SECTOR

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ABSTRACT

Lean leadership is crucial for the technology sector, as it facilitates continuous improvement, rapid innovation, and adaptability in a fast-paced and ever-changing environment. The purpose of this study was to identify the key leadership skills necessary for effective lean management in the technology sector. This was achieved using a mixed-methods approach, where data were gathered through surveys with frontline staff and semi-structured interviews with managers at three different companies. The findings underscore the importance of leaders in establishing a collective vision to provide the team with a clear direction, embracing decentralised problem-solving for agility, and the need for coaching and development to enhance operational excellence. A lean leadership framework has been proposed, with three key elements at its core, to help leaders facilitate lean implementation within the technology sector. The framework is human-centered, ensuring an inclusive leadership approach that emphasises employee empowerment and fosters a culture of transformation to drive sustainable success and innovation.

Keywords: lean leadership skills, lean leadership framework, technology sector, operational excellence

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1 INTRODUCTION

The technology sector has experienced rapid growth due to innovation and the increasing adoption of digital solutions across various industries. While lean principles have proven effective globally, the unique structure of the technology sector poses challenges to their successful implementation. A key obstacle is the lack of detailed studies focusing on lean leadership in this sector, limiting insights into the specific challenges faced by leaders. Innovation, characterised by the introduction of new ideas, methods, or products, is central to the tech industry, prompting companies to prioritise creativity, research, and development to remain competitive and meet evolving consumer demands. Innovation requires a distinct leadership approach, one not fully addressed by traditional leadership models [1]. Leadership approaches significantly influence organisational behaviour in technological environments, where managerial decisions shape strategic outcomes and impact organisational performance. Patrick [2] reinforces this, stating that 'managerial behaviour in information technology organizations is affected by leadership behaviour,' underscoring the critical role of leadership in these settings.

In innovative sectors like technology, leadership is crucial for fostering creativity, supporting professional growth, and driving organisational success. As the demands of the modern workplace become increasingly unpredictable, there is a growing need to provide ongoing professional development and learning opportunities for employees. In the technology sector, where knowledge-intensive tasks and the ability to adapt quickly are crucial, creativity is essential for staying competitive. It is also emphasised as a critical response to the ever-changing challenges of the modern workplace, especially in the field of information technology [3].

Leadership practices are essential to both professional agency and creativity within organisations [3]. This approach shifts the focus from individual traits or behaviours to collective organisational efforts aimed at problem-solving, routine development, and reaching organisational goals [4]. In a sector like technology, which is driven by constant change and innovation, this approach becomes even more critical. Lean leadership, in particular, provides a unique approach that aligns well with the needs of the technology sector. Unlike traditional leadership styles, which often focus on maintaining existing processes, lean leadership emphasises continuous improvement and empowers employees [5]. This approach decentralises decision-making authority, fostering greater collaboration and harnessing collective intelligence throughout the organisation. By empowering employees, especially those on the front lines, lean leadership fosters a culture of innovation, enabling organisations to stay adaptable and responsive to market changes [6].

The study analysed three technology companies as case studies to identify leadership practices in the technology sector. The first company, Company A, is a high-tech firm that supplies automated mining machinery to various mines. While the company's services enhance productivity in the mining industry, automating mining equipment also improves social sustainability by reducing risks to workers who would otherwise perform hazardous tasks, thereby increasing safety. Additionally, automating repetitive processes helps workers avoid monotonous tasks, which enhances job satisfaction. The second company, Company B, is an information technology firm offering IT solutions and consulting services across various sectors, including mining and manufacturing, as well as government agencies and municipalities. The third company, Company C, is a global engineering firm that provides solutions to enhance productivity and sustainability in the manufacturing, mining, and infrastructure sectors.

To gain a comprehensive understanding of the challenges related to leadership in the rapidly evolving technology sector, the research question was defined as follows: What are the key leadership skills required for effective lean management in the technology sector? A lean leadership framework has been proposed to help integrate effective leadership within the technology sector.

The organisation of this paper is as follows: the literature review discusses previous work on lean leadership and its contributions to social sustainability within technology organizations. The methodology section outlines the methodology used to execute the study, and the results section highlights the results obtained from the study, which include both quantitative and qualitative data collected from managers and frontline workers at the companies involved in the study. A lean leadership framework has been proposed for the technology sector based on the results obtained. Lastly, the discussion section presents the results and details the lean leadership framework, along with each of its components.

2 LITERATURE REVIEW

2.1 Development and structure of lean leadership

Liker's 4P Model provides a foundational approach to lean leadership, comprising four levels: philosophy, process, people and partners, and problem-solving. Most organisations tend to focus on the process level, emphasising waste elimination, while neglecting the other three levels, and this imbalance often leads to stagnation in lean leadership practices over time. Lean leadership is defined as 'a methodical system for sustainable implementation and continuous improvement of lean production systems' [5]. It also describes the cooperation between employees and leaders in striving for perfection while integrating customer focus, employee development, and long-term leadership growth to achieve organisational goals [7].

Lean leadership development is described as an everyday activity within managerial hierarchies, requiring a paradigm shift from individual learning to team-based and organisational learning [8]. While some researchers argue that organisations not structured like Toyota may struggle to replicate its success, others suggest that tailored programs addressing organisational needs can yield significant benefits. Effective programs should balance technical and interpersonal leadership skills, utilise multiple delivery methods, and occur on-site to maximise individual and organisational outcomes [9]. Moreover, lean leadership must align management structures and corporate strategies across all levels to ensure a cohesive approach [10].

Despite its growing prominence, lean leadership research remains fragmented and underdeveloped, with insufficient connections to general leadership theories. Existing definitions often lack a theoretical foundation, resulting in inconsistencies across studies. Lean leaders play a crucial role in eliminating waste, training team members, developing problem-solving capabilities, and aligning teams with organisational objectives. Their responsibilities extend to setting challenges and goals that drive team performance and organisational success [11].

2.2 Frameworks and principles of lean leadership

Several frameworks highlight the principles of lean leadership. The Diamond Model, one of the more popular lean leadership frameworks, emphasises four core principles centred around true north values, which include self-development, coaching others, supporting daily kaizen, and creating vision-aligned goals [7]. Liker's 4P Model similarly underscores the importance of continuous improvement, positioning problem-solving as central to sustainable lean implementation. Organisations must foster a culture where problem-solving is a daily activity, and learning from mistakes is encouraged [12]. The Toyota Kata introduces two methodologies, the Improvement Kata and the Coaching Kata. The Improvement Kata enables employees to experiment and refine processes through incremental improvements, while the Coaching Kata focuses on embedding these practices organisation-wide [5]. Leaders guide employees using structured questions to promote effective problem-solving and process improvements [13]. Across various lean leadership models, key principles emphasised by all include the leader's self-development and the coaching of employees, all grounded in the concept of continuous improvement. This approach focuses on the ongoing enhancement of both the company's systems and processes, as well as the development of its individuals.

Coaching is a crucial aspect of lean leadership, making a significant contribution to both individual and organisational development. In lean environments, the emphasis is on building the improvement capacity of individuals rather than solely focusing on immediate results. A lean leader's primary duty is to enhance the team's ability to improve through systematic coaching, often referred to as a "coaching routine" or "coach the coach" approach. Ideally, each management level should possess the skills to coach its subordinates effectively. However, this is often hindered by top management appointments based on external credentials or connections rather than internal development, posing a significant challenge for lean leadership [14]. Effective lean leadership requires consistent support, clear communication, visibility, and coaching to build trust and promote a culture of continuous improvement [8].

Coaching is inherently personalised, recognising and respecting individual differences while enhancing performance across teams and departments. It aligns with lean principles by addressing problem-solving, reducing waste, and creating value [15]. Jones notes that coaching improves work outcomes such as goal achievement, professional development, managerial flexibility, productivity, resilience, and overall workplace well-being [16]. These attributes are particularly valuable in innovative industries, such as the technology sector, where expanding coaching initiatives could yield significant benefits. Despite its importance, many managers resist adopting a coaching role, preferring traditional decision-making and supervisory approaches [14]. Furthermore, a lack of formal training in coaching skills impedes the success of such initiatives [17].

While certain leadership qualities are inherent, others require intentional cultivation through self-development [5]. Continuous self-improvement is crucial for leaders to effectively lead their teams in embracing and maintaining lean practices. To maximise self-development, hiring a specialised lean coach or mentor can greatly enhance self-development efforts. External support from lean consultants can aid in the effective development of lean leadership within an organisation [18]. However, relying entirely on lean consultants has its limitations. Although consultants offer valuable expertise, they may lack a deep understanding of the organisation's unique culture and work environment, which can reduce the impact of their recommendations. Halling and Renstrom [19] highlight this issue by describing how a shared company vision was lost once a consulting firm's involvement ended, emphasising the need to develop internal lean leadership capabilities. One of the most effective ways for leaders to build their lean leadership skills is through hands-on experience [20].

Overall, lean leadership is frequently misinterpreted as merely implementing a few visible techniques, whereas these are surface-level indicators of a much deeper organisational culture [21]. For organisations to succeed in their lean transformation, it is crucial to strengthen leadership roles. This requires managers to use their actions and interactions with employees to motivate and involve them in ongoing, systematic improvement efforts [22].

2.3 Lean leadership competences

Key competencies for lean leaders include encouraging self-development, visiting the work floor, coaching employees, communicating effectively, promoting motivational skills, and fostering a culture of continuous improvement. Among these, self-development is considered the most critical for upcoming leaders. These competencies are echoed across models such as the Diamond Model and Liker's 4P Model. Leadership is a practical task requiring ongoing practice and on-the-job learning [23]. It is a complex role that involves making critical decisions affecting organisational performance. With sustainable leadership relying on a deep understanding of both positive and negative leadership traits, most studies emphasise the behaviours and traits that lead to success, with fewer studies examining the traits that contribute to leadership failure within organisations. Some factors contributing to leadership failure, such as arrogance, lack of proactivity, and destructive behaviours, must also be addressed to build resilient leaders [24] [22] [25].

The difference between a leader and a manager has been widely discussed and analysed in organisational studies. While both roles are crucial to an organisation's success, they vary significantly in their methods, responsibilities, and influence on their teams. The manager's role involves overseeing and controlling an organisation's operations to ensure smooth functioning in accordance with established procedures. At the most basic level, the difference between a leader and a manager lies in the way they motivate their employees. Managers are the primary decision-makers, influencing their teams both directly and indirectly [26]. Their primary responsibility is to manage the organisation so that the production process proceeds as planned without disruptions [27]. This requires effective planning, organising, directing, and controlling resources, including human, financial, physical, and informational resources, to achieve organisational goals [28]. Managers are typically viewed as authoritative figures who adopt a transactional leadership style. They prioritise work and results, focusing on task completion over addressing employee needs and aspirations. Their approach often emphasises maintaining comfort, stability, order, and control within the organisation [26].

In contrast, leaders are defined by their ability to inspire and motivate others. They possess unique qualities such as strategic and multidimensional thinking, professional intuition, and excellent communication skills [27]. Leaders are often seen as charismatic individuals who influence and guide their teams through their vision and strong personal connections. Leadership centres on creating a vision and inspiring others to work toward it. Unlike managers, leaders focus on building morale and motivation within their teams, ensuring alignment with the organisation's collective goals [26]. They act as a bridge, facilitating communication between organisational objectives and the aspirations of their team members [29].

Lean leadership is not limited to managing processes; it is a holistic and social process that demands continuous learning and adaptation. While theoretical frameworks like the Diamond Model, Toyota Kata, and Liker's 4P Model offer valuable guidance, effective lean leadership requires practical application, a focus on personal growth, and fostering a culture of improvement. Organisations can achieve sustainable lean leadership practices by addressing leadership failures through a balance of technical and interpersonal skills.

3 METHODOLOGY

A mixed-methods approach was employed, utilising both qualitative and quantitative data. The qualitative data were collected through semi-structured interviews conducted with individuals in managerial roles within the company. Quantitative data were collected through survey questionnaires administered to frontline workers from the three companies. The integration of multiple data collection methods, triangulation, and standardised procedures strengthened the study's validity and reliability. This comprehensive approach ensured that the research findings were credible and consistent, offering valuable insights into the implementation of lean leadership within the technology sector.

3.1 Semi-structured interviews

Semi-structured interviews were conducted with industry experts holding managerial positions across the three companies. This method was chosen for its flexibility and focus, enabling researchers to explore predetermined topics while accommodating spontaneous discussions and follow-up questions based on participants' responses [30]. The interview protocol is available in Appendix A. The interview questions were designed to align with existing lean leadership frameworks, allowing for a systematic exploration of industry challenges. This ensures validity, aligns findings with established practices, supports comparisons, and highlights gaps or barriers within the current state. Tailored solutions can be developed by linking results to specific framework components, addressing broader trends and unique sector needs.

A total sample of 15 managers participated in the study, with five from each company. Given the study's focus on lean leadership in the technology sector, purposive sampling was employed. This method was deemed appropriate as it allowed the researchers to target a specific subset of individuals with the necessary expertise and experience relevant to the research topic [31]. Across the three companies, participants hold positions ranging from top to middle management, each with varying responsibilities within their managerial roles. This diversity provides a broad and valuable range of perspectives and insights into the challenges and practices of leadership within the respective companies. Figure 1 illustrates the participants' positions and years of experience within the company. In the figure, the participants' positions and rankings within the company are displayed in hierarchical order, from the highest to the lowest position. In Companies A and B, the human resources managers fall under level two. Company C, on the other hand, has the general manager at level two and the human resources manager at level three. This is because Company C is bigger in size compared to the other two, and the general manager oversees all managerial roles within the Southern African Development Community (SADC).

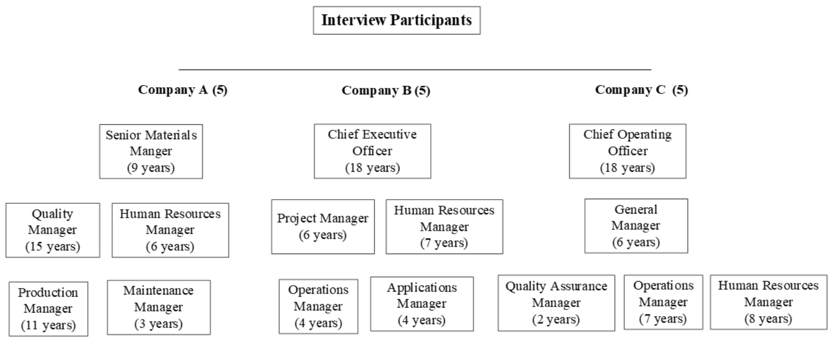

Figure 1: Participant information

3.2 Survey questionnaires

Survey questionnaires were distributed to a sample of 60 frontline workers across the three companies, with 20 participants selected from each organisation. Convenience sampling was used based on the availability of the frontline workers on the day of the study. The survey questionnaire (Appendix B) consisted of 24 structured questions. It was designed to be completed within 10 minutes, considering both the participants' time constraints and the fact that the study was conducted during work hours. To simplify responses and ensure consistency, the questions were closed-ended, offering a fixed set of multiple-choice options for respondents to select from [31]. The surveys were conducted using the "face-to-face interview"' method, which facilitates higher response rates, allows for clarification of questions when necessary, and provides an opportunity to motivate respondents to participate fully [31]. This method enhanced the quality and completeness of the data collected by facilitating direct interaction with the participants.

4 RESULTS

4.1 Survey results

Table 1 presents a summary of the results obtained from the survey questionnaires distributed to frontline workers across the three companies.

A total of 60 participants were included in the survey. The table highlights the questions, the number of respondents, their responses, and the corresponding chi-square and p-values.

Table 1: Survey Responses

N = 60		N (%)	Chi Square	P value*
Gender	Female	0 (0%)	30.0	<0.0001
	Male	60 (100%)	30.0	<0.0001
Number of years at company	< 1 year	14 (23.33%)	0.0667	0.116
	1 – 3 years	6 (10%)	5.40	0.00219
	3 – 5	29 (48.33%)	13.1	<0.0001
	> 5 years	11 (18.33%)	1.07	0.0617
Work Scope	Wide range of responsibilities	25 (41.67%)	6.67	0.00195
	Routine tasks with occasional projects	17 (28.33%)	0.267	0.0956
	Specialized tasks	16 (26.67%)	0.0667	0.111
	Other	2 (3.33%)	11.3	<0.0001
Work-life balance	Poor	16 (26.67%)	0.80	0.0534
	Neutral	13 (21.67%)	2.45	0.118
	Good	31 (51.67%)	6.05	<0.0001
Employee Motivation	Low	9 (15%)	6.05	0.0864
	Average	8 (13.33%)	7.20	0.0598
	High	43 (71.67%)	26.5	<0.0001
Contribution to solutions	Very involved	6 (10%)	5.40	0.00219
	Somewhat involved	5 (8.33%)	6.67	0.000717
	Rarely involved	18 (30%)	0.60	0.0761

N = 60		N (%)	Chi Square	P value*
	Not involved	31 (51.67%)	17.1	<0.0001
Working preference	Individually	11 (18.33%)	12.0	<0.0001
	Teamwork	49 (81.67%)	12.0	<0.0001
Relationships with managers	Poor	17 (28.33%)	0.267	0.0956
	Average	24 (40%)	5.40	0.00407
	Good	13 (21.67%)	0.267	0.103
	Excellent	6 (10%)	5.40	0.00219
Training provided by the company	Regularly scheduled programs	4 (6.67%)	12.8	0.00292
	Occasional training	8 (13.33%)	7.20	0.0598
	No training	48 (80%)	39.2	<0.0001

The survey results offer detailed insights into the workplace dynamics of the organisation, with the data highlighting trends, strengths, and potential areas for improvement. All 60 survey participants were male (100%), highlighting a notable lack of gender diversity among the respondents. Women remain significantly underrepresented in the technology sector due to societal and cultural factors. The Matilda effect shows that women's contributions in STEM are often overlooked. Furthermore, the absence of visible female role models in the technology sector can lead to underrepresentation, creating an environment that can feel isolating for women. Addressing this is vital when recruiting talent in the technology sector, as diversity tends to promote innovation and foster a more inclusive workplace.

The most significant proportion of respondents (48.33%) have worked at their respective companies for three to five years, with this group showing strong statistical significance ($p < 0.0001$). This suggests a relatively stable core of experienced employees. Employees with less than one year of service account for 23.33%, followed by those with more than five years (18.33%) and those with one to three years (10%).

Most respondents view work-life balance positively, with 51.67% rating it as "Good." This is likely due to the prevalence of flexible work arrangements, including remote options, which are common in the technology sector. This category showed strong statistical significance ($p < 0.0001$), highlighting the sector's effectiveness in promoting employee well-being. However, 26.67% rated it as "Poor," and 21.67% as "Neutral," suggesting there is still room for improvement.

Most respondents (71.67%) reported high levels of motivation, supported by a highly significant p-value (<0.0001), which is linked to a positive work-life balance. A good work-life balance enhances productivity and overall motivation. This underscores the importance of effective engagement practices, as the 15% reporting low motivation indicates areas where leadership can address individual concerns.

Regarding the work scope, 41.67% of employees reported managing a wide variety of responsibilities, which showed significant relevance ($p = 0.00195$). The core business operations that employees are responsible for include infrastructure management, software development and maintenance, technical support, and vendor and asset management. Routine tasks with occasional projects (28.33%) and specialised tasks (26.67%) were less common, with only a small percentage (3.33%) categorised as "Other." This distribution suggests a somewhat dynamic workplace where a significant portion of employees are expected to handle diverse roles.

Most employees (81.67%) preferred teamwork, with a significant chi-square value (<0.0001), indicating a strong collaborative culture. This is likely due to the diverse projects (manufacturing, mining, and infrastructure) managed by tech teams, which require working in cross-functional or hybrid setups. Conversely, only 18.33% of employees preferred working alone.

Regarding contributions to solutions, a significant 51.67% of employees are not involved, with this category showing strong statistical significance ($p < 0.0001$). This underscores a gap in participatory decision-making, which could hinder innovation and employee engagement. The other participants were rarely involved (30%), somewhat involved (8.33%), or very involved (10%).

Manager-employee relationships were mainly rated as average (40%), followed by poor (28.33%). Strengthening these relationships can be achieved by involving employees in the development of solutions, which promotes mutual trust and helps ensure the long-term success of those solutions. Good and excellent ratings were less common, with only 10% of respondents describing their relationships as excellent.

Regarding the training provided by companies to their frontline workers, a concerning finding was that 80% of respondents reported receiving no training, with this category showing a highly significant p-value (<0.0001). Managers in the technology sector must prioritise skills development and professional growth to improve their employees' skills, which in turn enhances their company's overall expertise. This helps foster innovation and drive successful outcomes, resulting in improved financial performance. Only 6.67% participated in regularly scheduled programs, and 13.33% received occasional training, highlighting a key opportunity to boost workforce skills and professional development.

4.2 Interview results

The survey findings revealed a lack of collective vision, as employees were not involved in the development of solutions. Additionally, a gap was identified in skills development, which negatively impacted the relationship between managers and employees. The interviews help expand on the different criteria to provide a broader understanding of the gaps existing within the current state of the technology sector. Most managers were focused on production output and process optimisation rather than the philosophy, people, and problem-solving principles required when implementing lean leadership as a whole. The primary focus for managers was to achieve annual targets and meet established deadlines.

Therefore, in an attempt to meet operational requirements, managers often end up micro-managing and limiting frontline workers' involvement in contributing to solutions, decision-making, and creativity within the workplace. Furthermore, there are limited opportunities for development for both managers and frontline workers. Thus, the interview results further validate those of the survey questionnaires.

4.2.1 *Vision alignment*

Under the first theme, vision alignment, managers were asked questions about the company's vision and goals, employee responsibilities, and leadership styles across departments. A common trend emerged across the three companies: while most managers acknowledged the importance of the company vision, many admitted that they either rarely communicated it to employees or did not emphasise it as much as they should have.

Company C has a structured approach by which the company's vision is embedded into the operational framework, ensuring that employees' efforts align directly with organisational goals. In contrast, Company B, being smaller than the other two companies, demonstrates more frequent, though informal, discussions about the company vision among internal employees. These regular interactions foster better alignment within the internal team. However, as noted by the project manager, Company B's contracted frontline workers are less engaged in these discussions and have limited interaction with internal employees, highlighting a gap in vision alignment for external staff.

A clear trend observed across the three companies is the strong alignment between individual roles and the organisation's strategic objectives. Employees across various departments consistently demonstrated an understanding of how their tasks contribute to the company's vision, reflecting effective communication and alignment within these organisations. One of the managers mentioned that quality and safety are priorities, and stated that, in completing his tasks, he works with the company to reduce operating costs. This perspective underscores the integration of personal responsibilities with broader organisational goals. Similarly, HR managers at Companies B and C emphasised the critical role of their positions in advancing the company's mission by maintaining a safe and supportive work environment for all employees. This shared focus across roles demonstrates a cohesive effort toward achieving each company's vision and priorities.

All the managers agreed that frontline workers contribute to the company's vision through their daily tasks, whether by following direct instructions, as is more common in Companies A and C, or by having some freedom to develop solutions, as observed with the programmers at

Company B. However, notable differences in role execution were evident, shaped by each company's structure and operational requirements. At Company B, some managers give their employees the freedom to devise solutions. At the same time, the project manager has significant autonomy in selecting team members and managing projects, reflecting a more decentralised approach to project management. Conversely, Company C's HR manager described a structured environment where tasks are clearly defined for employees, indicating a more hierarchical management style. Despite these variations, a consistent principle emerges; roles are well-defined, and their execution is closely aligned with the company's overall success.

4.2.2 Employee relationships

Employee relationships emerged as a central theme in the study, focusing on the dynamics between managers and frontline workers. Communication was identified as a vital component of these relationships, with managers across the three companies describing varied but consistent efforts to maintain open and effective communication channels. Interview responses highlighted generally positive communication practices, characterised by frequent interactions across all organisational levels. Managers commonly described the communication within their companies' using terms such as "good," "efficient," and "regular." A noticeable trend across the companies was the emphasis on daily communication. Many managers reported engaging with their teams daily through meetings, one-on-one discussions, or informal interactions. This daily communication was deemed crucial for aligning teams with project objectives and addressing any emerging issues promptly.

The analysis of the organisational culture subtheme revealed both notable differences and shared perspectives on how organisational culture impacts the implementation of lean leadership. A recurring observation, particularly from respondents at Company A, highlighted contrasts within its divisions. The quality manager noted that while the chemical plant has an open and collaborative culture, the steel plant operates in a more rigid and reserved environment. When asked about the importance of organisational culture and its role in the success or failure of implementing lean leadership, all the managers unanimously agreed that it is a critical factor. Leadership styles also reflected the varying organisational cultures across the companies. Company C was described as having an "inclusive and high-performance-focused" leadership style, with a strong emphasis on recognising and rewarding achievements. In contrast, Company A faces challenges in unifying the distinct cultural dynamics within its divisions, illustrating the complexities of aligning organisational culture with leadership strategies.

The companies generally lack formal team-building activities designed to enhance teamwork and collaboration on projects. This highlights a significant gap in cultivating cooperation between frontline workers. Although no formal team-building initiatives exist for shop floor employees, informal activities are occasionally organised. However, employees often see the team-building component of these gatherings as secondary to their social purpose. Therefore, team-building events may not effectively address the need for structured development activities to strengthen team dynamics.

4.2.3 Self-development

The final theme of the study, Self-Development and Coaching, examines how managers coach employees for specific tasks and continuous improvement while also focusing on their own skills development outside of work to stay current with industry trends. When asked about training opportunities for employees, all managers at Company A confirmed that the company has provided training over the past two to three years but acknowledged that the training is tailored specifically for select individuals in management positions. As noted by the senior materials manager, training is provided whenever the company deems it necessary. Of the five managers interviewed, only two reported participating in the company's training programmes, as they were among the individuals required to attend. The other three indicated that they had not been invited to participate. At Company B, training is reportedly limited to employees working under the applications manager, who oversees the company's software development. In contrast, Company C has the most organised and structured training programmes for employee development. However, like Company A, the training is exclusively available to individuals in managerial roles, with no initiatives aimed at frontline workers. This underscores a gap in inclusive training opportunities across all three companies. Currently, most training programmes are directed at individuals in senior positions to ensure they are skilled and capable of managing their teams effectively. Emphasis is placed on the managers' role in fostering the ongoing development of their team members.

The self-improvement subtheme highlights the managers' efforts to pursue personal and professional growth. Overall, participation in self-development practices is very low, with only a few managers being actively involved. Among these, approaches to self-improvement include both formal and informal methods. Managers who engage in self-development reported activities such as reading industry-related books, conducting online research, and attending conferences and seminars with peers. While these proactive efforts demonstrate a commitment to staying updated, they lack the structured guidance and comprehensive learning offered by formal training programs. For the majority of managers who do not engage in self-improvement activities, time constraints and challenges related to maintaining a work-life balance were identified as significant barriers. These findings suggest that companies should create environments that prioritise continuous learning by addressing the obstacles that hinder self-improvement, thereby empowering managers to effectively enhance their leadership capabilities.

The surveys and interviews revealed the attributes most required by leaders in the technology sector, and Figure 2 below was created from these findings, highlighting the key considerations for leaders in the technology sector.

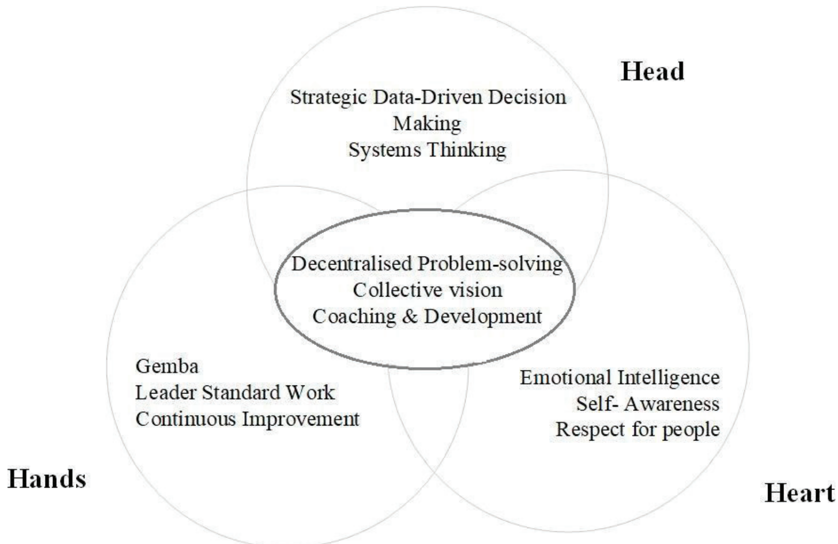

Figure 2: Head, heart, and hands proposed framework for lean leadership, adapted for this study from Sipos et al. [32]

The core of the framework emphasises the importance of decentralised problem-solving, which enables companies to adapt, innovate, and operate efficiently. It also fosters a collective vision as the true north (overarching purpose) and provides coaching and development to enhance skills and decision-making. These were the three dimensions that required the most focus, not only to help improve leadership skills but also to enhance the operational excellence of companies within the technology sector.

5 DISCUSSION

The findings from this study, when compared to the literature, reveal a mix of alignment and gaps in how companies integrate their vision into daily operations and employee responsibilities. The survey results showed that while 81.67% of employees prefer working in teams, 51.67% of the participants reported not being involved in contributing to solutions. The lack of frontline workers' involvement in decision-making within the surveyed companies suggests missed opportunities to leverage employee insights and enhance organisational performance. Additionally, it hinders collaboration and meaningful engagement in decision-making processes, which are essential for aligning employees' contributions with the company vision. Lean leadership principles emphasise the importance of integrating vision-aligned goals at all organisational levels, with clear communication and decentralised problem-solving being key [10]. By decentralising problem-solving, managers can tap into the collective intelligence of their teams, leading to increased innovation and adaptability, promoting effective leadership. A good leader should not seek to solve every problem single-handedly; instead, a leader should seek to empower employees to find creative solutions by working together. This justifies representing decentralised problem-solving as a core leadership skill for the technology sector in the proposed framework (Figure 2).

While managers across the three companies acknowledge the importance of aligning roles with the organisational vision, their approaches vary significantly. Company C employs a structured approach to embed vision into operations, ensuring precise role alignment with organisational goals. However, its hierarchical structure limits frontline worker autonomy, which stifles innovation and contradicts lean principles of empowering employees to engage in problem-solving and continuous improvement. Company B demonstrates a more flexible approach, with frequent informal discussions within internal teams. However, this practice does not extend to contracted frontline workers, resulting in uneven alignment across the organisation. This discrepancy highlights a gap in inclusivity, which the leadership-as-practice approach identifies as essential for creating cohesive, vision-driven workplaces [4]. Company A presents the most significant challenges in terms of aligning its vision. Managers admitted that operational priorities, such as safety and immediate targets, often overshadow strategic discussions about the company's vision.

This reflects a common issue in organisations that focus predominantly on process-level goals while neglecting other critical aspects of lean leadership, such as philosophy and people development. Without consistent reinforcement of the vision, employees are likely to feel disconnected from long-term strategic objectives, which can lead to a decline in both engagement and productivity. To address these gaps, companies must prioritise balanced leadership practices that combine structured communication with inclusive decision-making processes. Effective lean leadership requires consistent reinforcement of the vision, ensuring it reaches all organisational levels [5]. By encouraging collaboration and empowering employees to actively contribute to organisational goals, companies can create a cohesive workforce that aligns with lean principles and drives sustainable success. The lean leadership framework, as illustrated in Figure 2, emphasises the importance of a collective vision at its core, as it promotes alignment among managers and employees. A collective vision also aids in enhancing innovation, as collaboration across different levels is facilitated when companies share a common purpose. This aligns with the Diamond Model, where core principles are centred around true north [7].

In addition to vision alignment, employee relationships are fundamental to building trust, fostering collaboration, and enhancing employee engagement — essential components for effective lean leadership. While the survey results highlight positive teamwork preferences, the limited opportunities for participation undermine the potential to build strong relationships and trust between employees and managers. Managers across all three companies describe communication within the organisation positively. In Company A, cultural differences were evident between the more open and easy-going chemical plant and the steel plant, which exhibits a more rigid and reserved culture. These disparities highlight the complexities of aligning cultural practices with leadership strategies. These divisions, along with the absence of formal team-building initiatives across the three companies, weaken collaboration and impede the effectiveness of leadership practices.

Regarding development practices, the findings reveal varying approaches, highlighting gaps in inclusivity and the need for structured training opportunities for managers and frontline workers. Survey results show that 80% of respondents reported receiving no training, with only 6.67% participating in regularly scheduled programmes and 13.33% in occasional training. These statistics demonstrate a significant lack of organisational commitment to continuous learning, reflected by a highly significant p-value of <0.0001. This deficiency hinders the broader implementation of lean principles, which emphasise continuous improvement through the systematic development of both individuals and processes [7]. Interviews confirmed this gap, revealing that training programmes across all three companies primarily target senior management and exclude frontline workers. At Company A, training opportunities are determined by perceived necessity rather than a systematic approach. Only two out of five managers interviewed had participated in these programmes, leaving others without opportunities for skills development. Similarly, Company B's training is restricted to employees under the applications manager, with no initiatives for other staff. In contrast, Company C offers more structured programmes, but they are still limited to managerial roles. These practices diverge from lean leadership frameworks, such as the Toyota Kata, which emphasise inclusive training to foster problem-solving and continuous improvement across all organisational levels. Excluding frontline workers not only limits their growth but also prevents companies from leveraging their insights to enhance processes and promote innovation.

Self-development among managers was found to be equally limited. While a few managers reported engaging in informal self-improvement activities such as reading industry-related books, attending conferences, and conducting online research, most cited time constraints and work-life balance as significant barriers. This is also evident in the existing literature, which highlights the challenges that managers face in adopting self-development practices due to competing priorities. Relying solely on informal methods lacks the structured guidance and depth offered by formal training programmes, reducing their impact on managerial growth. The Diamond Model and Liker's 4P Model emphasise self-development as a foundational principle of lean leadership, suggesting that structured programmes are essential for building resilient and effective leaders [7] [23]. Based on the gaps identified at the companies, as well as the frameworks from the literature, coaching and development were recognised as the foundation for building trust between managers and employees. The proposed framework in Figure 2 emphasises coaching and development as a core value to enhance leadership skills in the technology sector, which in turn leads to operational excellence.

Relationships between managers and frontline workers were highlighted as critical aspects of workplace dynamics. Survey results revealed that 71.67% of respondents reported high levels of motivation, while relationships between frontline workers and their managers were rated as average by 40% of respondents and as poor by 28.33%. This suggests a significant room for improvement, as strong relationships with managers are essential within the organisation. The strained relationships limit opportunities for building trust and engagement, creating potential barriers between employees and their managers, thus negatively impacting their relationships. Addressing this can significantly improve employee relationships within the technology sector, ensuring the social sustainability of the lean leadership practices in the industry.

5.1 Implications of the study

The findings carry significant implications for leadership practices within the technology sector. While the industry demonstrates specific strengths, such as fostering teamwork and motivation among employees, the gaps in vision alignment, employee relationships, and self-development reveal misalignments with established lean leadership frameworks. These misalignments, if left unaddressed, could hinder the sector's ability to fully realise the benefits of lean principles. A key implication lies in the sector's autonomy to experiment with new solutions for frontline workers. This limited involvement reflects a failure to incorporate decentralized problem-solving and employee empowerment, both of which are foundational to lean leadership frameworks, such as Liker's 4P Model and the Toyota Kata. The Improvement Kata emphasises experimentation and problem-solving across all organisational levels; however, the current hierarchical structures hinder the full implementation of these principles.

Employee relationships, central to effective leadership, also reveal areas of concern, underscoring the need for leaders to shift their focus from frequent communication to meaningful interactions that foster trust and engagement. The absence of formal team-building initiatives across all three companies limits opportunities to strengthen these relationships. In contrast, lean frameworks, such as the Diamond Model, emphasise inclusive leadership practices, continuous communication, and structured collaboration — practices that are crucial for enhancing organisational cohesion. Addressing these gaps through structured initiatives could create stronger bonds between employees and managers, improving engagement and fostering a more cohesive culture.

In comparison to established frameworks, the sector's current practices fall short in leader self-development, structured training for frontline workers, and employee involvement and contribution to solutions. To align more closely with lean leadership principles, organisations must prioritise structured and inclusive approaches that extend beyond senior management. Initiatives such as vision-focused communication, team-building activities, decentralised problem-solving, and comprehensive training programmes can bridge the existing gaps, empowering employees at all levels to contribute meaningfully. These steps are essential for cultivating a sustainable leadership culture that aligns with the principles of continuous improvement and innovation central to lean leadership.

6 CONCLUSIONS

The research question for the study was: What are the key leadership skills required for effective lean management in the technology sector? The proposed framework, presented in Figure 2, addresses the question by considering three key dimensions necessary for effective leadership: the Head (strategic skills), Hands (operational/practical skills), and the Heart (interpersonal skills). The core of the framework integrates the three dimensions to present the essential skills that are the foundation for lean leaders in the technology sector. Leaders must prioritise the involvement of frontline workers in problem-solving, ensuring that employees at all levels are empowered to make meaningful contributions to organisational goals. This would help foster buy-in for a collective vision that provides a clear direction and purpose (true north), thereby enhancing collaboration across different levels within the company. A collective vision enhances the team members' ability to support one another, increasing resilience and adaptability in a fast-paced and ever-evolving technology landscape. To facilitate cultural transformation, a lean leader must serve as a sensei, committing not only to their own self-development but also to coaching and developing their teams by addressing skills development gaps, fostering a culture of continuous improvement, and shared learning. Leaders must invest in their team's growth through formal training programmes, as well as helping them develop problem-solving skills by asking questions to help guide them towards their own solutions, rather than providing direct answers. Structured team-building initiatives are also essential for strengthening relationships between employees and managers, which are often strained in the current state.

The primary managerial implication of the proposed framework is that it helps identify the core skills necessary for leaders to facilitate transformation within the technology sector. Focusing on the core of the framework makes the other skills achievable, as it provides a strong building block for the associated skills to be assimilated. While the framework is developed specifically for the technology sector, it is adaptable to other industries and can help unlock the full potential of leaders. The framework provides a human-centered approach to transformation, empowering leaders to become the drivers of change within their organisations.

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APPENDIX A: Interview protocol

THEME 1: Aligning a Shared Vision with Daily Improvement Efforts

1. Can you describe the scope of your job and the main tasks you perform?

Probes: How do these tasks align with the overall goals of the company?

How long have you been in your current position at the company?

2. What are your professional goals within the company?

3. How do you define success within the company?

4. How do you communicate the organization's vision to employees at all levels?

Probes: How do you ensure that the vision is understood and effectively communicated?

How often is the vision revisited with the team?

5. In what ways do employees contribute to achieving the organization's vision through their daily tasks?

Probe: Are there specific goals or metrics that align daily tasks with the vision?

6. What strategies do you use to motivate employees to align their efforts with the organization's vision?

Probe: How much freedom do the employees have to experiment and try new approaches to come up with solutions?

THEME 2: Employee Relationships

1. How would you describe the leadership style within the company?

2. What leadership behaviors or styles do you believe are most effective in promoting a lean culture within the company?

Probe: Can you briefly explain why?

3. How would you describe the current organizational culture within the company?

Probe: Do you believe organizational culture influences the success or failure of lean leadership within the company? Can you briefly explain why?

4. How do you promote a sense of community and belonging within the organization?

Probe: Are there any programs or initiatives focused on team building?

5. How would you describe the communication style among employees in the company?

Probes: How often do you communicate with the employees you oversee?

How often do you give them feedback on their performance?

THEME 3: Commitment to Self-Development and Coaching Practices

1. How does the company support the continuous professional development of its employees?

2. Does the company provide any training programs for employees?

    - ***o*** **Probes if yes**: What types of training programs are available?

    How are employees selected or enrolled in these programs?

    How frequently are the training programs conducted for employees?

    - ***o*** **Probes if no**: Are there plans to implement training programs in the future?

    How do employees currently develop their skills and knowledge?

3. How do you prioritize your own self-development as a leader, and what strategies do you use to improve your skills and knowledge continually?

Probes: What specific resources or tools do you find most helpful in your self-development?

How do you stay updated with the latest trends and best practices in leadership?

4. How do you approach coaching your team members to enhance their skills and performance?

Probes: What coaching techniques or methods do you find most effective?

How do you tailor your coaching approach to meet the individual needs of each client?

APPENDIX B: Survey questionnaire

SURVEY QUESTIONNAIRE

1. How long have you been working at the company?

☐ Less than 1 year
☐ 1-3 years
☐ 3-5 years
☐ More than 5 years

2. How would you describe the scope of your job and the main tasks you perform daily?

☐ I perform specialized tasks with a clear focus.
☐ My job involves a wide range of responsibilities.
☐ I work on routine tasks with occasional special projects
☐ Other

3. Overall satisfaction with your current role at the company

☐ Very Dissatisfied
☐ Dissatisfied
☐ Neutral
☐ Satisfied
☐ Very Satisfied

4. What are your professional goals within the company for the next year or two?

☐ Advancement to a higher position
☐ Gaining new skills or certifications
☐ Taking on more responsibility

☐ Other: ____________

5. Clarity of your job responsibilities and tasks

☐ Very Unclear
☐ Unclear
☐ Neutral
☐ Clear
☐ Very Clear

6. Level of challenge and motivation from your daily task responsibility

☐ Very Low
☐ Low
☐ Neutral
☐ High
☐ Very High

7. How involved are you in contributing to solutions for challenges faced by the company?

☐ Very involved
☐ Somewhat involved
☐ Rarely involved
☐ Not involved

8. How much freedom do you have to experiment and try new approaches in your job?

☐ A lot of freedom
☐ Some freedom
☐ Limited freedom
☐ No freedom

9. Effectiveness of communication within your department

☐ Very Ineffective
☐ Ineffective
☐ Neutral
☐ Effective
☐ Very Effective

10. Collaboration with colleagues on projects or tasks

☐ Very Rarely
☐ Rarely
☐ Sometimes
☐ Often
☐ Very Often

11. Relationship with your immediate supervisors/management

☐ Poor
☐ Fair
☐ Average
☐ Good
☐ Excellent

12. Relationship with other managers

☐ Poor
☐ Fair
☐ Average
☐ Good
☐ Excellent

13. How often do you receive feedback on your work performance?

☐ Never
☐ Rarely
☐ Sometimes
☐ Often

14. How much are your ideas and suggestions valued in the company?

☐ Highly Valued
☐ Somewhat Valued
☐ Neutral
☐ Not valued

15. Comfort level in approaching coworkers for assistance or collaboration

☐ Very Uncomfortable
☐ Uncomfortable
☐ Neutral
☐ Comfortable
☐ Very Comfortable

16. Do you prefer working individually or in teams?

☐ Individually
☐ In teams

17. Does the company provide you with any training or development programs?

☐ Yes, regularly scheduled programs
☐ Yes, but only occasionally
☐ No, not at all

18. Satisfaction with the training and development opportunities provided

☐ Very Dissatisfied
☐ Dissatisfied
☐ Neutral
☐ Satisfied
☐ Very Satisfied

19. Participation in improvement workshops provided by the company in the past year

☐ Never
☐ Rarely
☐ Sometimes
☐ Often
☐ Always

20. Organizational culture at the company

☐ Poor
☐ Average
☐ Good
☐ Excellent

21. Work-life balance at the company

☐ Very Poor
☐ Poor
☐ Neutral
☐ Good
☐ Very Good

22. Recognition and rewards for employee contributions

☐ Very Inadequate
☐ Inadequate
☐ Neutral
☐ Adequate
☐ Very Adequate

23. Support received from your colleagues in achieving your job objectives

☐ No Support
☐ Less Supportive
☐ Supportive
☐ Very Supportive

24. How well do you understand the company's goals and objectives

☐ Very Poorly
☐ Poorly
☐ Neutral
☐ Well
☐ Very Well

TRANSPORTATION AND LOGISTICS MANAGEMENT CAPABILITIES AND PROJECT PERFORMANCE IN GCC CONSTRUCTION: AN SEM STUDY

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ABSTRACT

Gulf Cooperation Council (GCC) construction projects rely on import-heavy, multi-tier flows from port to site, where transportation and logistics management (TLM) often determines delivery reliability. This study asks: which TLM capabilities most enhance operational efficiency, integration, and overall supply chain performance and how do these capabilities translate to project outcomes? Constructs are defined via literature synthesis and expert panels, covering logistics planning and appointment scheduling, real-time visibility/track-and-trace, port/customs coordination, consolidation and staging, and last-mile/site logistics. A multi-country survey of owners, contractors, and logistics providers across KSA, UAE, Qatar, Oman, Bahrain, and Kuwait will measure these constructs. Confirmatory factor analysis establishes reliability and validity; structural equation modeling estimates direct, indirect, and mediating effects via delivery reliability and coordination quality on schedule adherence and logistics cost, with model fit assessed by SRMR and multigroup tests by country and delivery method. Expected findings are that visibility and appointment-based scheduling, combined with port-to-site coordination and consolidation/staging, reduce material-flow variability and idle time, and improve on-time delivery and

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cost performance. The study delivers a prioritised capability roadmap and practical TLM strategies for GCC construction.

Keywords: transportation and logistics management, GCC construction, structural equation modeling, on-time delivery

1 INTRODUCTION

Gulf Cooperation Council (GCC) constructions are generally dependent on extensive supply chains for the importation of the majority of structural and finishing materials . Partly due to this, the projects are vulnerable to global disruptions, which cause rapid fluctuation in lead times and a general increase in transportation costs, while the on-site teams expect stable, just-in-time flows [1]. However, the GCC governments, as part of their logistics and industrial strategies, are simultaneously throwing massive amounts of money into the development of ports, free zones, and multimodal corridors. Through these initiatives, the network capacity has been expanded; however, existing studies continue to highlight persistent challenges such as fragmented planning and weak coordination, which hinder effective integration among project stakeholders across the port-to-site supply chain [2], [3]. Thus, the transfer of goods and logistics from the port to the site is one of the critical and undeveloped factors impacting project performance. Construction supply chain studies show that reliability of material flow, visibility of information, and co-operative planning are mostly responsible for time and cost outcomes; however, the operational mechanisms are seldom measured at the project level [4]. Despite the application of SEM in examining the relationship between logistics implementation and project performance through coordination efficiency, the literature lacks explicit identification of discrete TLM capabilities and empirical investigation within the GCC context [5].

This paper bridges the gap in research by analysing how separate bundles of TLM capabilities, logistics planning and appointment scheduling (LPAS), real-time visibility (VIS), port/customs coordination (PCC), consolidation and staging (CONS), and last mile/site logistics (LMSL), impact the project performance. The performance lens looks at two widely accepted outcomes: schedule adherence (SA) and logistics cost performance (LCP). Building on previous work, this study presents two mediating constructs that embody the operational mechanisms through which capabilities are converted into outcomes: delivery reliability (DR), which is defined as the regularity of arrival times and lead time variability, and coordination quality (CQ), which is defined using clarity of roles, information sharing, and timely issue resolution among actors.

Using an empirical approach, the paper draws upon survey data collected from 183 owners, contractors, and logistics service providers involved in GCC construction projects. A questionnaire is used to distinguish the five capability domains, the two mediators, and the two performance outcomes by the implementation of multi-item Likert-type measures which have been refined through expert feedback and a pilot study. The data are processed via SEM to estimate the direct and indirect effects, and assess the relative importance of capability domains. The results demonstrate that delivery reliability is the strongest factor for both schedule and logistics cost outcomes, whereas last mile/site logistics and consolidation rank as the most significant upstream capabilities.

This research makes two main contributions. To start with, it is one of the earliest multi-country, project-level quantitative assessments of port-to-site TLM capabilities in GCC construction, moving from a simple "logistics challenges" approach to a more elaborated, capability-based model. Furthermore, it offers a prioritised roadmap for practitioners that marks out the best capabilities for improving reliability, coordination, and downstream cost and schedule performance. The remainder of the paper is structured as follows: the next section reviews the relevant literature and develops the conceptual model, followed by a description of the research methodology, presentation of the empirical results, and a discussion of the theoretical and practical implications for the GCC construction sector.

2 LITERATURE REVIEW

Construction supply chains typically have a fragmented structure, are composed of project-specific organisations, and possess a temporary site-specific production system which brings to the fore the coordination and logistics integration as the key determinants of project performance [4]. TLM , due to its limiting buffers, portable resources, and variations in environments, is the most essential element for ensuring materiel deliveries to the places and times they are required. An examination of construction logistics has pointed out that ineffective planning, low transparency, and weak cooperation among organisations are the major reasons for unreliability and productivity decrease, especially in GCC import-dependent situations [1], [2], [6], [7]. Recent studies have begun to examine TLM practices and capabilities in greater depth, moving beyond general discussions of logistics challenges to more systematic and capability-based analyses.

LPAS is widely recognised as a critical mechanism for aligning upstream supply flows with site capacity constraints. Studies on delivery time windows and slot-booking systems indicate that structured appointment scheduling reduces arrival variability, mitigates yard congestion, and aligns deliveries with work-package [8]. By levelling the traffic that is coming into the site and linking the slots-to-site capacity, LPAS can cut down on labour idling and equipment downtime, which are inefficiencies that have been highlighted in the GCC construction supply chains time and again [2]. However, appointment systems without real-time visibility and effective last-mile control are limited in responding to disruptions. VIS complements these systems by reducing uncertainty through track-and-trace, predictive ETAs, and exception alerts. In import-dependent regions such as the GCC, visibility gaps are linked to delivery delays, missed milestones, and higher expediting costs [1]. Accordingly, VIS serves as both an information-sharing and risk-mitigation capability. In import-dependent contexts, PCC is equally critical, as advance documentation, digital pre-clearance, and coordinated terminal operations reduce dwell time, demurrage, and yard congestion, thereby lowering logistics costs and minimising schedule delays [9]. Work conducted in the GCC indicates that customs clearance and port handling variability persist as a recurrent constraint, especially when incoming large shipment volumes have to be scheduled through tight delivery windows for significant projects [2]. Effective PCC enhances predictability and stability across port-to-site flows. CONS at off-site hubs reduce upstream variability by enabling kitting, sequencing, and load transfer operations, thereby minimising partial loads and site congestion while supporting just-in-time delivery [10].

Effective consolidation improves labour productivity and reduces re-handling by ensuring materials are delivered in the correct sequence and quantity. However, it increases coordination demands among project actors if roles and information flows are not clearly defined. As sites become more congested, LMSL capabilities such as controlled access routing, phased deliveries, and coordinated unloading are critical for enhancing safety and delivery reliability [11], [12], [13]. The performance constructs examined in this study are grounded in established supply chain and operations theory. CQ, defined in terms of role clarity, information sharing, joint planning, and timely issue resolution, has been associated with improved operational alignment and enhanced project performance in both construction and broader supply chain contexts [14], [15]. DR is a primary SCOR metric and a crucial component of logistics performance indices; empirical research has discovered that reliability, rather than speed, is the driving factor for cost, schedule, and productivity outcomes in logistics-intensive sectors [16]. SA and LCP are the most common key performance indicators in construction and project management, with previous studies confirming their sensitivity to variability, flow disruptions, and logistics constraints [17], [18].

Despite the expanding body of research on construction logistics, critical gaps persist. Most studies focus on individual practices or isolated interventions rather than adopting an integrated model encompassing multiple TLM capability domains. Furthermore, limited research explicitly examines port-to-site logistics within the GCC context, despite the region's high import dependency and large-scale infrastructure development, which make logistics performance particularly critical [1], [2]. Also, mechanisms (LPAS, VIS, PCC, CONS, and LMSL) that affect performance outcomes such as delivery reliability and coordination quality are seldom examined within a holistic cause-and-effect framework. This study synthesises extant literature into an integrated framework comprising five core TLM capabilities (LPAS, VIS, PCC, CONS, and LMSL), two mediating constructs (DR and CQ), and two performance outcomes (SA and LCP).

The theoretical basis of the categorisation is represented in Table 1 and serves as a diagnostic tool for the SEM modelling. This, in turn, allows the study to quantify how the identified TLM capabilities, through delivery reliability and coordination quality, shape schedule adherence and logistics cost performance across GCC construction projects.

Table 1: Summary of constructs, indicators, and observable items

Construct	Indicator	Observable item (measured statement)	Relevant Literature
LPAS	LPAS1	Inbound deliveries are assigned appointment windows and site slots.	[1], [2], [7], [16], [18], [19], [20], [21], [22], [23]
	LPAS2	Arrivals are level-loaded across days/shifts.	
	LPAS3	Appointments are synchronised with work packages/ crews.	
	LPAS4	Early/late/missed arrivals trigger standard re-scheduling rules.	
	LPAS5	Appointment adherence is monitored and acted upon.	
VIS	VIS1	Shipments are tracked in real time from port/yard to site.	
	VIS2	Predictive ETAs are available and accurate.	
	VIS3	Exception alerts (delays/deviations) are timely and reliable.	
	VIS4	Milestones/geofence events are captured consistently.	
PCC	PCC1	Pre-clearance/advance filing reduces holds.	
	PCC2	Terminal coordination minimises dwell/demurrage.	
CONS	CONS1	Materials are consolidated at off-site yards before delivery.	
	CONS2	Kitting/packaging aligns with installation sequences.	
	CONS3	Partial loads are minimised through consolidation planning.	
LMSL	LMSL1	Site access/traffic plans are defined and enforced.	
	LMSL2	Cranes/hoists/offloading resources are pre-booked to time slots.	
	LMSL3	Last-mile routing accounts for restrictions/work zones.	
CQ	CQ1	Roles/responsibilities for logistics are clear across parties.	
	CQ2	Issues are escalated and resolved quickly.	
	CQ3	Plans/changes are communicated in a timely, transparent way.	
DR	DR1	Deliveries arrive within the agreed appointment window.	
	DR2	Lead times from yard/port to site show low variability.	
SA	SA1	Logistic related delays to milestones are rare.	
	SA2	Activities start on time when logistics is a dependency.	
	SA3	Workface planning proceeds without waiting for materials.	
LCP	LCP1	Actual logistics spend is within budget.	
	LCP2	Demurrage/detention costs are minimal.	

3 METHODOLOGY

The methodology of this study was systematically structured to examine how TLM capabilities influence coordination quality, delivery reliability, and project performance outcomes within GCC construction supply chains. As illustrated in the Methodology Framework (Figure 1), the research followed a sequential process. The study began with a focused review of the literature to define the nine latent constructs, develop their measurement indicators, and establish the hypothesised relationships. The questionnaire was subsequently refined through pilot testing and expert validation to enhance clarity and contextual appropriateness. The final survey was then distributed to relevant stakeholders across GCC countries. After data screening and preparation, the dataset was analysed using partial least squares structural equation modelling (PLS-SEM) to evaluate the measurement properties and test the proposed structural relationships, including direct and mediated effects.

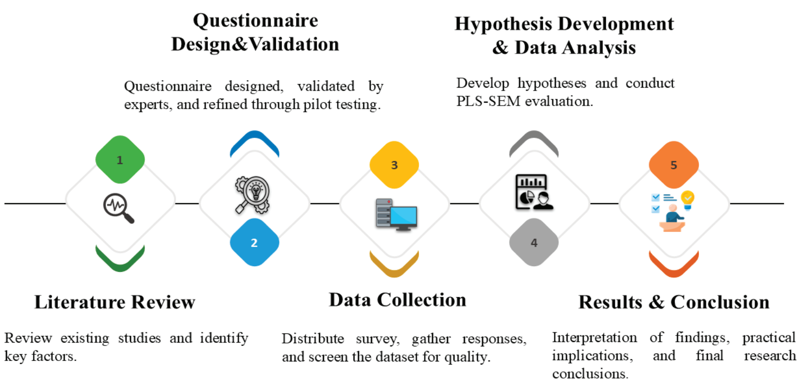

Figure 1: Methodology framework

3. 1 Questionnaire development and validation

The questionnaire was developed by converting the constructs identified in the literature into measurable indicators appropriate for the GCC construction logistics context. The survey consisted of two sections: a respondent-profile section and a construct-measurement section. All items were measured using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). Prior to large-scale distribution, the survey was refined through a pilot study and subsequently reviewed by 15 industry experts to enhance clarity, ensure contextual relevance, and revise or remove items that were ambiguous or conceptually overlapping. This process strengthened the content validity of the measurement framework.

3.2 Data collection

The final survey was distributed to construction and logistics stakeholders across GCC countries, including owners, contractors, and logistics providers. Following data screening for completeness and response quality, incomplete and low-quality submissions were excluded, resulting in 183 valid questionnaires retained for analysis. The proposed model comprises nine latent constructs, and the final sample size satisfies established minimum requirements for PLS-SEM. According to the widely cited 10-times rule, the minimum sample should be at least ten times the largest number of structural paths directed at any single construct in the model [23]. The available data set meets this requirement. In addition, analytical minimum-sample estimation approaches for PLS-SEM confirm that samples above these lower-bound thresholds are adequate for stable and reliable model estimation [24].

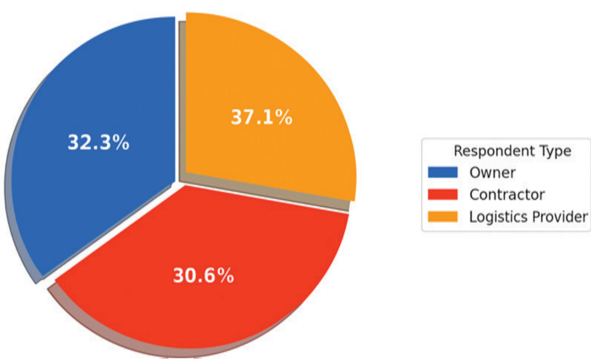

Figure 2: Distribution of respondents by organisation type

3.3 Hypothesis development and data analysis

The study hypotheses were formulated based on the literature review and the underlying theoretical framework, specifying empirically testable relationships among transportation and logistics management TLM capabilities, coordination quality, delivery reliability, and project performance outcomes. These relationships are illustrated in the conceptual framework shown in Figure 3. The model was estimated using (PLS-SEM), an appropriate technique for analysing multi-construct latent-variable models with an emphasis on variance explanation. A two-stage evaluation procedure was applied. First, the measurement model was assessed for reliability and validity using standardised loadings, Cronbach's alpha, composite reliability, average variance extracted (AVE), and discriminant validity criteria. Second, the structural model was examined using bootstrapped significance testing (5,000 resamples) and explained variance (R^2) for the outcome variables[25].

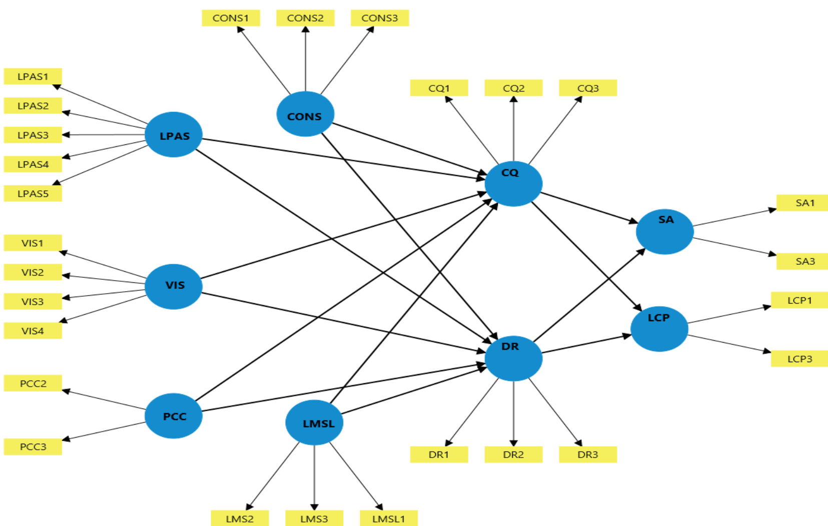

Figure 3: Hypothesis development using SEM

4 RESULTS

In this part, we present the results of the SEM analysis carried out to investigate the impact of TLM capabilities on coordination quality, delivery reliability, and project performance outcomes in GCC construction projects. The key results are grouped based on the SEM output available, which include the structural model, direct and indirect effects, indicator reliability, internal consistency, convergent validity, and model fit indices.

4.1 Indicator reliability

In the SEM presented in Figure 4, all indicators belonging to the constructs (LPAS, VIS, PCC, CONS, LMSL, CQ, DR, SA, and LCP) achieved standardised loading values above the critical threshold of 0.70, thereby confirming their reliability. The VIS indicators had values from 0.817 to 0.843, the LMSL indicators between 0.823 and 0.857, the DR indicators between 0.753 and 0.839, and the CQ indicators ranged from 0.857 to 0.931. This signifies that the observed variables are not only sufficient but also reliable in representing the latent constructs in the model.

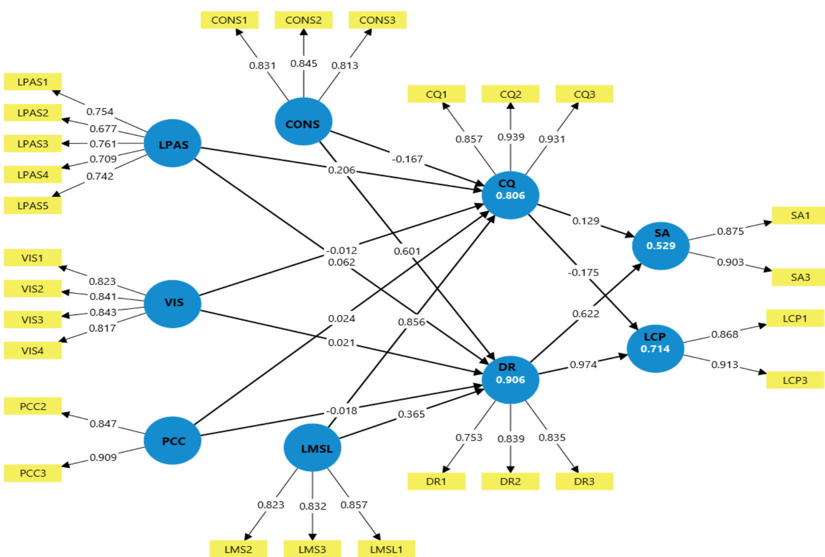

Figure 4: Validated framework using SEM

4.2 Internal consistency and convergent validity

The internal consistency of the constructs was assessed using Cronbach's alpha and Composite Reliability (CR), while convergent validity was evaluated through the Average Variance Extracted (AVE). All reported values meet or exceed the recommended thresholds ($\alpha \geq 0.70$, CR ≥ 0.70, AVE ≥ 0.50), indicating satisfactory measurement properties.

Notably, Coordination Quality (CQ) achieved $\alpha = 0.895$ and AVE = 0.827, Logistics Cost Performance (LCP) reported AVE = 0.793, and Delivery Reliability (DR) recorded AVE = 0.656, demonstrating strong internal consistency and adequate convergent validity across the constructs. Figure 5 summarises these results and supports the reliability and validity of the measurement model.

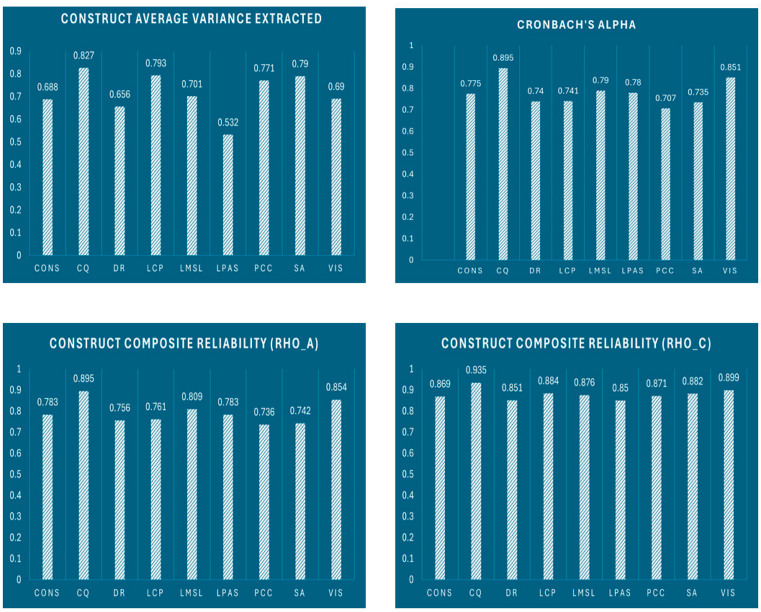

Figure 5: Construct reliability and convergent validity results

4.3 Direct effects of latent variables

Table 2 (Direct Effects) summarises the direct statistically significant relationships, where the strongest effects were noticed in DR → LCP (β = 0.974) and DR → SA (β = 0.622). Thus, delivery fidelity has been confirmed as the main predictor for the logistics cost performance and schedule adherence. The most important capability-to-coordination link was LMSL → CQ (β = 0.856), while the role of the consolidation branch in improving delivery reliability was pointed out by the coefficient of CONS → DR (β = 0.601). On the other hand, the connection of CONS → CQ (β = –0.167) manifested the negative coordination effect. In such a way, the consolidation processes might increase the coordination load or make the procedures more complex. LPAS, VIS, and PCC showed statistically significant but comparatively weaker effects, meaning that their involvement was more in the form of support rather than as a main direction in this sector.

Table 2: Statistically significant direct relationships

Paths	β (Path Coefficient)	T-value	P-value
CONS -> CQ	-0.167	3.001	0.003
CONS -> DR	0.601	6.715	< 0.001
CQ->LCP	-0.175	3.825	0.002
CQ -> SA	0.129	3.042	0.003
DR -> LCP	0.974	4.588	0.001
DR -> SA	0.622	3.886	0.002
LMSL -> CQ	0.856	7.226	< 0.001
LMSL -> DR	0.365	6.963	< 0.001
LPAS->CQ	0.206	4.401	0.001
LPAS -> DR	0.062	5.354	< 0.001
PCC->CQ	0.024	6.321	< 0.001
PCC -> DR	-0.018	4.304	0.001
VIS -> CQ	0.0012	3.137	0.003
VIS -> DR	0.021	7.353	< 0.001

4.4 Indirect effects of latent variables

Indirect pathways highlighted in Table 3 disclosed several TLM capability dimensions that affect performance outcomes through the mediation of delivery reliability and coordination quality. Delivery reliability was the most impactful mediating construct accounting for significant indirect effects for both LMSL and CONS on the two performance outcomes. These results, in turn, keep the original theoretical expectation of the model intact: TLM capabilities mainly improve project outcomes by elevating the reliability and coordination of material flow, instead of relying on direct effects solely.

Table 3: Statistically significant indirect relationships

Paths	T statistics	P values
CONS -> LCP	4.88	< 0.001
CONS->SA	5.86	< 0.001
LMSL->LCP	6.04	< 0.001
LMSL->SA	3.06	0.003
LPAS->LCP	4.32	0.001
LPAS->SA	3.11	0.003
PCC->LCP	2.97	0.004
PCC->SA	4.04	< 0.001
VIS -> LCP	3.13	0.003
VIS->SA	3.44	0.002

4.5 Model fit evaluation

Model fit indices shown in Table 4 provide a strong basis for the fact that SEM has achieved a good fit with the data. The value of SRMR of 0.073 is below the recommended cutoff of 0.08, which shows adequate fit. The NFI value of 0.804 indicates an acceptable level of model fit for exploratory research, while the R^2 value of 0.800 demonstrates strong explanatory power, with the model accounting for 80% of the variance in performance outcomes. The indices are evidence that the structural relationships being estimated are true, robust, and appropriate.

Table 4: Model fit indices

Model fit	Saturated model	Estimated model
SRMR	0.073	0.073
d_ULS	1.402	1.402
d_G	2.514	2.524
NFI	0.872	0.804
R^2	0.798	0.800

5 DISCUSSION

Evidence from SEM analysis shows that TLM capabilities not only have different effects but also have substantial effects on coordination, delivery reliability, and project outcomes in GCC construction projects. The capability that has the most significant effect on the coordination quality is LMSL, which has a coefficient of $\beta = 0.856$. This means that organising site logistics well, with the help of planning, control of access, and optimal routing, can bring about a major improvement in the overall coordination process. This finding agrees with operational problems faced in the GCC construction environment, as the sites that are congested and have limited access require last-mile practices to be very efficient. Meanwhile, the connection between CONS and delivery reliability is also crucial since it positively affects delivery reliability ($\beta = 0.601$) and negatively affects coordination quality ($\beta = -0.167$). Taken together, these findings indicate that while off-site kitting, staging, and consolidation stabilise material flows, they may increase coordination complexity due to additional process stages and handoffs. The coefficient variations underscore the need to integrate consolidation practices with clear communication protocols and role alignment to mitigate coordination inefficiencies.

The mediating constructs performed as expected. DR stood out as the most successful mediator in the model, which in turn, influenced logistics cost performance ($\beta = 0.974$) and schedule adherence ($\beta = 0.622$). The values certify that the reduction of delivery variability and the improvement of on-window arrival performance contribute significantly to the stated outcomes of downstream projects. CQ was found to have a more modest but equally relevant effect, by positively influencing the schedule adherence ($\beta = 0.129$) and negatively affecting the logistics cost performance ($\beta = -0.175$), meaning that coordination improvements should be mainly concentrated on schedule efficiency rather than cost efficiencies in this setting. LPAS, VIS, and PCC were found to be less potent, yet direct effects were markedly decreased, thereby confirming their role in enabling conditions rather than major stand-alone drivers. Low coefficients $|\beta|$ (generally $|\beta| < 0.10$) indicate that the improvements of the scheduling discipline, visibility, and port procedures play more of a supportive role rather than being independent factors for performance change.

The overall discussion suggests a logistics environment that is characterised by the stability of the flow through CONS and LMSL, combined with a coordination mechanism that improves performance. These findings extend the logistics management literature by offering empirical evidence from the GCC construction context and highlighting the performance advantages of reliability-focused and site-centric logistics capabilities.

6 CONCLUSION

This research employed structural equation modelling to probe how the capabilities of TLM can impact project performance in GCC construction settings. The findings provide evidence that DR is the key mediating mechanism, showing exceptionally strong influence on both logistics cost ($\beta = 0.974$) and schedule performance ($\beta = 0.622$). These findings confirm that precise delivery scheduling and the reduction of lead-time variability are the most significant determinants of project performance improvement, suggesting that embedding reliability-oriented logistics practices should be considered a strategic priority for construction projects across the GCC region.

In the context of upstream capabilities, Last-Mile/Site Logistics (LMSL) proved to be the most potent performance driver, significantly affecting the coordination quality ($\beta = 0.856$) and, in addition, the delivery reliability ($\beta = 0.365$) positively. It contains a message about the need for systematic site logistics planning, controlled access routing, and appropriate communication/coordination mechanisms, which can change upstream planning into effective site deliveries. CONS also contributes significantly to the process by reliability ($\beta = 0.601$) enhancement, but its negative influence on coordination ($\beta = -0.167$) indicates that these strategies are to be complemented with clear communication channels and well-aligned responsibilities to prevent operational friction.

The other capability areas like port/customs coordination, visibility systems, and appointment scheduling are indicated by lower coefficients, which means that, even though these functions are still very important to logistics flow, most of the project performance improvements can be ascribed to site-proximal capabilities and reliability-driven interventions.

With an overall explanatory power of $R^2 = 0.800$, the validated model demonstrates that the integrated framework effectively captures how logistics capabilities converge to influence performance. The results provide a practical roadmap for industry practitioners by illustrating that prioritising last-mile logistics, optimising consolidation processes, and strengthening reliability management will yield the most substantial improvements in both cost and schedule performance.

Future research could extend these insights by comparing capability impacts across project types, exploring country-specific operational differences within the GCC, or incorporating emerging digital technologies into the capability framework.

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PRODUCT AND PROCESS TECHNOLOGICAL INNOVATION AND FIRM'S PERFORMANCE IN SOUTH AFRICAN AUTOMOTIVE AND AUTOMOTIVE PARTS INDUSTRY

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ABSTRACT

With rapid technological innovations in the global automotive industry, the appreciation of the issues and decision-making for managers becomes relevant. An investigation is undertaken to determine whether product and process technological innovation options selected produce a measurable positive impact on firm performance and how the impact should be effectively assessed to inform managerial decision-making. An online survey, using a questionnaire, was undertaken among knowledgeable people conveniently sampled in selected firms, including managers and executives in production and sales functions, business development, CEOs and equivalent. The results showed a positive and significant relationship between product and process innovation, but not between product technological innovation and organisational performance. Similarly, no significant positive relationship was found between process innovation and firm performance. Segmentation by level of seniority, however, showed that results at lower and top management levels showed a negative correlation between all innovation and organisation performance, while middle management level results showed a positive correlation between process innovation and organisation performance. The findings suggest a lack of

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common understanding and unified purpose among management levels in the South African automotive industry on the critical role of technology innovation in driving competition, which may be a disadvantage for the sector, given the growing external competition.

Keywords: product innovation, process innovations, firm performance

1 INTRODUCTION

1.1 Research background/context

The South African automotive industry contributes about 5.3% of the country's Gross Domestic Product (GDP), and it is currently experiencing a shift in the matrix of car sales, with Chinese brands increasingly taking their share in the South African market [1]. Chinese brands in the South African market offer fresh, affordable products with new technological features, which can be seen as a threat to old players in the automotive market. Rapid technological innovations in the automotive industry, like self-driving motor vehicles, data analytics, data sensors, 360-degree-view camera systems, and lane assist and sleep detection systems, propel different entities to change their business models [2]. Digital transformation in the automotive industry enables businesses to innovate and change their business models to stay competitive in the market [3]. The use of technological innovation is vital for the growth, sustainability and success of business in the automotive industry [4].

Technological innovations are at the centre of the current evolution in the automotive sector. Artificial intelligence (AI), the Internet of Things (IoT), and 5G connectivity are among the innovations that are transforming the industry as enablers of interconnected systems and autonomous driving systems [5]. Machine learning (ML) is changing how vehicles are designed, manufactured and maintained. Robotics and automation are therefore increasingly being adopted in the manufacturing process of vehicles, allowing for a high degree of efficiency [6]. The objective of this study is to analyse the association between product and process technological innovation and firm performance in South Africa's automotive manufacturing industry.

2 LITERATURE REVIEW

2.1 Innovation

Innovation is described by Taylor [7] as the process of creating and implementing novel ideas, methods, products, services and solutions that yield significant improvements and value. The Organisation for Economic Co-operation and Development (OECD), a membership-based organisation of over thirty developed countries, initially classified innovations into two main categories, namely product innovation and process innovation. This segmentation was later expanded to include services like marketing and organisation [8]. For purposes of this paper, this study limits the scope to product and process innovation, and to the automotive industry. Koelmel et al. [9] found that technological innovations, such as advancements in electrification, connectivity, autonomous driving, artificial intelligence, and machine learning, amongst others, are changing the automotive industry on a global level. Changing consumer preferences, environmental regulations, and growing competition associated with lower prices of electric vehicles (EV) encourage transformational activities in the automotive industry. This is evidenced by global sales in electric vehicles increasing to over 17 million in 2024, an increase of about 26% over the previous year, with about half the sales attributed to China [10]. Autonomous driving technology, enabled by innovations like machine learning, sensors, and AI, represents a paradigm shift in the automobile sector [11]. Henao-García et al. [12] found that product and process innovations propel businesses towards economic growth and improved financial performance. Chen et al. [4], in studying the entire automotive supply chain industry in China, found that digital technology innovation impacts the performance of firms in the automotive industry.

2.2 Product innovation

Product innovation occurs when there is a major alteration in the features of current goods or when completely new and unique products are created [8], [13], new goods and services are released [14] or when there is an improvement in product functionalities attained by the customer [15]. Obtaining adequate capital investment to make new goods and services is important to the long-term viability of innovative operations [14]. In the automotive industry, embedded systems or innovative control systems have transformed the products from basic control systems to sophisticated systems that are mostly connected to engine control units (ECU), which enhance the interconnections, safety, communications networks, and decision-making, with some automotive manufacturers incorporating in their vehicles the capability to perform self-driving functions [16]. Saharti [17] notes that research and development (R&D), which is associated with product innovation, has an impact on firm performance.

2.3 Process innovation

Process innovation is defined in an earlier version of the Oslo manual [18] as:

> *"the implementation of a new or significantly improved production or delivery method',*

while a later version [8] expands the definition to include innovation in marketing and organisation, which may not suit this paper. This includes significant changes in techniques, equipment and/or software. Chigbu [19] found that job automation and automation of manufacturing factories are rapidly increasing in the automotive industry in South Africa, leading to less demand for labour and increased production efficiency and output. According to Sonko [16], the embedded systems or innovative control systems are shaping and changing the automotive industry with the introduction of artificial intelligence systems that can make decisions in real time, and businesses are changing their manufacturing processes to accommodate the changing environments. The changing environments, according to Chigbu [20] and Deonarain [21], necessitate joint human-machine interaction and collaboration, which in turn requires training and development of the workforce in the automobile manufacturing sector. Chigbu et al. [19] observe that there was increased human and machine collaboration in the South African automotive industry during the COVID-19 pandemic, although they also raise concern that the automation of manufacturing activities has contributed to the high unemployment rates in developing countries, including South Africa.

2.4 Product and process innovation

It is suggested that Toyota's operational processes, which allow for creative thinking and open innovation, lead to new product features and processes, suggesting a direct link between process innovation and product innovation [22]. For example, Chigbu et al. [20] found that changing environments led to the automation of processes and new products with AI abilities, necessitated by the need for automated processes in the automotive manufacturing sector in South Africa. Bogetoft's study [21] of several firms indicates that combining product innovation with process innovation drives higher performance in both the short and long run. With this background information, this study proposes the following hypothesis:

> ***H0: Product innovation has a positive correlation with process innovation.***

2.5 Innovation and firm performance

Gerguri-Rashiti [23] states that innovation is an important factor in determining the success of a business. Both financial and non-financial metrics may be used to highlight the effects of innovation on a company's performance [24]. There are several examples of this. Yang [25] states that innovative activities improve profitability by introducing fresh products and enhanced processes, leading to improved income and reduced expenditure. Sales growth and production output are used to rank the best companies in the automotive industry [1]. Furthermore, Becerra-Vicario [26] found that the use of technology and optimised methods of production led to high return on assets (ROA). Good financial management propels companies to invest in innovative activities, leading to improved firm performance [27]. Nwiepe and Grend [28] found that customer satisfaction and client loyalty, which are driven by product quality, improve sales and enhance profitability.

2.6 Measurement of innovations

Scholars have shown interest in understanding the measurement of product innovation and its impact on performances of organisations. Björk [29] states that measuring innovation is difficult and complex, but emphasises its importance for any firm that aims to achieve its innovative objectives. Nathan [30] used descriptive statistics analysis to measure the impact of new product performance in Small and Medium-sized Enterprises (SMEs) in the UK, which yielded positive results. Similarly, Feng [31] utilised descriptive statistics to measure the relationship between service innovations and the firm's performance, which yielded favourable results. Correlation and regression analyses were used by Gupta [32] to measure the relationship between product innovations and the firm's performance, with data obtained by means of a survey. Their findings yielded a positive relationship between product innovation and the firm's financial performance, but a negative correlation between process innovation and the performance of the firm. In a study to test performance in the automotive industry, Lascu [33] likewise obtained data by means of a survey, while hypothesis testing was conducted using statistical methods.

2.7 Product innovation and firm performance

The performance of a company is directly and favourably impacted by product innovation [34]. Yu [35] found a positive return on investment when measuring new product innovation performance, with product quality indicating a significant overall improvement. Despite findings from several scholars that product innovation has a positive impact on a firm's performance, Shouyo [36] argues that innovation may be resisted and even rejected outright by suppliers, customers and employees if the importance of the innovation initiatives is not recognised. It is of interest whether the same relationship would be observed in South Africa, as some authors hint of contextual differences [37], [17]. From the above arguments, the following hypothesis is proposed:

H1: Product innovation has a positive correlation with a company's performance.

2.8 Process innovation and the firm's performance

Hervas-Oliver [38] found that process innovation reduces manufacturing cost, increases production speed and has a favourable effect on performance. According to Lee [34], the output of process innovation is seen in the improvements in product quality, reduction in/production costs and higher efficiency during the manufacturing. Cherrafi [39] indicates that process innovation improves operational efficiency of the entire supply chain processes and positively affects the performance of a firm. Canh [40] found that process innovation in Vietnamese firms improved business operations, making them more appealing and leading to a positive performance. Katebi [37] found that there is a positive relationship between process innovation and a firm's organisational performance. However, they suggest that country and continent may be moderating factors. These arguments suggest that , while the findings for South African firms may be similar, they could also show differences. Therefore, the study proposes the following hypothesis:

H2: The performance of a company is positively linked with process innovation.

The conceptual model from the hypotheses proposed above is shown in Figure 1.

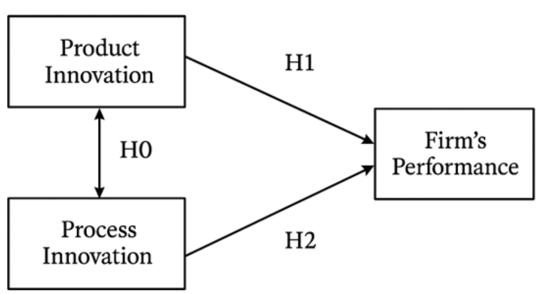

Figure 1 Conceptual model of innovation and firm performance

3 RESEARCH METHODOLOGY

The OSLO manual [8] is identified in the literature as the foremost authoritative guide on the measurement of innovations and is internationally recognised as the standard. Based on the guidelines of the OSLO manual [8], therefore, this study prepared a research instrument with the objective of measuring selected innovation types against firm performance. A quantitative research approach was selected to reach as many people as possible in the target population and reduce subjectivity bias [41]). The study made use of a survey to collect primary data and sought to relate two independent variables (product innovation and process innovation) with a dependent variable (firm performance).

While a longitudinal design is recommended by the OLSO manual [8] and Diaz-Fernandez [42], this study used a cross-sectional design to obtain information on innovation experience from participants. This choice was driven by constraints encountered at the inception of this research. A cross-sectional study is efficient and inexpensive without subjecting the process to any attrition, since information is only collected once from the participants [43]. The survey consisted of four sections, namely demographic, product innovation, process innovation and firm performance, making up a total of 31 questions. Demographic questions covered gender, age, tenure, company age and level of seniority. Product innovation consisted of six questions requiring the use of a 5-point Likert scale from "Strongly Disagree" to "Strongly Agree", including a neutral option. Guidance was obtained from the OLSO manual [8] and the questions were then converted into statements that made them suitable for the selected format of measurement. Scholars like Lee [34] and Tuan [44] also developed product innovation measurement instruments using the definitions and guidelines from the OLSO manual [8]. The process innovation section consisted of five questions, also using a 5-point Likert scale and developed with the guidance of the OLSO manual [8], then converted into statements that made them suitable for the selected format of measurement. The section on the firm's performance consisted of sixteen measurement questions created using a 5-point Likert scale from "Very Strong" to "Very Weak". The performance measurement questions were initially developed by Khandwalla [45] and have been used by other scholars like Miller [46] and Cragg [47]. The performance questions were both financial and non-financial key performance indicators (KPIs) that companies can use to measure performance, namely profitability, sales growth, financial resources (liquidity and investment capacity), production output, ROA), quality of the goods and services, public image, and client loyalty.

A questionnaire was distributed electronically to participants who held the following positions within firms: innovators, production/manufacturing managers, general managers, business analysts, sales executive managers, sales managers, business developers, COOs, CEOs, and similar positions. The survey included three response options for management level, namely lower management, middle management, and top management, selected to be broad enough to accommodate a wide range of job titles across different organisations. The survey link was sent via email, WhatsApp, Facebook and LinkedIn platforms.

Participants were obtained using convenience sampling. Initially, the survey was distributed on LinkedIn and Facebook platforms. However, as response was slow, a decision was made to have face-to-face consultations to ensure a better response. Respondents were sent a link via WhatsApp/email messaging systems to enable them to complete the surveys. While doing the consultations, complex company structures were identified; for instance, the Toyota Group has three main operations, namely the Toyota brand, the Lexus brand and the Hino truck brand. Toyota and Lexus operate as separate businesses, with Hino operating as a separate subsidiary. On the other hand, the retail distribution side of the business is affiliated with multiple entities who have the rights to use the Toyota brand name as their trading name. These entities, such as Motus Toyota and Bidvest McCarthy Toyota, among others, have their own financial reporting. Innovations have varying effects on these entities, whether emanating from the Toyota brand or from their own initiatives.

Only respondents who were willing and readily accessible participated. This yielded a response rate of 66.67%, considered acceptable for survey-based research and amenable to statistical analysis [48]. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was used to evaluate the data's suitability for multivariate analysis, with the range from 0 to 1 benchmarked, where values below 0.60 indicate insufficient sampling for factor analysis and values above 0.80 are deemed meritorious [49]. Cronbach's alpha [50] factorial analysis was conducted to test the validity and reliability of the measurement tool. Face validity check was applied to the survey [51]. Statistical Package for the Social Sciences (SPSS) software was used to analyse the data, from which Pearson's correlation and descriptive statistics were extracted to analyse the data obtained from the survey. The interval nature of the data gathered led to the selection of Pearson's correlation coefficient.

4 RESULTS

The results from forty responses will be discussed. While sixty firms were contacted, the forty responses received span the range of targeted respondents. The result is presented by demographic profiles, followed by the Correlation analysis with a drill-down correlation analysis segmented by level of seniority and descriptive statistics. Tests were conducted for validity and reliability. Sales volumes and production output data from NAAMSA were presented as supporting data for the presented results.

4.1 Reliability

Table 1 Cronbach's alpha

Variables	**Cronbach's alpha**
Product Innovation	.874
Process Innovation	.857
PerformAV	.938
PerformCOM	.938

Cronbach's alpha was used to measure the internal validity of the questionnaire tool used for the study and currently indicating an excellent average 0.922 reliability of the questions (Refer to Table 1).

4.2 Validity

Table 2 KMO and Bartlett's Test

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of sampling adequacy.		.754
Bartlett's Test of Sphericity	Approx. Chi-Square	755.489
	df	210
	Sig.	<.001

Factorial analysis was conducted for this study, using a Principal Component Analysis extraction method, with Varimax with Kaiser Normalisation rotation-. The Kaiser-Meyer-Olkin Measure of sampling adequacy indicates a good 0.754 measure (Refer to Table 2).

Table 3 Factorial analysis: Rotational components matrix

Variables	**1**	**2**	**3**
PerformCom_5	.901		
PerformCom_3	.879		
PerformCom_1	.872		
PerformCom_2	.856		
PerformAV_2	.850		
PerformAv_1	.849		
PerformCom_8	.832		
PerformAV_7	.824		
PerformAV_3	.814		
PerformAV_4	.803		
PerformAV_8	.798		
PerformCom_4	.795		
PerformAV_6	.782		

Process_4		.920	
Process_3		.789	
Process_6		.788	
Process_2		.763	
Process_5		.629	
Product_3			.837
Product_1			.827
Product_2			.817

The initial results were not meeting the validity standard required or desired for the study and as such the following variables were eliminated from the validity measurement tests shown in Table 3: product4, product5, process1, performAV5, performcom6 and performcom7. The table shows that all factors have values that are more than 0.6, which means that they are robust and proven to be strong measurements for the study. The performance variables are grouped together in column 1, process innovation variables are grouped together in column 2 and the product innovations are grouped together in column 3.

4.3 Demographic

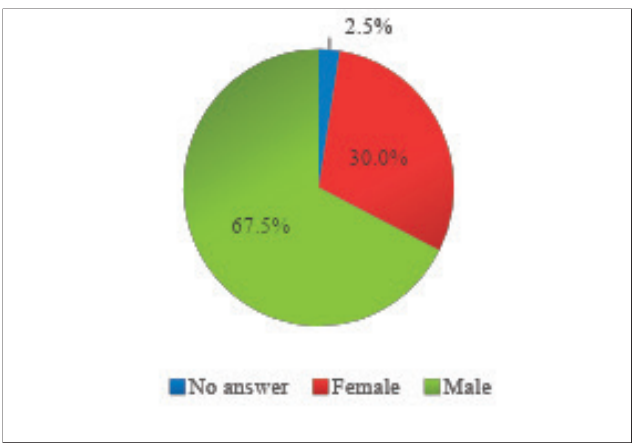

Figure 2 Gender

The gender participant statistics indicate a significantly high participation level among males, who comprised 67.5% of the survey, while females accounted for 30%, and 2.5% remains unspecified (Refer to Figure 2). According to NAACAM [52], 33.4% are in the automotive industry workforce, while 66% are male.

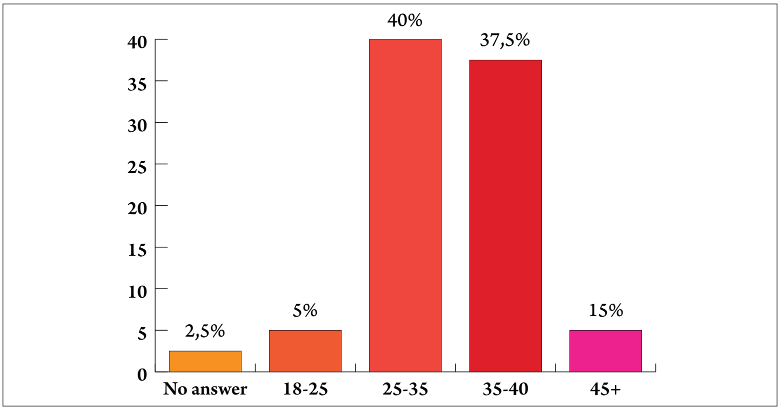

Figure 3 Age

The age demographic statistics show that 40% of participants are between the ages of 25-35, while 37.5% of participants are between the ages of 35-45 and 15% of the participants are 45 and older (Refer to Figure 3).

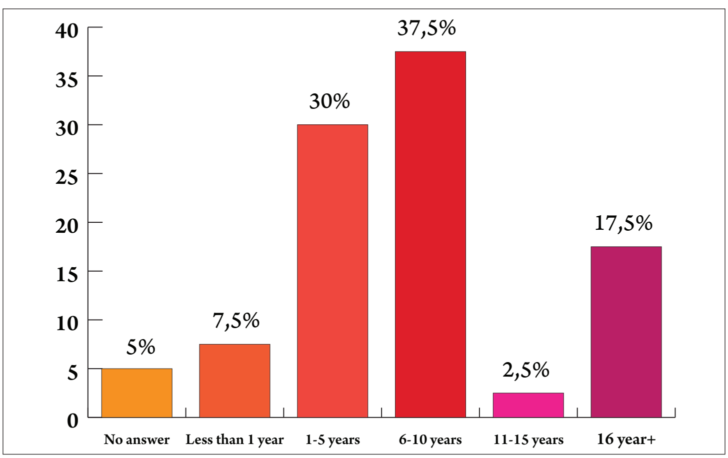

Figure 4 Tenure

The tenure demographics statistics indicate that 37.5%percent of the participants have worked at the same company for six to ten years, while 30% have worked at the same company for one to five years, and 17.5% have worked at the same company for 16 years or more (Refer to Figure 4).

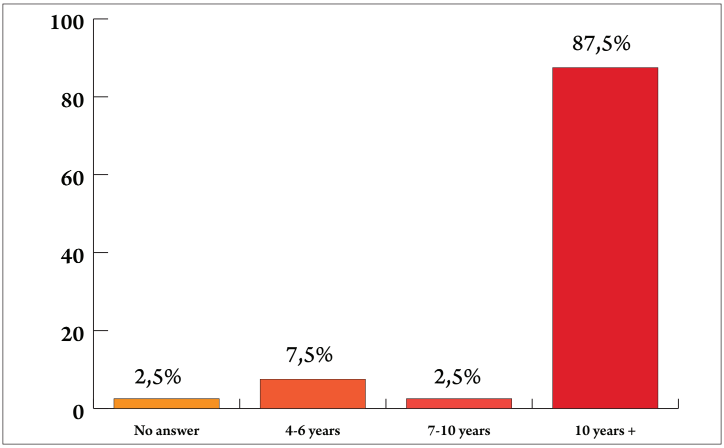

Figure 5 Company age

The demographics indicate that 87.5% of the participants work for companies that were started more than ten years ago, and 7.5% indicated that they work for companies that were started between four to six years ago (Refer to Figure 5).

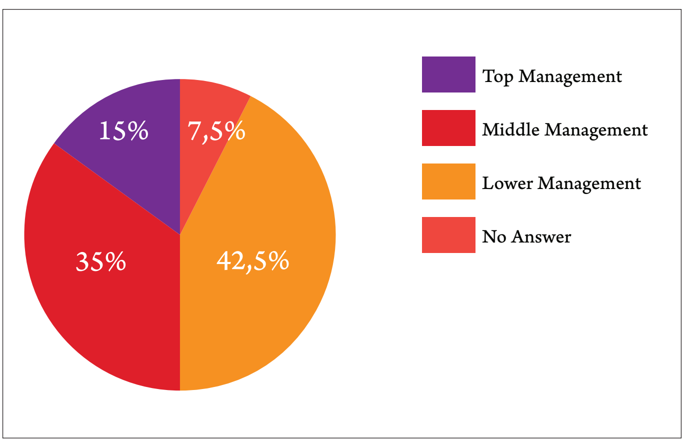

Figure 6 Level of seniority

The highest percentage of participants (42.5%) were at the lower management level, while 35% were in middle management, and 15% in top management (Refer to Figure 6).

4.4 Correlation analysis

Before conducting the correlation analysis, four indices were developed to systematically group related and highly correlated survey items (Refer to Table 4).

Table 4 Index summary

Index Name	**Purpose**	**Items Included**
INDEX-Product	Measures Product Innovation	Product_1, Product_2, Product_3, Product_4, Product_5
INDEX-Process	Measures Process Innovation	Process_1, Process_2, Process_3, Process_4, Process_5, Process_6
INDEX-PerformAV	Performance and Industry Average	PerformAV_1, PerformAV_2, PerformAV_3, PerformAV_4, PerformAV_5, PerformAV_6, PerformAV_7, PerformAV_8
INDEX-PerformCOM	Performance and Comparable Organisations	PerformCOM_1, PerformCOM_2, PerformCOM_3, PerformCOM_4, PerformCOM_5, PerformCOM_6, PerformCOM_7, PerformCOM_8

4.4.1 Main correlation analysis

Table 5 Pearson's Correlations (Summative correlations of the study)

		1	2	3	4
INDEX-Product	Pearson Correlation	--			
	N	39			
INDEX-Process	Pearson Correlation	.70^{5*}*	--		
	Sig. (2-tailed)	<.001			
	N	39	39		
INDEX-PerformAV	Pearson Correlation	.031	.015	--	
	Sig. (2-tailed)	.850	.928		
	N	39	39	39	

INDEX-PeformCOM	Pearson Correlation	.103	.068	.930**	--
	Sig. (2-tailed)	.533	.683	<.001	
	N	39	39	39	39
**. Correlation is significant at the 0.01 level (2-tailed).					

Main correlation analysis summary (Refer to Table 5):

- Correlation of product and process innovation = 0.705, significant at 0.01 level ($p < 0.01$) → H0 supported;
- Correlation of product innovation and PerformAV = 0.031, not significant → H1 not supported;
- Correlation of product innovation and PerformCOM = 0.103, not significant → H1 not supported;
- Correlation of process innovation and PerformAV = 0.150, not significant → H2 not supported, and,
- Correlation of process innovation and PerformCOM = 0.068, not significant → H2 not supported.

4.4.2 Correlations segmented by level of seniority

The results were segregated by the level of seniority in management ranks to understand the perspective derived from the impact of innovation from different levels of management. Different managerial ranks play a significant role in the decision-making or in influencing the decision-making process, particularly in the innovation initiatives of the business. Data were filtered into three sets, categorised by the three levels of seniority, and it was then used to evaluate the hypothesis. The three categories are as follows: Lower-level management, middle management and top management.

4.4.2.1 Lower-level management

Table 6 Lower-level management correlations

		1	2	3	4
INDEX-Product	Pearson Correlation	1			
	Sig. (2-tailed)				
	N	17			
INDEX-Process	Pearson Correlation	.823**	1		
	Sig. (2-tailed)	<,001			
	N	17	17		
INDEX-PeformAV	Pearson Correlation	-.400	-.437	1	
	Sig. (2-tailed)	.112	.079		
	N	17	17	17	
INDEX-PeformCOM	Pearson Correlation	-.486*	-.435	.883**	1
	Sig. (2-tailed)	.048	.081	<.001	
	N	17	17	17	17
**. Correlation is significant at the 0.01 level (2-tailed).					
*. Correlation is significant at the 0.05 level (2-tailed).					

Summary of lower-level correlations (Refer to Table 6):

- Correlation of INDEX-Product and INDEX-PerformAV = -0.400, not significant → H1 not supported;
- Correlation of INDEX-Product and INDEX-PerformCOM = -0.486*, significant at 0.05 level → H1 Accepted;
- Correlation of INDEX-Process and INDEX-PerformAV = -0.437, not significant → H2 not supported; and,
- Correlation of INDEX-Process and INDEX-PerformCOM = -0.435, not significant → H2 not supported.

4.4.2.2Middle management correlations

Table 7 Middle management correlations

		1	2	3	4
INDEX-Product	Pearson Correlation	1			
	Sig. (2-tailed)				
	N	14			
INDEX-Process	Pearson Correlation	.654*	1		
	Sig. (2-tailed)	.011			
	N	14	14		
INDEX-PerformAV	Pearson Correlation	.356	.542*	1	
	Sig. (2-tailed)	.212	.045		
	N	14	14	14	
INDEX-PerformCOM	Pearson Correlation	.195	.429	.922**	1
	Sig. (2-tailed)	.505	.126	<.001	
	N	14	14	14	14
*. Correlation is significant at the 0.05 level (2-tailed).					
**. Correlation is significant at the 0.01 level (2-tailed).					

Summary of the correlations for middle management (Refer to Table 7):

- Correlation of PerformAV and product innovation = 0.356 → H1 not supported;
- Correlation of PerformAV and process innovation = 0.542*, → H2 accepted;
- Correlation of PerformCOM and product innovation = 0.195 → H1 not supported; and,
- Correlation of PerformCOM and process innovation = 0.429 → H2 not supported.

Performance and industry average - Performance variables:

- Sales growth and process innovation-correlation = 0.652, $p < 0.05$* → Accept H2;

- Financial resources and process innovation: correlation = 0.853, $p < 0.01$ → Strongly accept H2; and,
- Client loyalty and process innovation: correlation = 0.561, $p < 0.05$* → Accept H2.

Performance and comparable organisations - Performance variable

- Financial resources and process innovation: correlation r = 0.549, $p < 0.01$ → Accept H2.

4.4.2.3 Top management

		1	2	3	4
INDEX-Product	Pearson Correlation	1	.823**	-.400	-.486*
	Sig. (2-tailed)		<.001	.112	.048
	N	17	17	17	17
INDEX-Process	Pearson Correlation	.823**	1	-.437	-.435
	Sig. (2-tailed)	<.001		.079	.081
	N	17	17	17	17
INDEX-PerformAV	Pearson Correlation	-.400	-.437	1	.883**
	Sig. (2-tailed)	.112	.079		<.001
	N	17	17	17	17
INDEX-PerformCOM	Pearson Correlation	-.486*	-.435	.883**	1
	Sig. (2-tailed)	.048	.081	<.001	
	N	17	17	17	17
** Correlation is significant at the 0.01 level (2-tailed).					
* Correlation is significant at the 0.05 level (2-tailed).					

Summary of top management correlations (Refer to Table 8):

- Correlation of INDEX-Product and INDEX-PerformAV = -0.400, not significant → H1 not supported;
- Correlation of INDEX-Product and INDEX-PerformCOM = -0.486*, significant at 0.05 level → H1 Accepted;
- Correlation of INDEX-PerformAV and INDEX-Process = -0.437, not significant → H2 not supported; and,

- Correlation of INDEX-PerformCOM and INDEX-Process = -0.435, not significant → H2 not supported.

4.5 Descriptive statistics

The analysis of the data from the survey reveals insights into the innovation activities and their performance within the surveyed organisations.

Table 9 Descriptive statistics

Variables	N	Minimum	Maximum	Mean	Std. Deviation
Product Innovation	39	1.00	5.00	3.9987	.85889
Process Innovation	39	1,00	5.00	3.6385	.89683
Perform AV	39	1.00	5.00	2.5449	1.11711
Perform COM	39	1.00	5.00	2.4602	1.12248
Valid N (listwise)	39				

Descriptive analysis summary (Refer to Table 9):

- Product innovation shows a mean of 3.9987 (SD = 0.85889), displaying strong presence;
- Process innovation shows a mean of 3.6385 (SD = 0.89683), also indicating significant activity;
- Performance and industry average scored a mean of 2.5449 (SD = 1.11711), reflecting low perception;
- Performance and comparable organisations scored a mean of 2.4602 (SD = 1.12248), similarly low; and,
- Performance perceptions are uncertain and generally below average, with high variability.

5 DISCUSSION

The discussion section will focus on the three sets of hypotheses, H0, H1 and H2. Descriptive statistics and NAAMSA data will be used to support the discussion.

H0: Product innovation has a positive relationship with process innovation.

The aim of H0 is to establish whether process innovation leads to product innovation, or whether product innovation leads to process innovation. The main finding of the study is that there is a positive, significant correlation between product and process innovation with a correlation of 0.705**, significant at 0.01. H0 was accepted.

H1: Product innovation has a positive correlation with a company's performance.

H1 aims to evaluate whether there is a positive correlation between product innovation and a firm's performance. The findings of this study imply a positive relationship between product innovation and a firm's performance, as shown by the correlation coefficients of 0.031 and 0.103. The correlation may be positive, but statistically not significant. Consequently, H1 is rejected. The results suggest that while product innovation may influence improvements in performance, the effect is not adequate to be considered significant in this study. Ayinaddis [41] found positive relations between product innovations and a firm's performance with a Pearson's correlation of 0.672**, significant at 0.01. The similarity with this study is the application of the measurement tools. However, while the result is positive for both studies, as mentioned, this study indicated insignificant relations with correlations of 0.031 and 0.103.

H2: The performance of a company is positively linked with process innovation.

The aim of H2 was to assess whether there is a positive relationship between process innovation and a firm's performance. Pearson's correlation coefficients of 0.015 and 0.068 show an insignificant positive relationship between process innovation and the organisation's performance. However, H2 was not accepted, since the relationship is insignificant. Ayinaddis [53] found a positive and significant relationship between a firm's performance and process innovations with a Pearson's correlation of 0.591**, significant at 0.01. The similarity with this study is again the application of the measurement tools.

H1 and H2 Segmented by level of seniority

For Lower-level management, both product innovation and process innovation show significant negative correlations between industry average performance and performance against comparable organisations. Specifically, product innovation has a correlation of -0.400 with industry average performance and a correlation of -0.486* with performance against comparable organisations, significant at 0.05 level, while process innovation has correlations of -0.437 with industry average performance and -0.435 with performance against comparable organisations. These negative correlations suggest that improvements in product and process innovation do not translate into better performance in terms of industry average performance and performance against comparable organisations for lower-level management. Consequently, both hypotheses H1 and H2 are rejected for this segment.

For middle management, the correlations displayed varied results. Industry average performance shows a weak positive correlation with product innovation (0.356), which is not statistically significant, and a positive correlation with process innovation (0.542*), significant at the 0.05 level. This shows that process innovation positively impacts performance benchmarked against an average industry performance, supporting H2 (accepted) but not H1(rejected). On the other hand, comparable organisations' performance has very weak and not statistically significant correlations with both product innovation (0.195) and process innovation (0.429). Therefore, both H1 and H2 are rejected for comparable organisations' performance. These findings suggest that while process innovation can enhance industry average performance, it does not have a significant impact on comparable organisations' performance at the middle management level.

Furthermore, a drill down of middle management correlation analysis was conducted, in order to understand the variables which revealed that process innovation is positively correlated with performance. Process innovation has a positive correlation with sales growth (0.652*), significant at the 0.05 level, implying that process innovation is important in enabling sales growth. Financial resources, which include liquidity and investment capacity, have a strong positive relationship with process innovation, with a correlation of 0.853**, significant at the 0.01 level, implying that a healthier financial position supports innovation effort. Client Loyalty positively correlates with process innovation, with a correlation of 0.561*, significant at the 0.05 level, signifying the importance of innovation in sustaining customer relationships. Moreover, performance against comparable organisations shows a positive correlation with financial resources (0.549*, significant at the 0.01 level), implying that financial strength can enhance competitive performance.

For top management, the correlations are predominantly negative. Product innovation has a -0.400 correlation with industry average performance and a 0.486* correlation with comparable organisations' performance, significant at the 0.05 level. Process innovation shows negative correlations with both the industry's average performance (-0.437) and comparable organisations' performance (-0.435), neither of which is statistically significant. These results suggest that product innovation has a considerable inverse association with performance in comparable organisations, while process innovation does not significantly impact performance metrics at the top management level. This could imply that top management may prioritise other strategic factors over product and process innovations when it comes to performance.

5.1 Descriptive statistics

Product innovation scored a mean of 3.998, indicating a strong presence perception by the participants. A standard deviation of 0.85889 was obtained, meaning that most respondents agreed that there is product innovation. The process innovation questions yielded a mean of 3.6385, meaning that most respondents agreed that process innovations exist in their organisations. The standard deviation of .89683 indicates that most responses were leaning towards the agree sections, which strongly confirms that process innovations exist within those organisations. Descriptive statistics firmly confirm that both process and product innovation exist in the surveyed entities.

Performance questions for industry average (Perform AV) indicated a mean of 2.5449, showing the uncertainty that exists among the respondents since most answers expressed a preference for neutrality. A standard deviation of 1.11711, with the range of the answers between 1 (very strong) and 4 (weak), strongly suggests that, while the average response may be neutral, the actual answers varied greatly. This supports some of the findings, particularly of the segmented sections, where middle management shows positive performances, while other tiers of management show negative performances. Similarly, performance questions for comparable organisations in the industry (Perform COM) indicated a mean of 2.4602, which, when rounded off to the nearest number, will be 3 (Neutral). The standard deviation is 1.12248, and the range of answers is between 1 (very strong) and 4 (weak).

5.2 Previous research

Innovation and firm performance findings from previous studies show mixed results. For example, in a study conducted by Na et al. (2019), the findings indicate that product innovation is significantly correlated to the sales growth of the firms, while process innovation negatively correlates with the growth of the firms. On the other hand, Kijkasiwat's [54] study on innovation and firm performance shows a significant positive correlation of 0.318 *** between innovation and firm performance and a substantial favourable relationship of 0.160 *** between financial capital and firm performance. The results are comparable to the segmented findings, where financial resources are positively associated with process innovation. While negative results have been reported in previous studies, most studies show positive results. Ayinaddis [53] found a positive association between product and process innovation with firm performance, yielding correlations of 0.672** and 0.591** respectively. These findings align with the segmented finding on process innovation of middle management, which positively correlates with performance.

5.3 Automotive market

Production of vehicles and sales of vehicles declined immediately after COVID-19 but have steadily recovered in the past five years. These findings suggest that external factors like supply chain disruption and decline in economic activities can lead to downtime for businesses [1]. Despite the harsh economic conditions experienced by the South African market, the market shows signs of resilience, with average sales increasing every year since COVID-19 regulations and supply chain disruptions ended.

Chinese brands like Cherry and GWM are strongly increasing their presence in the South African market, proving that the influence of technological features and sophisticated car design are positively impacting the sales growth of the businesses in the automobile sector [1]. New energy vehicles are also taking a stance in the market, showing that futuristic products with zero emissions may soon dominate the market. For example, major players in the market, like BMW and Mercedes-Benz, have plans in place to rapidly produce cars in this segment, hoping to dominate future markets [55].

6 CONCLUSION, LIMITATIONS AND FUTURE STUDIES

6.1 Conclusion

The main aim of the study was to investigate the connection between product technological innovation, process technological innovation and an organisation's performance. The overall results showed a positive, insignificant association between product and process technological innovations and an organisation's performance. However, findings from segmented results showed a positive and significant relationship between process innovation and an organisation's performance.

Segmented results, which were categorised by level of seniority, painted a mixed picture where top and lower-level management correlations indicated an inverse relationship between product and process innovation and the organisation's performance, while middle management correlations indicated that there is a positive and significant relationship between process innovation and a firm's performance and product innovation presented an insignificant association with performance. The findings from the middle management segment indicated that client loyalty, financial resources and sales growth are correlated to process innovations. These results from middle management are strongly aligned with the literature. By concentrating on process innovation, businesses can get client loyalty and attain a competitive advantage in the market.

Despite the findings used to test our hypotheses, the emergence of Chinese brands in the market cannot be ignored and brings new challenges to the industry, as these brands have already taken a significant portion of the South African market share. By observation, their success suggests that technological features and sophisticated design can enable a new entrant to the market to partake in a share of the market [44]. The success of Chinese brands suggests strong market forces at play by which customers' needs are satisfied via both technological and pricing models.

In conclusion, process and product innovations lead firms to achieve financial and non-financial objectives and enable firms to remain competitive and sustainable in the automotive industry, even in harsh economic conditions.

6.2 Limitations and future research recommendations

A cross-sectional approach for the survey design was used due to time constraints instead of a longitudinal approach recommended by the OLSO Manual [8]. Future research is encouraged to pursue a longitudinal method. This will allow for a more extended timeframe for the study, offering the potential for richer and more comprehensive data compared to the current cross-sectional approach.

During the COVID-19 pandemic, specifically between 2020 and 2022, industrial activity and data collection were disrupted by nationwide lockdowns. Consequently, the findings may show unusual circumstances that are not typical of how the industry functions. Additionally, the limited time and sensitivity of the information made it difficult to collect data from many companies, hence the sample size is limited to only 40 firms.

Future studies could benefit from exploring the relationship between the impact of product innovation and the impact of process innovation on customer satisfaction, particularly in the South African market, in an environment experiencing successful new entrants to the market. Another focus area for future research is the long-term impact of innovation on firm performance while considering additional moderating variables such as government policies, industry competition and technological adoption rates. As this study mainly focused on the management perspective, exploring the customer perspective presents a valuable opportunity for future research.

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COLLABORATION BETWEEN BUSINESS AND TECHNOLOGY TEAMS USING KNOWLEDGE MANAGEMENT SYSTEMS – LESSONS FROM FINANCIAL SERVICES

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ABSTRACT

The South African financial services sector, like manufacturing, faces growing pressure to deliver innovative products rapidly while complying with stringent regulatory requirements. Collaboration between business and technology teams becomes essential, yet is often hindered by organisational knowledge silos, inconsistent engagements across specialist teams, and an overreliance on tacit knowledge. Knowledge Management Systems (KMS) are widely adopted across the sector to address these challenges, but their effectiveness in enabling collaboration outcomes remains underexplored. This study examined the role of KMS in supporting cross-functional collaboration within a leading South African banking group. A mixed-methods approach was adopted by surveying KMS users across departments and conducting semi-structured interviews with senior technology and business executives. Most survey respondents believe KMS improve decision-making through shared insights and enhance performance in cross-functional projects. However, training gaps, poor user interfaces, overreliance on tacit expertise and the lack of integration

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of KMS in users' daily workflows emerged as persistent barriers limiting effectiveness. Executives reinforced these sentiments describing KMS as largely ineffective, static, and non-strategic. Executive sponsorship and organisational culture were noted as a positive driver of adoption, lessons manufacturing can learn. Leaders stressed the strategic imperative of AI-enabled KMS tools to transform static knowledge repositories into interactive decision tools.

Keywords: Knowledge Management System (KMS), cross-functional collaboration, South African financial services, knowledge management, technology adoption

1 INTRODUCTION

The development of financial products and services requires frequent collaboration between business and technical specialists across the organisation. Product development teams often include project managers, product managers, customer support specialists, business analysts, business intelligence analysts, legal and risk managers, software developers, and IT architects, each contributing their distinct domain knowledge. However, this diversity of domain knowledge among these stakeholders often results in communication barriers, knowledge silos, and ineffective decision-making. Enhancing cross-functional collaboration between these teams is, therefore, a crucial factor to the innovation success of new products in financial services [2].

KMS are widely acknowledged as collaboration tools within organisations. KMS can be defined as a class of information systems that facilitate and enhance the transfer of knowledge within an organisation [3]. Early research suggests that organisations that require cross-functional teams to develop products and services could potentially benefit from KMS [4]. More recently, it has been emphasised that Knowledge Management practices that facilitate the sharing and integration of knowledge across functions are essential for collaboration [5].

However, despite the known benefits of KMS in supporting collaboration between knowledge workers in financial services organisations, challenges persist. Domain knowledge in organisations remains largely tacit, embedded in individuals, and therefore difficult to codify, while additional barriers such as cultural resistance, fragmented systems, and siloed practices often limit the effectiveness of KMS in achieving their intended outcomes.

Financial services organisations in South Africa invest in KMS to support their product development efforts. In an early study of the implementation of knowledge management in South African financial organisations, 75% of respondents cited increased value for customers as a reason for investment in KMS [6]. South African authors have primarily addressed KMS themes such as the influence of organisational culture and multiculturalism on knowledge sharing [7], [8]. Another prominent theme is the factors influencing KMS adoption in organisations as reflected in a recent study which examined the adoption and use of KMS in South African municipalities [9]. Despite this body of work, there remains limited empirical evidence on the effectiveness of KMS in enabling collaboration between cross-functional teams engaged in product development within South African financial services firms.

The urgency of this research is heightened by converging external pressures on South African financial services organisations. The sector is the single largest contributor to the national economy, accounting for 0.8 percentage points of the 0.6% GDP growth in 2024 [1], which places organisational performance under heightened public and regulatory scrutiny. Simultaneously, the speed at which business and technology teams can collaborate to deliver innovations from concept to marketable product has become a critical competitive advantage [10], while the regulatory environment imposes compressed timelines for implementing compliance-driven projects [11]. These pressures, that is, economic significance, competitive speed-to-market demands, and regulatory deadlines converge toward a single organisational imperative: the need for rapid, effective decision-making across cross-functional teams, particularly between business specialists who define customer requirements and technology specialists who architect and build solutions.

KMS are adopted by financial services organisations precisely as a response to this imperative. By facilitating the codification, storage, and retrieval of institutional knowledge, KMS are intended to accelerate decision-making, reduce dependency on individual expertise, and enable distributed teams to access the knowledge required for rapid product development and regulatory compliance. However, the extent to which KMS effectively support cross-functional collaboration specifically, the knowledge transfer between business-focused and technology-focused teams remains underexplored in South African financial services contexts.

Knowledge gaps between collaborating project team members can significantly hinder timely decision-making required to deliver projects at market speed. These knowledge barriers are worsened by the increased dependence on experienced specialist employees' institutional knowledge, which increases operational risks. Although project teams are often staffed with roles such as project managers and business analysts whose purpose is to translate and coordinate information between business and technical expert contributors, they often lack the essential tacit knowledge required to understand domain specialists. Such roles are broadly characterised as boundary-spanning positions whose function is to import, translate, and transfer knowledge across the boundaries that separate distinct communities of practice within an organisation, such as by Tushman and Scanlan [12]. Levina and Vaast [13] also agree that individuals formally nominated to boundary-spanning positions frequently fail to become effective knowledge intermediaries in practice, because doing so requires legitimate participation in the practices of the specialist domains being bridged.

This research is therefore motivated by the need to find ways in which KMS can be effectively utilised to drive collaboration across cross-functional teams in South African financial services organisations. The South African financial services sector includes banks, insurers, investment managers, and financial technology firms. In 2024, The financial services industry in South Africa was the single largest contributor to GDP growth, adding a reported 0.8 percentage points to the overall 0,6% GDP growth rate [1]. Given its importance, enhancing collaboration and performance within financial services organisations are crucial for both organisational innovation and competitiveness, and the national economic wellbeing.

2 LITERATURE REVIEW

Cross functional collaboration is essential to project success in financial services organisations. Cross-functional integration is identified as a critical success factor in new product development [12]. It is argued in the literature that all forms of collaborative environments are fundamentally rooted in knowledge exchange, and that a strong relationship exists between collaboration and knowledge management [13]. However, such collaborative environments do not emerge automatically. The level of cross-functional collaboration in an organisation is influenced by factors such as the extent to which the organisational structure and culture encourage and promote knowledge sharing among its employees [14], [2]. Financial services organisations rely on knowledge workers to collaborate and drive innovation. Knowledge workers are defined as highly educated professionals who combine deep expertise in specific domains with broad interdisciplinary understanding, and who focus primarily on the creation, distribution, and application of knowledge [17], [18], [19]. Recognising the value of knowledge workers aligns with the Knowledge-Based View (KBV) of the firm, which is a theory that defines a firm as an institution for integrating knowledge in pursuit of competitive advantage [20].

The growing prominence of knowledge workers in global organisations has influenced the adoption of KMS to support collaboration, knowledge sharing, and enhance innovation in the workplace [21]. KMS can be broadly defined as software-based or process-based organisational systems that facilitate the capturing, transforming, sharing, and usage of knowledge within an organisation. By seamlessly integrating diverse knowledge sources within and outside an organisation, KMS can enhance cross-functional collaboration, and influence decision-making [22]. The management of a firm's knowledge assets is vital for gaining competitive advantage through innovation [23].

Before deploying KMS it is crucial for organisations to understand the different types of knowledge these tools are required to manage. Knowledge in an organisation can be generally classified into explicit and tacit types [24]. Explicit knowledge is unambiguous knowledge which can be easily documented or codified to be stored in information systems for sharing [25]. Examples of explicit knowledge in an organisation include manuals, white papers, and databases [26]. Tacit knowledge is defined as personal insight gained through human experience in a specific context [27]. Tacit knowledge is thus difficult to capture in a standard way without consulting the human source or knowledge holder [28]. Examples of tacit knowledge in an organisation include specialist skills and experience [26].

Organisations deploy various KMS tools to manage explicit knowledge efficiently and effectively. Document Management Systems (DMS) are an example of a KMS tool which serves as a repository for various file types, such as word documents, images, and Portable Document Format (PDF) files. DMS enhance organisational efficiency by streamlining the process of acquiring, organising, sharing, and retrieving data and information [29]. Knowledge portals are another common KMS tool that consolidates an organisation's data, documents, and services [30]. Atlassian Confluence, Microsoft SharePoint, and Google Workspace are common DMS and knowledge portals brands used in financial organisations.

Given its informal nature and difficulty to codify, managing tacit knowledge requires a different set of KMS tools. Organisations invest in discussion forum platforms that enable employees to informally exchange ideas and insights, therefore promoting a culture of collaboration and knowledge sharing within the organisation [31]. Common discussion forum KMS tools used in organisations include Slack, Microsoft Teams, Stack Overflow for Teams, and Confluence Questions.

While the strategic case for KMS is well documented, adoption and acceptance remain major challenges. Adoption depends not only on technological advancements but also on organisational recognition of knowledge as a strategic asset [32]. Similarly, some authors cite cultural misalignment and user resistance as barriers [33]. The difference between adoption (firm-level decision to implement a system) and acceptance (the behavioural and perceptual shifts of employees toward using it) should be well understood [34]. This distinction highlights why understanding user acceptance is crucial for the success of KMS.

The Technology Acceptance Model (TAM) offers a framework for explaining user acceptance. It posits that acceptance is shaped by two perceptions: whether a system enhances job performance and whether it is easy to use [35]. Later adaptations have reframed these as perceived usefulness and perceived ease of use, with studies showing that perceptions of difficulty or uselessness can drive resistance to new systems [36]. The model's strength lies in its empirical robustness across diverse technologies and its adaptability [37]. Extensions such as TAM2 and TAM3 incorporate external variables including social influence, voluntariness, and cultural dimensions, thus enhancing its predictive power [38].

Figure 1 below illustrates how users come to accept and use a technology through a sequence of interrelated factors. External variables (such as system design, organisational support, or training) influence users' perceptions of Perceived Usefulness and Perceived Ease of Use. A system that is easy to use tends to be perceived as more useful, thereby strengthening Attitude Toward Using the technology. This positive attitude, together with perceived usefulness, shapes the user's Behavioural

Intention to Use, which in turn leads to Actual System Use. In essence, TAM shows that when users find a system both easy to use and beneficial to their performance, they are more likely to adopt and consistently use it.

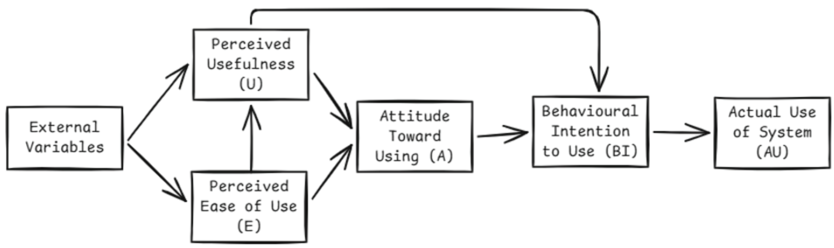

Figure 1: Technology acceptance model [35]

Despite these strengths, TAM faces important limitations in the organisational context of KMS. Its focus on individual-level acceptance overlooks organisational dynamics, reducing its explanatory power for collective adoption decisions [39]. The model is also criticised for being static, failing to capture evolving user behaviour over time [40]. Finally, it inadequately accounts for cultural variations that significantly shape user attitudes toward technology [41]. These critiques suggest that while TAM is useful, it must be complemented by broader frameworks when applied to complex, organisational-level systems such as KMS.

Scholars recommend several best practices to address the challenges of KMS adoption and acceptance. At the organisational level, leadership and strategic alignment are repeatedly emphasised. The importance of top management involvement and the use of incentive programmes to embed knowledge management in organisational culture and processes is emphasised [42]. Some authors advocate for appointing a chief knowledge officer (CKO) to champion the KM agenda [43]. The CKO has a key role to play in linking KM strategy to broader organisational objectives [44]. The agreement in the literature is that KM initiatives are most effective when fully integrated into business strategy and management activities [45], [46].

From a user perspective, research highlights the importance of social connection and perceived value in encouraging participation. Employees are more likely to adopt KMS if they feel socially connected and believe their contributions are valued and reciprocated [47]. Organisations must foster a culture where knowledge sharing is recognised as a valuable and rewarding activity [48], [49]. Together, these insights suggest that successful KMS adoption requires both strategic leadership from the top and supportive cultural conditions at the user level.

The intersection of collaboration and KMS adoption is particularly significant in financial services organisations. KMS investment supports IT service managers in resolving disruptions efficiently, thereby strengthening collaboration between technology and business functions [50]. South African financial organisations primarily invest in KMS to streamline processes across business units and enhance customer value and reduce costs [51], [6].

Taken together, the literature suggests that collaboration in financial services is both a precursor and a beneficiary of KMS adoption. Collaboration creates the cultural and structural conditions necessary for KMS to be effectively used, while KMS provide the tools that enable more efficient and productive collaboration. This reciprocal relationship underscores the centrality of collaboration-first approaches in conceptualising the role of KMS in South African financial services organisations.

3 METHODOLOGY

A pragmatic research paradigm is followed, chosen for its flexibility and problem-solving orientation in addressing under-researched and complex organisational challenges [52]. Pragmatism is particularly suited to exploratory studies, such as this one, which investigates how KMS drive collaboration between business and technology teams in South African financial services. A mixed-methods design was adopted to combine the breadth of quantitative data with the depth of qualitative insights. Five advantages of such an approach are:

- Triangulation: Cross- validates findings;
- Complementarity: Enables the elaboration of results across methods;
- Development: Uses insights from one method to inform the other;

- Initiation: Reveals contradictions and new perspectives; and,
- Expansion: Broadens the scope of inquiry [51].

In this study, the survey provided an overview of user-level perceptions and behaviours, while interviews offered in-depth exploration of leadership perspectives. This design aligns with a sequential exploratory strategy, where quantitative data offered a foundation that was later deepened through qualitative inquiry [54]. Although this design supported triangulation, the smaller than anticipated survey sample constrained the statistical power of the quantitative strand. As such, the qualitative component played a dominant role in validating and enriching findings.

A questionnaire was administered to 70 employees within a large South African financial services organisation. Fifty-three (53) out of the 70 participants responded to the survey. Respondents represented seven key departments or product areas, that is, EFT payments, insurance, core banking, home loans, corporate banking, vehicle finance, and credit card, and included both business-focused and IT-focused professionals. Business team respondents are defined as individuals whose primary responsibilities involve translating customer needs into documented business requirements, managing product ownership, assessing the operational impact of new innovations, managing operational risk, and overseeing process design. This category includes roles such as business analysts, product managers, business architects, and risk managers. Technology team respondents are defined as individuals primarily responsible for converting business requirements into software architectural designs, developing software applications that meet customer needs, and assessing the impact of new innovations on the organisation's technology portfolio. This category includes roles such as software engineers, solution architects, systems analysts, and system architects.

By targeting respondents in their capacity as active KMS users, the survey captured first-hand experiences of adoption, collaboration practices, and barriers to knowledge sharing. The survey was restricted to a single organisation rather than multiple institutions. While coverage of three departments provided some variation in perspectives, findings cannot be assumed to represent the broader South African financial services industry.

The questionnaire included both closed-ended Likert scale items, to measure perceptions of usefulness, ease of use, managerial encouragement, and collaboration behaviour; and open-ended questions, to identify challenges, enablers, and suggestions for improving adoption. Survey items were informed by established theoretical frameworks, such as the TAM and the KBV of the firm [20].

To complement the survey findings and capture leadership perspectives, four semi-structured interviews were conducted with senior executives across the South African financial services sector: the technology executive at a large South African insurer; head of the business project management office for the EFT payments division at a large South African bank; the chief operations officer (COO) for a retail home loans division of a large South African bank; and the business process optimisation head at the international division of a large South African bank. The interviews explored themes of organisational culture, structural enablers of collaboration, and the alignment of KMS with strategic objectives. Following principles of the Biographic-Narrative Interpretive Method (BNIM) [55], participants were encouraged to share personal narratives and experiences, allowing for emergent insights while maintaining a semi-structured format. Each interview lasted approximately 45 to 60 minutes. Data collection was deemed sufficient when thematic saturation was reached [52]. The interview sample was weighted heavily towards business-side leaders. While this yielded valuable executive leadership insights into KMS adoption, perspectives from technology-focused executives were less represented, limiting the balance of viewpoints.

A purposive sampling strategy was employed to ensure the inclusion of participants with direct knowledge of KMS use and project delivery in financial services. Purposive sampling is a non-random technique that enables researchers to target specific population groups most relevant to the research objectives [56]. For the survey, respondents were drawn from a single large financial services organisation but across diverse departments or product areas including EFT payments, insurance, core banking, home loans, corporate banking, vehicle finance, and credit card, thus offering variation in perspective despite being limited to a single organisation. For the interviews, an expert purposive sampling approach was used to target executives with strategic oversight of both business and technology functions. Although purposive sampling ensured relevance, the non-random nature of selection introduces potential bias. Respondents with positive or negative experiences may have been more motivated to participate, which could skew results. Results from the questionnaires were analysed using descriptive statistics to capture the frequency and distribution of responses in close-ended questions. This helped identify patterns and trends by showing how frequently specific responses occur in the data [57]. A thematic analysis was applied to categorise the most prevalent themes in the questionnaire and interview responses to open-ended questions. This method is typically used to analyse textual, visual, or audio content to identify patterns and emerging themes [58]. Content analysis typically involves two key steps, namely, coding, which involves categorising text segments using either predetermined or emerging themes, and interpretation, which focuses on finding patterns, as well as similarities and differences within those categories [59].

4 SURVEY RESULTS DISCUSSION

4.1 Profile of survey respondents

The survey respondents represent a diverse set of business and technology professionals within the South African financial services organisation. The most common job titles reported by respondents include systems analyst (14), business analyst (13), and business architect (7), collectively accounting for 64% of all survey participants. Supporting roles such as project managers, software engineers, and product specialists further illustrate a balanced representation across operational, technical, and managerial functions. Approximately 60% of respondents classified their roles as business-focused, while the remaining 40% identifying their roles as technology-focused. This distribution of roles as shown in Figures 2 and 3 below, illustrates that the survey represented both the creators and users of organisational knowledge, that is, those responsible for documenting business requirements and processes, implementing technical systems, and managing cross-functional projects.

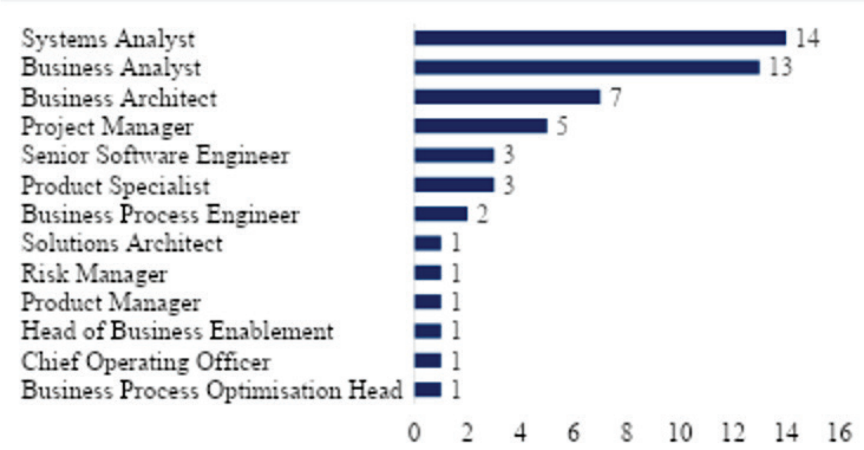

Figure 2: Number of survey respondents by job title

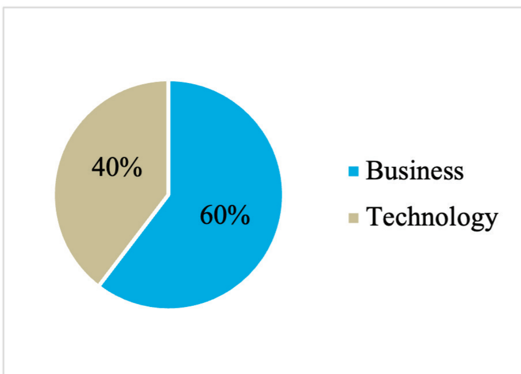

Figure 3: Distribution of respondents according to their organisational focus area

All respondents reported prior exposure to a KMS, with 72% using it daily, indicating both the awareness and experience to assess the practical value of KMS in supporting collaboration. The respondents had a balanced distribution of experience, with 36% of respondents having 5–10 years' experience, 32% of respondents having 0-5 years' experience, and another 32% having more than 10 years of experience delivering projects in financial services.

4.2 Reasons for knowledge management system use

The results in Figure 4 below show that collaboration on projects is by far the dominant reason respondents engage with their organisation's KMS , as cited by 51 out of the 53 participants. A substantial share of the participants uses KMS for sharing insights (33 out of 53), learning and development (25 out of 53), and understanding organisational processes (24 out 53), indicating that the platform plays a dual role in both knowledge dissemination and employee enablement. Other reasons noted by respondents include documenting business and technical requirements, as well as tracking project deliverables. Collectively, these findings highlight that while KMS are strongly embedded in daily collaboration and learning activities, there is an opportunity for them to evolve past their static knowledge repository use cases.

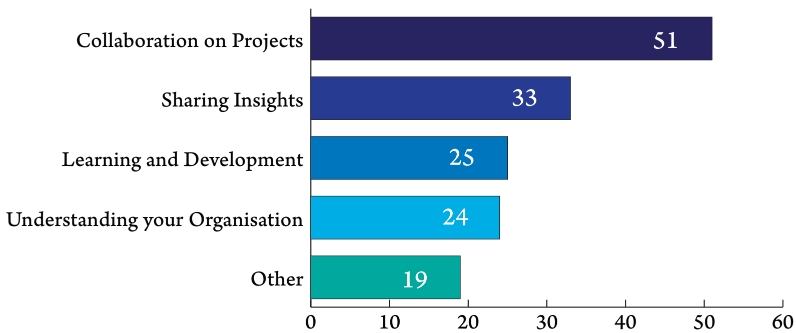

Figure 4: Survey respondents' reasons for using Knowledge Management Systems in the organisation

4.3 Barriers in Knowledge Management System use

The most frequently cited challenges in using the KMS include lack of system integration into daily workflows (29 responses; 55%) and insufficient user training (26 responses; 49%), highlighting structural and capability-related barriers to adoption. Other common issues include resistance to change from colleagues (24 responses; 45%), lack of incentives to share knowledge (20 responses; 38%), and limited time to contribute content (19 responses; 36%), reflecting cultural and workload constraints that hinder active participation. Less prevalent but still significant concerns are the poor KMS user interface (14 responses; 26%) and miscellaneous technical or procedural issues captured under the "Other" category. Collectively, these findings show that over half of respondents view workflow integration and user capability gaps as the primary impediments to effective KMS use, while nearly half attribute adoption challenges to cultural and motivational factors such as change resistance and limited recognition for knowledge sharing.

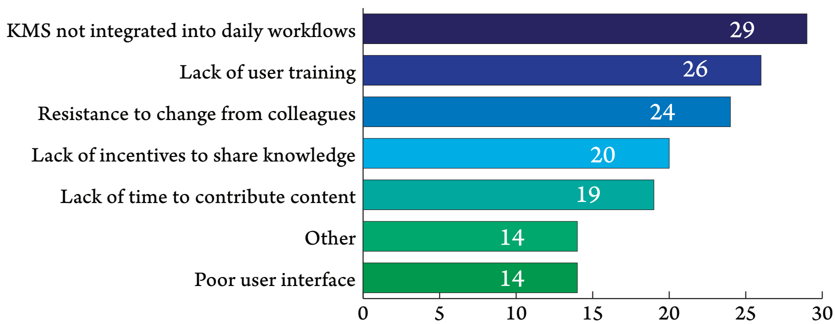

Figure 5: Barriers to effective use of Knowledge Management Systems

4.4 Issues hindering cross-functional collaboration

The leading KM issues hindering cross-functional collaboration, illustrated in Figure 6 below, were reliance on a few key individuals for critical knowledge (40 responses; 75%) and knowledge scattered across multiple unconnected sources (39 responses; 74%), both reflecting structural weaknesses in how knowledge is shared and stored. Other major barriers included inadequate documentation or capture of tacit, experience-based knowledge (35 responses; 66%) and a steep learning curve for understanding technical or business concepts (25 responses; 47%), indicating that both information management and skill accessibility constrain collaboration. Less frequent but still notable challenges were limited social interaction with subject-matter experts (18 responses; 34%) and minor "other" issues (5 responses; 9%). Collectively, these responses reveal that knowledge fragmentation, over-reliance on key individuals, and insufficient documentation are the primary obstacles to seamless cross-functional collaboration in the organisation.

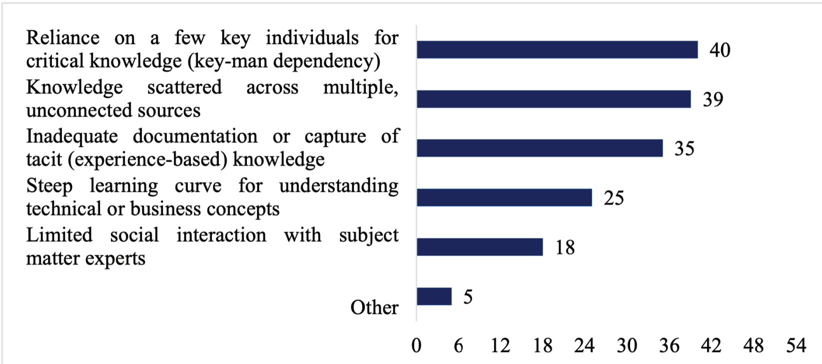

Figure 6: Prevalence of Knowledge Management specific issues hindering collaboration between business and technology teams

4.5 Perceived usefulness of Knowledge Management Systems

The results, in Figure 7 below, reveal a strong consensus among survey respondents that the KMS significantly enhances work performance and collaboration across departments. The highest-rated statement, 'Using the KMS enhances my performance in cross-functional projects', achieved a 91% positive response rate, showing that users clearly associate KMS use with improved productivity and collaboration outcomes. Similarly, 87% of respondents agreed that the system improves the quality of collaboration between business and IT, and 83% believed it helps them make better cross-departmental decisions. Interestingly, a little over half of the respondents (55%) agree that KMS helps reduce the time spent resolving cross-departmental issues. This suggests that cross-functional issues supersede the scope of KMS. These findings confirm a high level of Perceived Usefulness of KMS, a core predictor of technology acceptance under Davis's Technology Adoption Model.

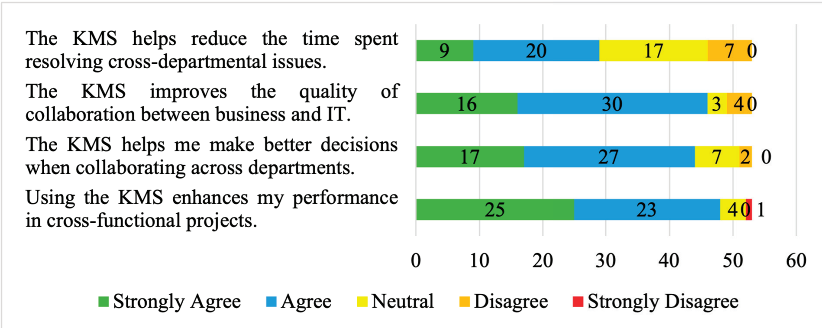

Figure 7: Survey responses to the question 'To what extent do you believe the Knowledge Management Systems enhances their job performance and supports collaboration?'

4.6 Perceived Ease of Use of Knowledge Management Systems

Respondents generally found their KMS easy to use, with 75–85% agreeing that it is simple to learn and operate, although fewer (around 60%) described it as fully intuitive or easy to navigate. The highest-rated statement, 'It is easy for me to learn how to use the KMS', achieved around 85% agreement, suggesting that initial adoption and onboarding are not major barriers. Similarly, 72% agreed that interacting with the KMS requires little mental effort, reinforcing a general sense of usability. However, slightly lower agreement levels for 'The KMS is intuitive and user-friendly' (~63%) and 'It is easy to retrieve the knowledge I need' (~58%) indicate some challenges in the KMS interface design and search efficiency. Overall, the findings reflect a positive but slightly uneven Perceived Ease of Use, suggesting that interface improvements and enhanced search functionality could further strengthen user experience and adoption.

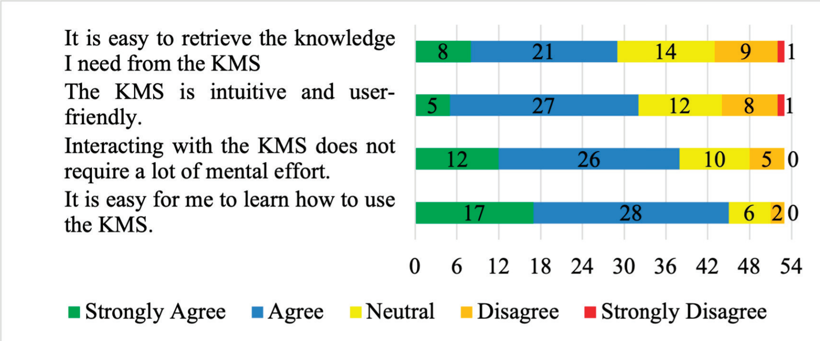

Figure 8: Survey responses to the question 'To what extent do you agree that Knowledge Management Systems is effortless and intuitive to use?'

4.7 Behavioural Intention to Use (BI) and Actual Use (AU) of Knowledge Management Systems

The results in Figure 9 below show strong behavioural intention to continue using the KMS, coupled with slightly lower levels of actual contribution activity. Almost all respondents (94%) either agreed or strongly agreed that they intend to continue using the KMS for future collaborative projects, and 90% would recommend it to colleagues. However, slightly fewer (~79%) reported actively contributing new or updated content, pointing to a gap between usage and content creation. Overall, these results confirm a strong Behavioural Intention (BI) under the Technology Adoption Model, but suggest that enhancing contribution incentives could strengthen Actual Use (AU) and turn passive users into active knowledge contributors.

The high behavioural intention (94%) contradicts the substantial barriers (55% lack workflow integration, 49% insufficient training) mentioned earlier. Behavioural intention, defined in TAM as an individual's subjective probability of performing a target behaviour [36], should theoretically be negatively influenced by such structural impediments. We interpret this deviation from classical TAM predictions as evidence that organisational norms and leadership endorsement override individual perceptions of barriers. In the financial services firm studied, KMS use is not discretionary but organisationally mandated and reinforced through managerial expectations. When technology adoption is subject to strong normative pressures, employees form high behavioural intention regardless of encountered barriers.

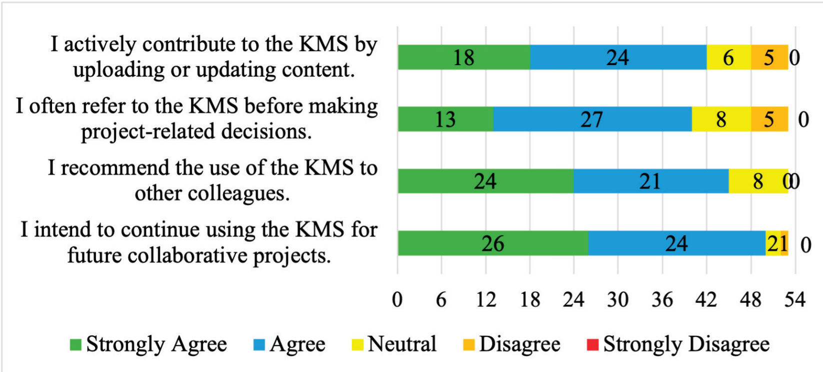

Figure 9: Survey responses to the question 'To what extent do you agree with the following statements?'

4.8 Organisational factors encouraging Knowledge Management Systems use

Figure 10 below illustrates that the majority of respondents (85%) felt that managers encourage KMS use, and 75% noted that their teams discuss it during project work, showing strong cultural support. However, fewer than half (43%) agreed that adequate training is provided, and only 64% felt the KMS aligns with departmental strategic goals. From a Technology Adoption Model (TAM2/TAM3) perspective, these organisational factors act as external variables influencing both Perceived Usefulness and Ease of Use. While cultural encouragement is clearly present, the limited training and alignment highlight a need for stronger facilitation, onboarding structures, and strategic linkage to sustain and deepen adoption across the organisation.

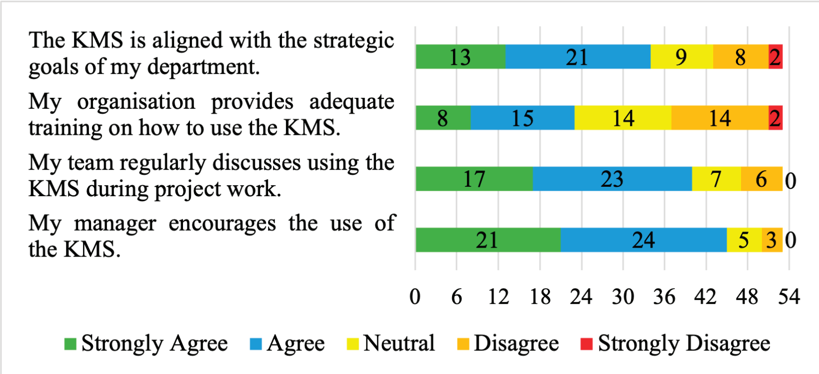

Figure 10: Survey responses to the question, 'To what extent do you agree with the following statements?'

4.9 Recommendations for Effective Knowledge Management Systems adoption

Most respondents emphasised frequent, practical, and role-specific training as the strongest driver of adoption. Statements like 'Frequent training and disabling manual operations' and 'Make training part of the onboarding process for new joiners' highlight a need for consistent upskilling across teams. Many participants stressed that visible leadership support and cultural alignment were essential. Responses such as 'Leaders must use KMS visibly to set the tone' and 'Strong leadership support and integration into daily workflows is essential' indicate that senior endorsement and consistent messaging are critical to changing user behaviour.

Several respondents argued that adoption will improve only when KMS tools are seamlessly integrated into existing platforms like Teams, Outlook, or JIRA. Respondents also suggested incentives, scorecard inclusion, and recognition programmes to drive accountability. One noted, 'Make it a performance goal in the scorecards and incentivise compliance', while another called for knowledge champions and curators to maintain clean, relevant content.

Lastly, participants highlighted the importance of content freshness, structure, and user experience. Several urged for a 'well-structured taxonomy with searchable keywords', 'reduction in login barriers', and 'AI-enabled summarisation tools. Respondents believe that clean, updated, and intuitive systems would foster trust and voluntary usage, especially if AI-driven insights reduce time spent searching for information.

The word cloud in Figure 11 below summarises the most common sentiments shared in the response to the open-ended question.

Figure 11: Common themes shared by survey respondents on how to improve Knowledge Management Systems adoption

5 INTERVIEW RESULTS AND DISCUSSION

5.1 Current use and effectiveness of Knowledge Management Systems

Interviewed executives recognise the use of their organisation's KMS mainly for their function as repositories rather than collaboration tools. These repositories are created and used in different ways depending on the business unit and organisation level. Interviewee C captured the different ways of work across the organisation by stating that 'at a group level we have the X toolkit...[where] you can find information about different capabilities and even watch videos', whereas 'In my business area, we use Teams channels with folders for strategy, values, and processes so that knowledge is easily accessible'.

Executives expressed mixed sentiments about the effectiveness of KMS for collaboration. Some, like Interviewee A, highlighted that users often create and use knowledge repositories individually which does not foster collaboration. She stated that 'Multiple people may edit documents, but that's not true collaboration'. Interviewee B, who framed his view from a project management perspective, believes that 'Effectiveness really depends on who's driving the project…if leadership enforces documentation, people comply; otherwise, it falls away'.

Their collective views suggest that although KMS are widespread, they are underutilised for interactive collaboration and their effectiveness hinges less on the technology and more on leadership and culture.

5.2 Non-KMS factors influencing cross-functional collaboration

All four interviewees underscored culture and change management as critical determinants of KMS success. Interviewee A linked collaboration quality to 'the ways of work that you've established as a team', while Interviewee B asserted that 'if your teams don't see value in sharing, no system will fix that'. Interviewee C warned that 'unless people use it and see the benefit, it won't add value' and Interviewee D pointed to 'different teams having different cultures' that fragment collaboration. The findings reveal that behavioural alignment outweighs technical sophistication.

5.3 Strategic priority of Knowledge Management Systems adoption and leadership's role in encouraging Knowledge Management Systems use

Each respondent regarded KMS as strategically important but variably implemented. Interviewee A tied it to financial services competitiveness stating that 'Whoever gets better insights faster will win the game''. Interviewee B viewed it as essential for retention of intellectual property, stating, 'Knowledge loss is a real issue when people leave'. A shared belief emerged that executive sponsorship and visible champions are critical for KMS adoption. Interviewee C stated, 'you want to have that champion… who really believes in it and champions it within the right environments', likening this to the role of the chief knowledge officer explored by Chauke and Snyman (2003).

5.4 Future of Knowledge Management Systems with emerging technologies (GenAI and AI)

All participants were optimistic about AI transforming KMS from static document repositories into interactive intelligent systems. Interviewee A foresaw 'GenAI making systems smart' by surfacing insights from large volumes of documents in the KMS repository. Interviewee B envisioned an advanced 'interactive use' where AI could 'draw me a conceptual diagram… something that would take a week is now done in an hour'. Interviewee C cited 'GPT at Work' for querying repositories through prompts, and Interviewee D envisioned 'a chatbot for KMS' that 'only helps if documentation is proper'. The shared theme is that AI's value will depend on the quality of the content.

5.5 Recommendations for Effective Knowledge Management Systems use for cross-functional collaboration

Most interviewees suggested solutions that focus on improving the quality of the content/knowledge stored in KMS. Interviewee A warned that 'irrelevant data makes even the best KMS useless'. A cultural shift was also suggested as a potential solution, a sentiment echoed by Interviewee D who suggested that employees should 'intently read through documentation' rather than rely on others for information.

Respondents also viewed organisational standards for documentation as the remedy for key-man dependency risk. Interviewee B described efforts to build 'structured onboarding and handover packs' for knowledge consumers. Interviewee C stressed keeping content 'updated and relevant' and Interviewee D advocated a 'document-first operating model'. Timely, standardised knowledge capture is thus essential for institutional continuity.

6 CONCLUSION

Both survey and interview data revealed that the greatest challenges lie not in the technology itself, but in organisational and behavioural factors such as fragmented systems, reliance on key individuals, lack of incentives, and limited integration with daily workflows. Executives reinforced that leadership visibility, cultural alignment, and consistent training are essential for turning KMS from passive repositories into active collaboration platforms. The study concludes that effective KMS adoption requires embedding the systems into existing processes, incentivising knowledge sharing, and ensuring high-quality, up-to-date content.

Future research should focus on designing a structured decision-making framework that enables executives to systematically assess the maturity, effectiveness, and strategic alignment of their organisation's KMS. By combining organisational performance measures with technology acceptance dimensions, such a framework would help leaders identify whether their KMS operates merely as a document repository or as an active enabler of cross-functional collaboration. The model could further provide diagnostic tools to highlight specific gaps in training, governance, and technological integration, guiding investment decisions and prioritisation of improvement efforts. Importantly, future studies could validate the framework across multiple financial institutions to establish its robustness and generalisability within the South African financial services sector and beyond.

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IMPACT OF GREEN SUPPLY CHAIN PRACTICES ON OPERATIONAL PERFORMANCE: SEM ANALYSIS IN SAUDI ARABIA

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ABSTRACT

This study investigates the impact of Green Supply Chain Management (GSCM) practices on operational performance within Saudi Arabian firms. Employing a quantitative survey-based approach, data was collected from managers in diverse sectors actively engaged in sustainable practices. Structural Equation Modelling (SEM) was utilised to analyse the data, validating a theoretical framework that links specific GSCM practices, including eco-design, green procurement, internal environmental management, and cooperation with customers to enhance operational outcomes. Preliminary results indicate a significant positive relationship between adopting green practices and improvements in efficiency, cost reduction, and quality. This research highlights the importance of integrating sustainability into operational strategies and provides practical implications for managers seeking to enhance their firm's operational effectiveness through environmentally responsible practices.

Keywords: Green Supply Chain Management, operational performance, sustainability, Structural Equation Modelling, Saudi Arabia

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1 INTRODUCTION

To address environmental laws, stakeholder expectations, and climate change, modern organisations are under increasing pressure to integrate their supply chains and operations with sustainability. Green Supply Chain Management (GSCM) is a strategy that enhances the sustainability of operations and products while meeting environmental standards [1]. Businesses must reassess their supply chains to meet global environmental challenges, such as greenhouse gas GHG emissions, climate change, and the growing demand for sustainable products [2]. To promote sustainability, many companies have adopted more sustainable supply chain practices. These include carrying out environmental audits, putting certification systems in place, assisting suppliers with their ecological projects, and encouraging collaboration in environmental endeavours [3]. Governments and organisations worldwide are actively working to lessen their environmental impact by the use of sustainable materials, environmentally friendly production techniques, and effective post-consumer waste management strategies [4]. According to [5], [6], several companies have adopted green supply chain practices (GSCP) to enhance quality, reduce expenses, and benefit the environment. GSCM is considered an essential component of business growth and development [7]. It has been observed that companies have adopted GSCM strategies to meet environmental regulations and offer environmentally friendly products and services. Given the growing environmental concerns, businesses will likely need to deal with consumers as well as suppliers in a more environmentally conscious manner [8]. The literature on environmental management indicates that green operations are closely tied to the ecological practices that accompany them. This reduces product deterioration and benefits supply chain operations that rely on natural resources [9]. By adopting green business techniques like GSCM, companies can enhance operational performance and contribute to the creation of a more sustainable future [10].

The relationship between GSCM and performance has not yet been proved in every situation, despite the clear benefits. Since there is insufficient evidence that implementing GSCM enhances the performance of a firm in terms of economics, operations, or the environment, organisations have typically had trouble encouraging its adoption [11]. Given the conflicting findings from various studies, it is imperative to explore the potential advancements that GSCM can offer in understanding its impact on business success. Regarding the relationship between GSCM practices and business performance, conflicting information exists. The study by [12] also highlights the lack of studies on the relationship between GSCM and performance in developing countries. Moreover, developing nations still do not employ GSCM extensively [13]. Additionally, in a study conducted on manufacturing companies in Jordan [14], no connection was found between GSCM and commercial performance. These factors serve as the driving force behind the current investigation, which aims to better understand the connection between operational performance and GSCM. Moreover, COVID-19 has significantly increased awareness of GSCM. This ambiguity, combined with the comparatively small amount of GSCM research that focuses on the Middle East, provides compelling justification for the current investigation. Saudi Arabia offers a crucial context: the country is pursuing economic diversification and sustainable development as part of the Vision 2030 initiative, which is motivating its businesses to modernise their supply chains and embrace more environmentally friendly methods [15].

Saudi Arabia represents a relevant setting for examining the operational implications of GSCM. Recent empirical work in the Saudi industrial context explicitly frames GSCM adoption within the broader sustainability and diversification commitments associated with Vision 2030, suggesting that firms face increasing strategic incentives to embed environmental criteria into supply chain decisions [15]. At the same time, context-specific evidence on how distinct GSCM capabilities translate into operational outcomes remains limited, motivating the present study's focus on eco-design (ECO), green procurement (GP), Internal Environmental Management (IEM), and customer cooperation (CC) as pathways to enhanced operational performance (OP). However, there remains a lack of comprehensive research on how GSCM adoption affects OP in Saudi businesses. To close this gap, this study examines the impact of several GSCM practices: ECO, GP, IEM, and customer collaboration on OP outcomes. Using a survey-based methodology and Structural Equation Modelling (SEM), we aim to address the question of whether GSCM truly helps firms achieve the desired and better OP. Our paper addresses requests for additional empirical data on the connections between GSCM and performance in emerging nations by examining this subject.

2 LITERATURE REVIEW

2.1 Green Supply Chain Management (GSCM) and key practices

GSCM refers to the integration of environmentally friendly practices into supply chain operations, involving product design, material sourcing, manufacturing processes, distribution, and end-of-life management [16]. It is aimed at reducing environmental burden while achieving business objectives [17]. This concept gained popularity in the early 2000s with growing global emphasis on sustainability, as firms recognised that supply chains play an essential role in managing environmental impact [18]. Implementing GSCM has multiple benefits: it can reduce waste and emissions, improve resource efficiency, and strengthen compliance with environmental regulations, all of which contribute to better operational and financial performance [19]. It has been found that companies engaging in practices like green purchasing, eco-friendly product design, and recycling tend to achieve superior environmental and operational outcomes, including cost savings and innovation gains [20].

2.2 Eco-design (green product design) (ECO)

ECO techniques are incorporated into the production, packaging, and distribution of products. Among all the advantages, the organisation's sustainable performance is the most notable [6]. Because it offers a greater environmental commitment, ECO is an essential technique in GSCM for the company's sustainability performance [6]. ECO involves designing products and packaging with minimal environmental impact, focusing on resource efficiency and recyclability from the outset. Since ECO was first proposed by the World Business Council for Sustainable Development (WBCSD), it has affected a product's whole life cycle [21]. Eco-friendly designs enhance environmental performance by minimising environmental impacts [22]. Typical factors include designing products to reduce material and energy usage, designing for reuse/recycling of components, and substituting or eliminating hazardous materials in product and process design.

2.3 Green procurement (green purchasing) (GP)

Considering environmental concerns in purchasing is referred to as "green purchasing," also called "environmentally friendly purchasing" [23]. GP ensures that the material is free from hazardous substances and beneficial to the environment. The idea behind "green purchasing" is that suppliers have to comply with the organisation's established green standards [24]. By utilising and protecting resources, green purchasing enhances economic performance and provides a competitive advantage over the competition. GP promotes social performance by strengthening relationships with stakeholders and improving the organisation's reputation among consumers, society, and the government [25]. There is a favourable correlation between green purchasing and operational performance [26]. GP is essential for both economic and environmental performance, and it is a reliable strategy for reducing pollution [27]. This latent variable represents green purchasing practices in the supply chain. Its key factors include preferring eco-labelled products and environmentally friendly inputs, cooperating with suppliers on environmental objectives, performing environmental audits of suppliers, and requiring suppliers' environmental certification (e.g., ISO 14000). These items have been widely applied in GSCM studies to assess the extent to which ecological criteria are integrated into procurement.

2.4 Internal Environmental Management (IEM)

IEM encompasses the internal policies, systems, and initiatives within a firm that facilitate environmental stewardship in operations [28]. The tactical incorporation of environmental sustainability within a company, recognised and endorsed by managers at all seniority levels, is known as Integrated Environmental Management (IEM) [29]. It is regarded as a crucial part of GSCM [30]. Several environmental regulations, internal policies, assessments of environmental impacts, quantifiable environmental goals, action plans, roles and responsibilities, and regular audits are all part of this structured approach [12]. Therefore, the adoption of IEM requires a systematic monitoring and auditing mechanism [31]. This latent variable shows a firm's internal support for environmental initiatives. Factors include senior management's commitment to GSCM, cross-functional cooperation for environmental improvement, implementation of environmental auditing programmes, and attainment of ISO 14001 certification or an equivalent environmental management system.

2.5 Cooperation with customers (CC)

The company's primary stakeholders are its customers, who have the power to affect the company's policies and manufacturing processes [32]. This practice involves working closely with customers to achieve environmental objectives, such as developing greener products, implementing reuse or recycling programmes, or creating take-back systems for end-of-life products. Consumers can put pressure on businesses to adopt environmentally friendly practices to avoid environmental damage [33]. Strong customer collaboration improves an organisation's GSCM, which in turn boosts productivity and sustainability performance. To encourage GSCM practices in a business, management must accommodate all stakeholders, especially customers [34]. The relationship between supplier evaluation and selection has no significant impact on sustainability performance. When consumer cooperation was taken into account, it was discovered to have a substantial negative correlation with sustainability performance [35]. This latent variable illustrates the extent of collaborative environmental practices with downstream partners. Factors identified in the literature include joint ECO with customers, cooperation for cleaner production processes, and collaboration on green packaging or product recovery programs.

2.6 Operational performance (OP)

The effect of GSCM techniques on OP is frequently illustrated using the Resource-Based View (RBV) hypothesis [6], [30]. According to the RBV, to attain long-term profit, industries must improve their resources and capabilities and make efficient use of them [36]. An intentional asset is described by RBV theory as a resource with the characteristics of rarity, importance, and difficulty to duplicate or replace [37]. Businesses can increase their competitive edge and achieve above-average profits by creatively and strategically integrating these assets [38]. According to the hypothesis, a company's total OP can be significantly impacted by the use of GSCM procedures [30]. Empirical studies support this linkage: for example, implementing GSCM can improve resource utilisation (through energy and materials savings) and process efficiency (through waste reduction and streamlined workflows), leading to lower operational costs and higher productivity [19]. In this study, OP is the primary outcome latent construct, reflecting the firm's internal performance efficiency and effectiveness. Factors used to evaluate OP include on-time delivery improvement, reduction in inventory levels, decrease in scrap/rejection rates, improvement in product quality, and better capacity utilisation. Table 1 summarises the latent constructs, indicators, and measurement items used in the survey, adapted from validated GSCM measurement scales and OP indicators in prior research [28].

Table 1: Summary of constructs, indicators, and observable items [28]

Construct	Indicators	Factors
Internal Environmental Management (IEM)	IEM1	Senior management commitment
	IEM2	Cross-functional cooperation
	IEM3	Implementation of environmental auditing programmes
	IEM4	Attainment of ISO 14001
Green Procurement (GP)	GP1	Eco-labelling of products to prefer environmentally friendly inputs
	GP2	Cooperation with suppliers on environmental objectives
	GP3	Performing environmental audits of suppliers
	GP4	Requiring suppliers' environmental certification
Cooperation with Customers (CC)	CC1	Cooperation for cleaner production processes
	CC2	Collaboration on green packaging or product recovery programs
Eco-Design (ECO)	ECO1	Designing products to reduce material and energy usage
	ECO2	Designing for the reuse/recycling of components
	ECO3	Substituting or eliminating hazardous materials in product and process design
Operational Performance (OP)	OP1	On-time delivery improvement
	OP2	Inventory level reduction
	OP3	Decrease in scrap/rejection rates
	OP4	Improvement in product quality
	OP5	Better capacity utilisation
Green Supply Chain Practice (GSCP)	GSCP1	Integration of environmental requirements across supply chain stages
	GSCP2	Environmental collaboration with supply chain partners
	GSCP3	Monitoring and continuous improvement of green supply chain performance

3 METHODOLOGY

3.1 Research design and sampling

The research structure used in this study was a cross-sectional survey study. The survey was designed to test the proposed relationships between GSCM practices and OP in Saudi Arabia. The sampling frame included manufacturing and logistics firms actively operating within Saudi Arabia, identified through a database of industrial firms that participate in sustainable practices. Respondents were sampled using a purposive stratified random sampling approach to obtain informed key-informant data. The criteria for inclusion in the study were: (i) employment in Saudi Arabia at the time of data collection; (ii) a managerial or supervisory role in supply chain, procurement, operations, sustainability/HSE, or related decision-making roles; and (iii) a minimum of two to three years of experience. Data was excluded if the questionnaire was incomplete (for example, >20% missing data), if the respondent reported no involvement in supply-chain-related decision making, or if the response pattern was indicative of careless responding (for example, straight-lining). Figure 1 outlines all the steps involved in the procedure.

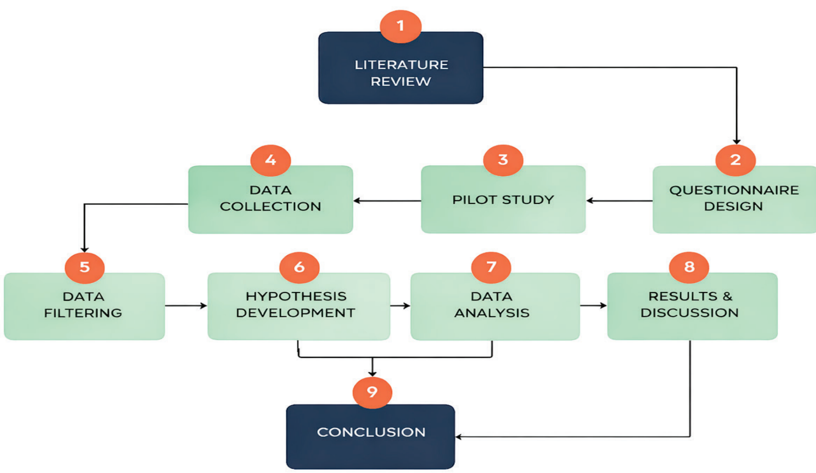

Figure 1 Methodological framework

3.2 Questionnaire structure

The questionnaire contained two sections. Section A asked for the respondent and organisational characteristics, such as role, sector, firm size, and years of experience, to describe the sample. Section B measured the latent constructs using multi-item scales: ECO, GP, IEM, CC, integrated GSCP, and OP. All construct indicators were measured on a 5-point Likert scale (1 = strongly disagree, to 5 = strongly agree). While Likert-type response options are ordinal, such scales are widely used in management and operations research, and SEM-type analyses are commonly applied when items have at least five categories and the analysis method is robust to distributional deviations [39].

3.3 Scale sources, expert evaluation, and pilot testing

Measurement items were adapted from previously validated GSCM measurement scales and OP measures in the green supply chain literature [28]. In particular, the GSCM practice dimensions (ECO, GP, IEM, and CC) and the implementation logic were adapted from established GSCM measurement work and were contextualised to Saudi Arabia through wording adjustments without altering the conceptual meaning of indicators. Consistent with recommended practices for survey measure development and adaptation, an expert evaluation was conducted prior to full deployment. Experts were eligible if they met all of the following criteria: (i) minimum of seven to ten years of professional or research experience in GSCM/sustainability/supply chain management; (ii) direct familiarity with Saudi organisational or industrial settings; and (iii) experience with implementing, auditing, or managing environmental initiatives. (Experts assessed each item for clarity and relevance; revisions were made based on consensus feedback. A pilot test (n = 20) was then conducted with practitioners meeting the respondent inclusion criteria to verify item comprehensibility, completion time, and response variability, after which minor refinements were implemented.

3.4 Data collection outcomes

A total of 300 survey invitations were distributed. We received 137 submissions, of which 121 were usable after applying the inclusion/exclusion criteria, resulting in an effective response rate of 40.33%. To assess potential non-response bias, we compared early and late respondents on key construct scores; no statistically meaningful differences were observed, suggesting that non-response bias is unlikely to materially affect the results. The distribution of respondents among the three primary stakeholder categories, namely owners, contractors, and project managers, is shown in the Respondent Profile chart (Figure 2). This distribution improves the likelihood that the data reflect diverse roles involved in supply chain supervision and execution.

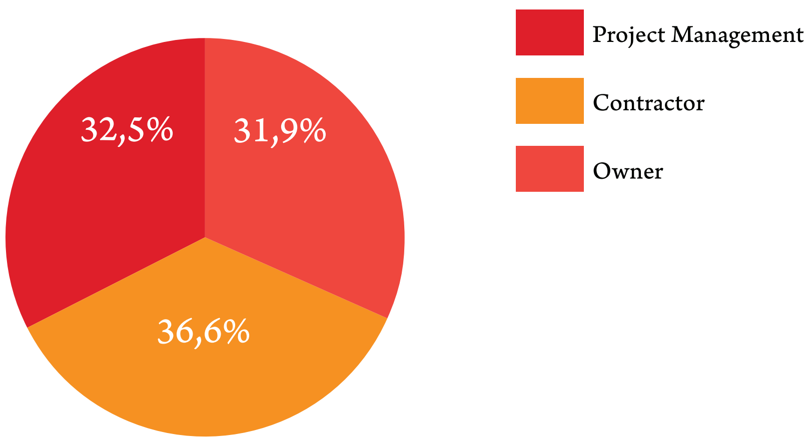

Figure 2 Distribution of respondents by organisation type

3.5 Data analysis: PLS-SEM

The hypothesised model was tested using Partial Least Squares Structural Equation Modelling (PLS-SEM). PLS-SEM is well suited for estimating complex latent-variable models with multiple constructs and indicators, with a primary emphasis on maximising explained variance and prediction-oriented model assessment. Following contemporary PLS-SEM reporting guidance, we evaluated the measurement model prior to interpreting structural relationships. Indicator reliability was assessed via standardised loadings; internal consistency was assessed using Cronbach's alpha and composite reliability; and convergent validity was evaluated using average variance extracted (AVE). Structural paths were estimated and their significance was assessed using bootstrapping (5,000 resamples), and explanatory power was examined using R^2values [40].

We propose that GSCPs improve OP and are driven by four variables: CC, IEM, ECO, and GP. This is based on the resource-based and natural resource-based views, as well as stakeholder logic. The hypothesised relationships shown in Figure 3 were evaluated using the estimated standardised path coefficients (β) and their significance, obtained via bootstrapping.

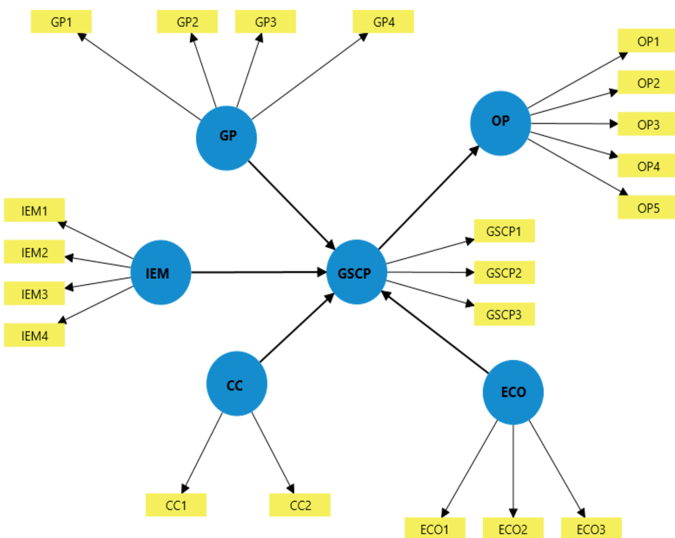

Figure 3 Hypothesis development using SEM

4 RESULTS

In this section, we present the results of the SEM analysis examining how GSCPs influence OP in Saudi Arabia. The findings are organised by measurement model assessment (indicator reliability, internal consistency, and convergent validity) and structural model outcomes (direct effects of latent variables and overall model fit).

4.1 Indicator reliability

All observed indicators demonstrated strong reliability in measuring their respective latent constructs. In the SEM measurement model, each item's standardised factor loading exceeded the recommended threshold of 0.70, indicating that the survey indicators were strong representations of the underlying constructs. High indicator reliability suggests that the measurement items consistently showed the intended aspect of CC, IEM, ECO, GP, GSCPs, and OP. Results can be seen in Figure 4.

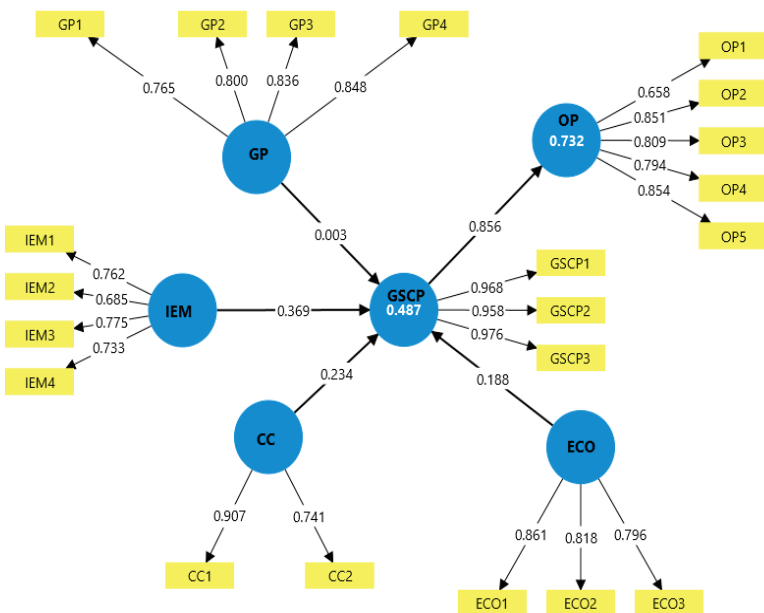

Figure 4 Validated framework using SEM

4.2 Internal Consistency and Convergent Validity

The measurement model fulfils all reliability and convergent validity criteria. Every construct achieved a Cronbach's alpha (α) well above the 0.70 benchmark (the lowest $\alpha \approx$ was 0.724), demonstrating strong internal consistency. Similarly, composite reliability (CR) values ranged from 0.812 upward, exceeding the 0.70 threshold. Convergent validity was confirmed by average variance extracted (AVE) values for each construct, all above the recommended 0.50 level (minimum AVE ≈ 0.547). These statistics indicate that the multi-item scales were reliable and that each set of items shared substantial variance with its intended construct, confirming adequate convergent validity of the measures.

Table 2 Internal consistency and Convergent validity of data

Construct	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
CC	0.761	0.742	0.812	0.686
ECO	0.769	0.787	0.865	0.681
GP	0.829	0.838	0.886	0.661
GSCP	0.966	0.966	0.978	0.936
IEM	0.724	0.729	0.828	0.547
OP	0.861	0.929	0.896	0.635

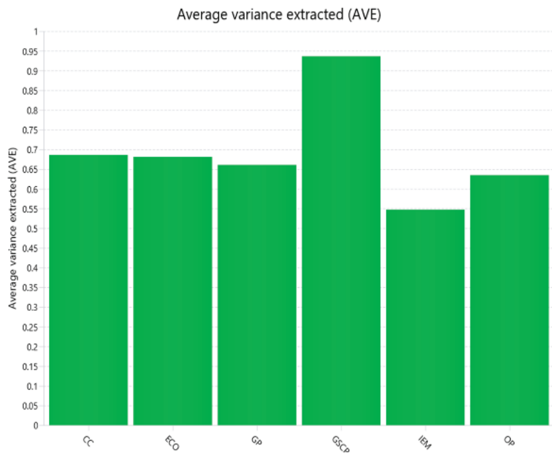

Figure 6 Composite reliability values

4.3 Direct effects of latent variables

Table 3 summarises the significant direct path coefficients in the structural model. The structural model confirms that all four antecedent capabilities have positive and significant direct effects on GSCP. CC (β = 0.234), ECO (β = 0.188), GP (β = 0.003), and IEM (β = 0.369) all contribute positively to GSCP, with IEM showing the most significant standardised effect. GSCP, in turn, has a powerful, positive and significant impact on OP (β = 0.856), indicating that higher adoption of integrated green practices can result in better operational outcomes in the Saudi Arabia context.

Table 3 Statistically significant direct relationships

Paths	T Statistics	P Values	Path Coefficient
CC → GSCP	3.847	0.001	0.234
ECO → GSCP	2.614	0.009	0.188
GP → GSCP	2.044	0.042	0.003
IEM → GSCP	5.312	< 0.001	0.369
GSCP → OP	7.183	< 0.001	0.856

Note: T statistics between 1.96 and 8 confirm statistical significance ($p < 0.05$). Path coefficients (β) retained from original model.

4.4 Indirect effects of latent variables

The mediation analysis shows that GSCP effectively transmits the influence of the four antecedent constructs to OP. All indirect effects from CC, ECO, GP, and IEM to OP via GSCP are positive and statistically significant. These results indicate that the primary route through which customer cooperation, ECO, GP, and IEM enhance OP is by strengthening GSCP, rather than through direct effects alone.

Table 4 Statistically significant indirect relationships

Paths	T Statistics	P Values
CC → OP	3.621	0.001
ECO → OP	2.531	0.012
GP → OP	2.108	0.036
IEM → OP	4.897	< 0.001

Note: All indirect effects via GSCP are statistically significant at $p < 0.05$. T statistics reflect bootstrapping with 5,000 resamples ($n = 121$).

4.5 Model fit evaluation

The SEM model achieved an acceptable fit to the data. The Standardised Root Mean Square Residual (SRMR) was 0.085, which is around the commonly recommended cutoff of 0.08, suggesting an adequate approximate fit of the model's predicted correlations to the observed data. The Normed Fit Index (NFI) reached 0.738; although this NFI value is below the conventional 0.90 criterion for an excellent fit, it falls within tolerable ranges for exploratory SEM models. Furthermore, the high explained variance ($R^2 \approx 0.735$) demonstrates substantial explanatory power for the proposed relationships. The combination of fit indices and R^2 results provide confidence that the specified structural model is sound and captures the key relationships between GSCPs and OP.

Table 5 Model fit indices

Model fit	Saturated model	Estimated model
SRMR	0.085	0.085
d_ULS	1.653	1.653
d_G	2.46	2.46
NFI	0.738	0.738
R^2	0.732	0.735

5 DISCUSSION

The SEM findings provide sufficient evidence that adopting GSCM practices leads to significant improvements in OP for Saudi firms. Our findings are consistent with broader empirical studies showing that GSCM practices are positively associated with firm performance, including operational outcomes, across diverse contexts [41], [42]. The structural model showed a valid fit, indicating that the hypothesised relationships align well with observed data. Strong model fit provides credibility to our framework, suggesting that integrating environmental sustainability into supply chain processes is not only statistically sound but also practically meaningful. The SEM approach also allowed us to capture both direct and indirect pathways among the constructs, revealing that each green practice influences performance in its own way, while also providing benefits through combination. This means that the benefits of one can amplify or enable the others.

Upon examining each construct, the results reveal the distinct roles that each plays. IEM emerged as a particularly influential driver of OP. This suggests that achieving strong internal capabilities, such as top management support for environmental goals, employee training in sustainability, and ISO 14001-aligned processes, directly enhances the efficiency and quality of the firm. Firms with better IEM are likely to achieve better production outcomes (through waste reduction, energy savings, etc.), which immediately increase productivity and reduce costs. Furthermore, IEM appears to enable other green practices as well, suggesting indirect benefits. For example, companies that are committed internally can more effectively implement external collaborations and ECO, ultimately achieving overall performance gains.

The external-facing practices also showed significant, yet varied, contributions to operational outcomes. GP was positively associated with OP; however, its effect in this study was not significant compared to other practices. This finding may reflect the challenges that Saudi firms face in integrating green practices into their supply chains. One interpretation is that the benefits of GP (for example, reduced hazardous materials) are real but not entirely accepted in short-term OP, possibly due to the limited availability of eco-friendly suppliers or higher initial costs in the local context. GP's weaker direct effect suggests that while selecting sustainable suppliers is essential, it may need to be complemented by internal process improvements and market alignment to achieve a significant increase in OP. By contrast, ECO demonstrated an apparent positive effect on OP. This indicates that integrating sustainability at the product design stage can benefit downstream operations. Designing for recyclability, lower material usage, or energy efficiency often leads to cost savings in production and distribution. Our results suggest that firms practising ECO likely reduce waste and improve resource utilisation, resulting in better quality control. Additionally, ECO's impact also carries a strategic dimension: by reconsidering product life cycles, companies not only improve their internal systems but also position themselves for future regulations and customer preferences, creating an operational advantage.

CC in environmental initiatives had a positive, significant linkage to OP in the model. This finding highlights that downstream collaboration can lead to internal improvements. By involving customers, firms become familiar with market demands for sustainability. They can innovate processes accordingly (for example, adjusting production to provide recycled materials or designing products for easier returns/end-of-life processing). The data suggest that customer cooperation not only enhances reputation but can lead to process and product innovations that improve efficiency and quality, thereby increasing OP. All four GSCM practices demonstrated positive roles in enhancing OP, either directly or indirectly.

The relationship among them is significant: for instance, a strong internal environmental foundation can amplify the benefits of collaborating with customers, while customer feedback can inform better ECO. Such a relation matches observations in the literature that GSCM practices are mutually reinforcing and should be addressed in an integrated manner for maximum impact.

From a practical perspective, these results offer important insights for firms operating in Saudi Arabia during the country's sustainability transition. The positive link between GSCM practices and operational efficiency conveys a clear message: embracing environmental sustainability can provide operational excellence, rather than a hindrance. Our findings indicate that companies aligning with Vision 2030's sustainability goals by implementing GSCPs are likely to reap dual benefits: improving their own efficiency and performance while also contributing to national objectives.

6 CONCLUSION

This study demonstrates that GSCPs have a significant positive impact on OP in Saudi Arabian firms. By quantitatively linking specific practices: ECO, GP, IEM, and CC, to key operational outcomes, we provide evidence that integrating sustainability into supply chain operations is an effective strategy for improving efficiency, quality, and cost performance. The main takeaway is that environmental sustainability and operational excellence are not competing goals but mutually reinforcing ones. Companies that invest in greener processes and collaborations get operational benefits, confirming that GSCM can serve as a pathway to both economic and environmental value creation. Our findings contribute to the growing consensus in the literature that sustainability practices can lead to improved internal outcomes, particularly when aligned with a firm's operational strategy and resources. For Saudi Arabia, a notable implication is that the business sector's engagement with Vision 2030's sustainability agenda can directly enhance firms' OP. By adopting green practices, Saudi firms not only support national policy goals but also position themselves for improved productivity and resilience in a changing global market. This study thus provides data-driven confirmation that pursuing sustainability through GSCM is compatible with OP improvements in the context of emerging economies.

These insights carry several practical and policy implications. For managers, the results highlight the importance of a comprehensive approach to GSCM: investing in IEM systems and ECO capabilities will amplify the gains from external collaborations with suppliers and customers. Firms should integrate sustainability criteria throughout their supply chain decisions, from procurement contracts to product development and customer engagement, as this integration provides an operational connection that single initiatives might not achieve. Policymakers and industry bodies in Saudi Arabia can benefit from these findings by creating incentives and guidelines that encourage broader adoption of GSCM practices. Finally, this research opens avenues for future inquiry. While we focused on four key GSCM dimensions and their impact on OP, future studies could explore additional green practices and broader performance outcomes. Examining how sustained GSCM adoption influences OP over time and whether the benefits grow as green capabilities mature can also be a good choice. Comparative studies across industries or countries would help generalise the findings and address context-specific factors. In conclusion, our study contributes to a deeper understanding of the GSCM performance relationship in the Middle East context. It affirms that sustainable supply chain practices are a viable route to operational excellence.

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VALIDATING METRICS OF A MODEL FOR AGILE SOFTWARE DEVELOPMENT TEAM PERFORMANCE (MASTEP)

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ABSTRACT

Maintaining consistent performance across Agile Software Development (ASD) teams is challenging due to the absence of standardised performance metrics, limiting visibility of team performance and impairing management decision-making at scale. This study extends previous work that identified five key metrics within the Model for Agile Software Development Team Performance (MASTeP), by validating their applicability using historical data from a real-world enterprise. Action science research was applied to examine whether these metrics reliably reflect changes in ASD team performance and illustrate their interpretation in pursuit of operational excellence.

Validation results confirmed that velocity, throughput, defect density, cycle time and lead time are affected when ASD team performance changes. Minimal correlation was observed between throughput and defect density, and between work time and velocity. However, strong positive correlations were observed between throughput and velocity, with strong negative correlations between velocity and defect density, work hours and cycle time, throughput and cycle time, velocity and cycle time, throughput and lead time, and velocity and lead time, and these combinations should be used together. Results further indicate that consistent performance improvements are supported when the ratio between committed and

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completed story points remains between 72% and 88%. Measurement reliability decreases, however, when team dynamics change significantly.

Keywords: Agile software development, team performance metrics, Agile operational excellence, team performance management

1 INTRODUCTION

With continuous innovations in the technology and software industry causing rapid growth, IT companies found that the traditional approaches to project management were not always appropriate as customer requirements often changed during a project [1]. An enterprise facing this challenge is the enterprise that initiated and sponsored this project, referred to throughout as a Large Software Development Company (LaSC). Agile approaches are found to work well in IT companies, where customer requirements change or increase rapidly, and frequent feature releases are needed [1]. One of the most popular Agile approaches often used in industry is Scrum, where developers usually work in small teams on smaller, more manageable tasks than is customary, over a shorter but fixed timeline [2]. While Agile methodologies have been successfully implemented in teams in the LaSC, its management wants to utilise these methodologies effectively to increase productivity and efficiency in teams.

The LaSC, however, lacks effective metrics and baselines to measure productivity and efficiency in Agile Software Development (ASD) teams, which makes it difficult for management to quantify performance improvements. Productivity can be defined as the ratio of the outputs of a system to its inputs, focusing on increasing the outputs [3]. Productivity differs from efficiency as efficiency focuses on reducing input while output remains constant [4]. Determining an exact metric for productivity in an ASD team is a challenging task, since little guidance is provided to companies and management, which makes it difficult to maintain consistent performance across teams [4] - [6]. Team leaders, usually called Agile masters, and management alike are thus interested in the relationship between different metrics, and how this relationship explains problem areas and inform actions needed in a team, as singular metrics give little indication of the causes of trends. The variance in the size and scope of the work of teams also makes it difficult for management to gauge the productivity and efficiency of a team, not necessarily for comparison, but to determine different teams' performances objectively. Management, therefore, wants to use metrics to manage team outputs and gauge whether interventions, such as the processes and structures that have been established, are benefiting the teams.

The problem is that the LaSC does not currently have a standard, cohesive, and validated set of metrics that can be used to quantify the performance of an ASD team, and determine whether a team is productive, efficient and continuously improving. Management currently lacks the knowledge of industry best practices and guidance from literature regarding which ASD metrics would be most practical to measure and track, which makes it difficult to reliably assess and evaluate the performance of ASD teams in the enterprise, and the enterprise as a whole. The lack of standard ASD performance metrics also makes it difficult for management and Agile masters to reliably identify problematic areas in a team, which leads to developers not being incentivised to continuously improve, since there is no reliable standard to measure performance improvements against.

This study is part of a larger research study, the first part of which indicated that the problem instance experienced at the LaSC also exists as a class-of-problems within literature. Section 2 provides additional background for our article, leading to the main research question addressed in this article. The research method applied in this paper is described in Section 3. The data collected and analysed during the demonstration of the solution are then discussed in Section 4. Section 5 gives the final conclusions, and makes recommendations for future research that could expand upon this study.

2 BACKGROUND AND RESEARCH QUESTION

This article presents the second stage of a study, with the first stage having updated a previous systematic literature review in order to understand the current maturity of the body of knowledge of Agile software development team performance metrics [7]. As part of the first stage, we identified the need for developing a Model for Agile Software Development Team Performance (MASTeP), based on the current gaps in the literature. These gaps were identified when we first investigated knowledge areas that might prove useful to develop a solution to the class-of-problems, and assessed the level of maturity of these existing knowledge areas, as discussed in the following section.

2.1 Research gap

One of the main goals in the operations of companies is to operate at optimal capacity, identifying bottlenecks to increase the productivity of development [8]. Teams can gain insight into their performance and improve their efficiency and effectiveness by using metrics [9]. While numerous studies have been done, key problems in the body of knowledge remain, such as a lack of definitions, explanations and formulas for measuring and using metrics [10]. There is also no Agile metric commonality initiative or industry standard [11]. Since there is no single universally applicable metric that can be used to determine the performance of an ASD team, various aspects of a team should be taken into consideration in order to give a holistic overview [8] , [12]. The various ASD metrics used in literature and industry were therefore investigated and classified into a hierarchical structure of five different enterprise levels with increasing order of generalisation, namely individual-, team-, program-, portfolio- and enterprise level. Through updating the previous systematic literature review (SLR), completed by Teiber [8], the 20 most frequently used metrics relating to the team-level were identified . Furthermore, these metrics were standardised, since some metrics were found to be ambiguous and could refer to the same underlying measure.

With the update of the original SLR by Teiber [8], the trends in metrics usage in literature were highlighted, indicating how teams and management have adopted and used metrics. When measuring productivity in a team, the trend in literature showed that velocity and throughput are the two most widely used metrics, with Lines Of Code (LOC) per hour recommended as a secondary productivity measure. When considering efficiency in teams, the usage of cycle time and lead time has shown an upward trend and the widest usage. The trend in metric usage for continuous improvement indicates that the metrics most often used for gauging this aspect in teams is the defect rate, or defect density, of Product Backlog Items (PBIs) in a team. The effect of qualitative aspects on continuous improvement cannot be deterministically defined but is important to gain holistic insights [13]. In order to use the metrics identified to coherently assess ASD team performance, an appropriate metric guidance artefact is needed.

While the concept of metrics and performance measurement is often seen as controversial in ASD, an important aspect of the Agile mindset is continuous improvement based on feedback, which is why measurement is pursued [14]. However, the implementation of metrics is a challenge in itself, since Agile teams are supposed to be autonomous and self-organising, and thus developers often see metrics as not exhibiting trust [15], [16]. The main challenges identified in literature include:

- *A lack of knowledge area depth.* While researchers may describe metrics in studies, details for fully understanding the metrics are often absent, along with no guidelines or standardised and agreed upon basis for constructing a measurement model required to promote trustworthiness [17]. There is also no secondary study that analyses how metrics are used, their impacts, context of usage, and their selection and classification [10].
- *Work requirement estimation difficulties.* Subjective size estimations are often based on team-specific capabilities, yet related metrics are frequently compared across teams in enterprises [18], [19]. The subjectivity of ASD metrics often gives metrics a team-specific characteristic which is not transferable, making fair comparison difficult without a set standard [20].
- *Ill-defined and unvalidated metrics.* The absence of an industry-wide standard or commonality initiative also causes inconsistencies, with researchers and practitioners appearing to add or invent new metrics as needed [11], [21]. Furthermore, few explanations or formulas are provided to aid in fully understanding the metrics, or to clarify different metrics with overlapping terms [17].
- *Data acquisition difficulties.* Poorly defined measurement attributes and fragmented data collection inhibit metric adoption in enterprises [22]. Clarification of operationalising metrics through the defining of measurement intentions, as well as tools

or data sources to use for measurement, must also be improved to reduce fragmentation and increase metric adoption in the enterprise [16], [17], [22].

- *Misalignment between metrics and goals.* A lack of a holistic evaluation approach often causes misalignment and miscommunication of expectations and IT operations business values due to confusion over objectives, wrong goals, and disputes over metrics used [23], [24]. Most misalignments between goals and metrics indicate that goals need to be shifted from technical aspects to business value [25], [26].

As suggested by Beh et al. [27], the findings from the analysis of the class-of-problems indicate that insight into the relationship between different metrics, and how metrics relate to different aspects of ASD and goals, are needed. However, enterprises implementing Agile methodologies often lack both knowledge of which metrics to implement, as well as guidance on how to use different metrics [10].

2.2 The Model of Agile Software-development Team Performance (MASTeP)

The true effectiveness of software development metrics lies in using simple existing metrics to construct management decision-support tools that provide holistic insights into different aspects of the software development lifecycle [28]. By rephrasing the problems noted in the literature in Section 2.1, we identified the need for developing the MASTeP. The MASTeP had to: (1) be based on knowledge rigorously validated in literature; (2) address work requirement and estimation accuracy difficulties; (3) make use of validated and well-defined metrics; (4) make use of metrics where data acquisition is easy; (5) align metrics with the goals in the enterprise [7].

Through extensive deliberation, certain ASD performance metrics were excluded in the MASTeP due to various factors. A metric like estimation accuracy was excluded because it is calculated as the difference in the estimated development time and the actual time to complete an issue. The metric is unreliable when measuring development size using SP, representing size based on complexity, uncertainty and effort, and not on time [9], [29]. Since both the estimated and actual time are subjective, metrics like estimation accuracy and complexity, also frequently used at the team level, lack a set reference point per PBI. Story-point-size estimates can however be standardised within a team using relative estimations to improve the reliability and consistency of size measurements [30]. Estimation accuracy and complexity, while frequently used, are thus weak performance indicators and it is not recommended that they be used for standardisation.

Teiber [8], moreover, notes that the burndown-chart also compares the number of PBIs scoped in a sprint to the PBIs completed to indicate sprint progress, which is just a visualisation of another core metric, namely throughput. A sprint is a short cycle of two to four weeks wherein a team will commit to completing a defined number of tasks. Since defects are also logged as backlog items, time-to-fix defects reflect the time it takes to fix a defect-related PBI, which is essentially the lead time of a PBI. Within the scope of this study, code coverage was also excluded as an ASD team performance metric, since it often relates more to code quality rather than to productivity in a team. While the Net Promoter Score (NPS) is likewise widely used, it was excluded since it relies on the judgement of the customer, with data usually collected via surveys or questionnaires. Therefore, when developing the MASTeP using existing theory, five main metrics were selected: *velocity, defect count, throughput, lead time* and cycle time.

2.3 Research question

Since previous work already developed the MASTeP as a solution artefact [7], this article answers the following research question:

> *How useful and usable is the proposed model of metrics in a practical application, and what real-world evidence demonstrates its effectiveness in quantifying and identifying changes in productivity, efficiency, and continuous improvement in teams?*

3 RESEARCH METHOD

DSR is focused on creating or developing a new, novel artefact or solution that solves practical problems of general interest, based on a strong theoretical background [23], [31]. This focus on a theoretical background means DSR artefacts require high technological rigor, ensuring correct theory and principles to guide artifact creation, rather than usability or applicability to an organisational context, which is necessary in the information systems field for solutions to be successful [32]. The DSR methodology contains a design cycle of six phases: (1) Define a problem, (2) Define objectives of a solution, (3) Design and develop, (4) Demonstrate, (5) Evaluate, and (6) Communicate [32].

This study used the six phases of DSR to develop a model as an artefact, namely the MASTeP. It should be noted that the artefact was developed and shaped by the stakeholder as well as participants from the LaSC. The first stage (that is, the first three DSR phases) was completed within the scope of the larger design-based study [7]. Section 2 provides background on the work undertaken to complete the first three phases of the project. This paper focuses on the 4th phase, namely, the demonstration of the solution artifact. Table 1 provides a summary of the data-gathering methods that were used in completing the *demonstration* phase.

Table 1: Data-gathering during the demonstration phase

Design-based phase	Applied to this study	Data-gathering methods	Participants involved
Demonstrate	Demonstrating the metrics of the main artefact (MASTeP) using LaSC data	Analysing quantitative data of metrics of a team in the LaSC	ASD team in LaSC, Agile Master, primary researcher

4 DEMONSTRATION RESULTS

To evaluate the applicability of the MASTeP and the specific metrics selected, the performance of an ASD team in the LaSC was evaluated. The Agile master and senior manager of the team were able to provide insights into the performance of a specific ASD team and operations of the team. Therefore, to validate the metrics selected for the MASTeP, historical data of the team were used and analysed to validate whether the metrics for the team indicated corresponding changes during the same time fragment that the Agile master and senior manager indicated a definite change in performance. The correlation between the different MASTeP metrics, indicating true changes in team performance, was thus evaluated, as shown in Section 4.1. Since the MASTeP metrics are usually not independent of each other, and changes in one metric could correspond to changes in another metric and provide more depth of insight into the true performance of a team, the correlation and relationship of the individual metrics were evaluated, as shown in Section 4.2.

4.1 Validating correlation between MASTeP metrics with team performance changes

The historical data of a team for the LaSC metrics were obtained from the LaSC management via a report drawn from the JIRA system, which is used to manage development work. The JIRA system automatically collects data of the work done by employees to calculate and monitor various metrics of an ASD team. Since the JIRA system also records historical data on the system, data for one team from 1 January 2024 to 3 June 2025 was downloaded. This study only used and concentrated on the data and metrics of one team, and all employee data of members in the team was anonymised by removing names of the employees from the data. Instead, a unique code was used to distinguish between developers. Thus, the various developers in the team, including their working hours, could be investigated. All the data for the performance metrics in the team were also already aggregated to a team level, again using a unique identifier to maintain the anonymity of employees and objectivity in analysis. The data for the performance metrics in the team were thus analysed from 1 January 2024 to 31 May 2025, which allowed performance metrics in full months to be compared.

A clear change to a team's performance and characteristics can be seen when there is a change in the dynamics of a team, such as when team members leave or new members join [12]. The management of the LaSC keeps clear employment records, including when new people join and leave teams, as shown in Figure 1. For the purposes of this study, the researcher refers to the team as Agile Team 1 (AT1).

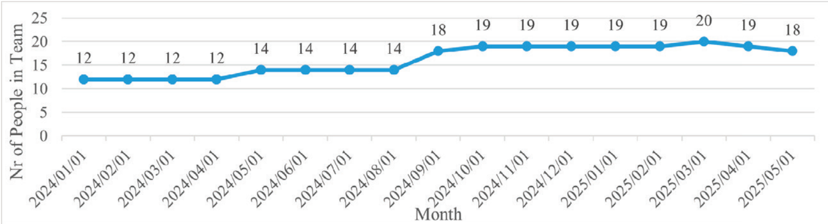

Figure 1: Number of people in the sprint

AT1 had two people who joined the team in May 2024, four people who joined the team in September 2024, one person who joined in October 2024, and one person who joined in March 2025. Furthermore, one person left the team in April 2025 and another person left the team in May 2025. To provide more clarity on the working trends and leave patterns in the team, the number of hours worked in the team is shown in Figure 2. Since the LaSC is in South Africa, employees will usually take leave over the summer holidays in December, which is evident from a sharp drop in the total hours worked by the team over December 2024. This information on the actual working time of team members adds insights into the metrics of the team and can help to inform some of the fluctuations seen in the metrics.

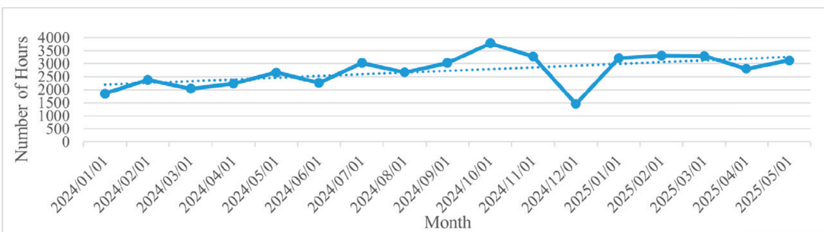

Figure 2: Total hours worked by team members in AT1 per month

Team change instances in time were of key interest when analysing the performance of the team and the data for the metrics selected for the MASTeP, as the changes in team members, either joining or leaving, should also reflect changes in the metrics being monitored. One of the metrics in the MASTeP that indicates changes in performance in AT1 is the throughput of the team over time, which measures the number of Product Backlog

Items (PBIs) completed in a sprint. The throughput of AT1 per month is shown in Figure 3, with the dotted vertical lines indicating the dates on which team members joined or left the team, thus causing a change in the dynamics of the team. In the months of February to April 2024 the Agile master indicated that the team had multiple large user stories to complete, and while the team performance was high, the Agile master believed that adding another person to the team would alleviate some pressure on the team. Two members were therefore added to the team in May 2024, with the performance of the team indicating improvement, as the team started to close more issues consistently. This can be seen in the throughput metric below, showing that the throughput (measured as PBIs completed) of AT1 increased from 29 in April 2024 to 40 in May 2024.

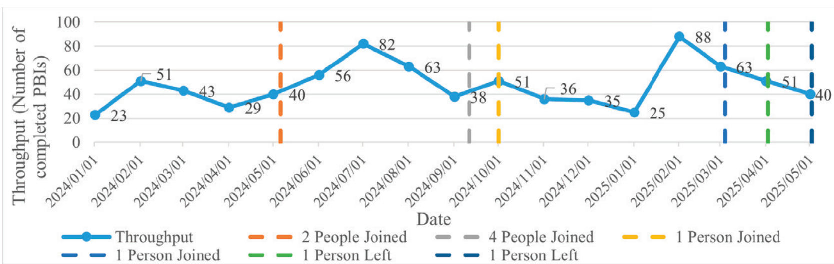

Figure 3: Throughput of AT1 per month

The increase in performance of AT1 represented in the throughput changes, closing over 50 PBIs per month until the end of August 2024, also aligned with the perceived improved performance noted by the Agile master over the same period after the change in number of team members. However, the Agile master noted that change in team dynamics when four new team members joined in September 2024 negatively affected the team performance initially, since many of the new members had to be onboarded and trained by the longstanding team members in the initial month. The throughput of AT1 reflected this negative change as it decreased to 38 PBIs, that is, below the previous norm of 50 PBIs closed per month. When the new team members were onboarded, the Agile Master reported that the team performance increased again in October 2024, but not significantly, because another member was added to the team in the same month.

Nevertheless, even with all team members on board, the performance of the team decreased again, in December 2024 and January 2025, which is when many team members took leave. This is evident from the few hours worked in December 2024, as shown on Figure 2. This decrease in productivity is also evident in the throughput of the team, which indicates a decrease in the number of PBIs completed in December 2024 and January 2025. Another decline in team performance, perceived by the Agile Master, was when some of the team members left the team in April 2025 and May 2025. This decline in performance is also reflected in the throughput of the team, which decreased in April and May 2025, with May, in particular, being much lower than usual, at 40 PBIs closed.

Thus, when monitoring the changes in team dynamics in the data, it was observed that throughput does reflect changes in team dynamics to a certain extent. The correlation of these metrics, however, does not imply causation, as a standard formula could not be derived to describe a direct relationship between the number of people in a team and throughput. The aim of this analysis was simply to confirm the observation that any changes in the dynamics of a team, such as a change in the number of people, affect the throughput in a team abnormally. However, when the team dynamics are stable, the changes and increases in throughput usually correspond to actual performance increases in the team. Throughput alone, however, cannot fully capture team performance as the other metrics included in the MASTeP, like velocity and defect density, also provide insights into various aspects of ASD team performance.

When monitoring the velocity of AT1, changes in team dynamics are also clearly reflected, as can be seen in Figure 4. As in Figure 3, the different vertical lines indicate changes in AT1 dynamics, such as people joining or leaving the team. The team's estimated story points of PBIs were collectively agreed upon during sprint planning meetings, using relative story-point estimation. When new members were added to the team, the standard relative estimation size was not updated, unless a new type of issue needed to be worked on in a sprint. This was done to maintain the consistency of story point estimations.

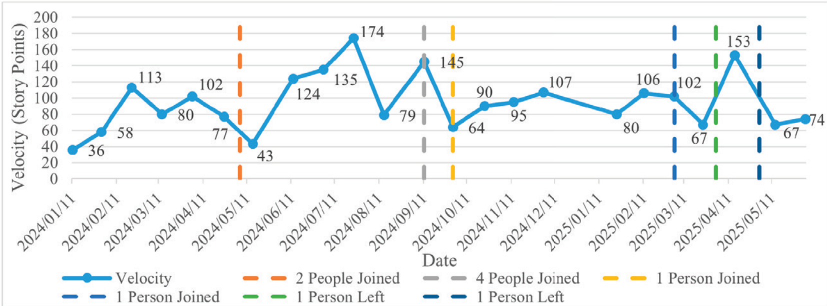

Figure 4: Sprint Velocity of AT1

The velocity of the team decreased significantly in Sprint 7, which ended on 15 May 2024. This coincides with the date on which the new team members were onboarded, namely 6 May 2024. During onboarding, some of the older team members had to take time away from their work to help the new members settle in, which thus resulted in a drop in performance and productivity. For the following sprint, however, the team members had been onboarded, taking on tasks and contributing to the team sprint, with the result that there was a significant increase in the perceived performance of the team. This is also visible with a significant increase in the velocity of the team in Sprint 8, ending on 12 June 2024. With the two new team members contributing to the work in the team, the following two sprints had better performance, with the team also having a high velocity.

The relatively lower velocity than usual in October 2024 could also have resulted from the four new team members being onboarded over that period. The lower-than-expected velocity in December and January is also likely due to fewer hours worked by the team overall, with many team members taking leave in the period. In the sprint ending 24 March 2025, another person had to be onboarded and trained, which again led to a lower team performance, with a decline in velocity also evident. The team dynamics did not change at the end of March 2025, correlating with an increase in velocity to 153 story points per sprint. When team dynamics changed again and team members left AT1 in April and May 2025, the negative impact on the performance of the team was evident in the velocity of the sprints in April and May 2025. Nevertheless, as with throughput, this evidence in the data is not implying causation, but rather correlation between velocity and change in the team dynamics. The correlation of velocity with perceived improvements or declines in team performance also validates the applicability for including velocity as a metric for ASD team performance.

An anomalous sprint seen in the velocity data is Sprint 12, which ended on 14 August 2024 with 79 story points completed, indicating a sharp decrease from normal. The Agile master indicated that there was no drastic change in perceived team performance, and thus additional data on other metrics around this time were needed. The defect density for each sprint was thus analysed, which is shown in Figure 5, with the changes in the team dynamics also indicated.

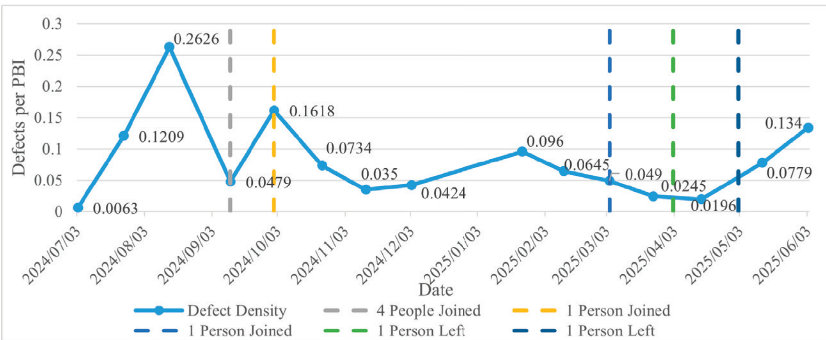

Figure 5: Defect density for AT1 per sprint

The defect density for AT1 provided clarity on the sharp decrease in velocity in Figure 4 in the sprint ending 14 August 2024, shown in Figure 5. This particular sprint had the highest defect density of all the sprints. This high defect density indicates that, during Sprint 9, the team likely had to work with new processes to fix defects and meet the original customer requirements. Having to follow the new process to log defects and needing to address more defects than normal could likely cause a decrease in velocity. While the team performance may be perceived to be high, fixing previous mistakes is not true productivity, as fixing mistakes can be seen as rework, which is often classified as waste in a production system.

The defect density also helped to monitor the performance of AT1, as the changes in the characteristics and dynamics of the team also caused changes in the defect density of the team. When four new developers were added in September 2024, they only started contributing to the codebase of the team around 1 Oct 2024, which was when the defect density initially increased. This is likely because the new team members still had to adjust and learn the new practices and code base. The defect density also stayed constant and relatively low during the period where there was little change in the team dynamics from November 2024 to March 2025, only increasing slightly in January as many team members were on leave in February, and thus it is likely that fewer people were available to check and test code. The final increase in defect density was most likely the result of team members having to take over the projects of those team members who had left in April and May 2025, and needing to familiarise themselves with unfamiliar code, leading to some errors being introduced.

To further measure how well team members were actioning and closing tasks, the cycle time and lead time of PBIs, which are also core metrics in the MASTeP, were investigated. The average cycle time per PBI is shown in Figure 6, where cycle time is the time in days since work has started on a customer PBI.

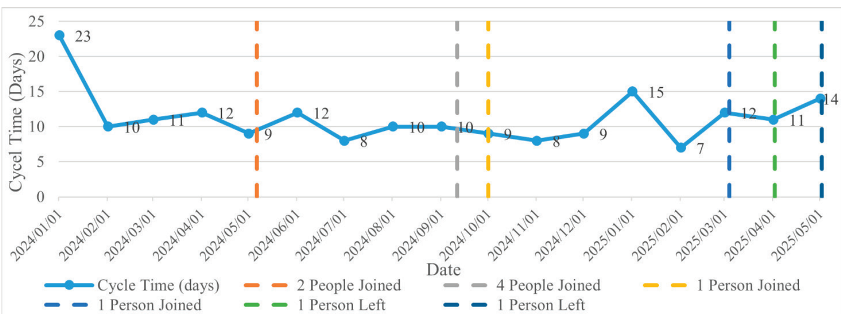

Figure 6: Average PBI cycle time per month for AT1

The cycle time also shows changes in the same period as other changes in team dynamics. The cycle time increased around the onboarding periods of the team members, in June 2024, September 2024, and March 2025, and then decreased thereafter, in July 2024, October 2024, and November 2024, indicating that the new team members made an impact on and contribution to the team. The large increase in cycle time in January 2024 and January 2025, with an unwanted increase, that is, PBIs took longer to complete, also reflected the change in team dynamics as a result of the annual leave-taking over December. It appears that the cycle times lag behind changes in team dynamics by a month.

Changes in lead time also provided insights into the impact that changes to team dynamics have, as evident from the lead time data for AT1 shown in Figure 7. The lead time reflects how long a customer would have to wait for a feature request to be completed, calculating from the date it was first added to the backlog of the team, up to the completion date. While not as pronounced, the lead time of AT1 reflected how well the team balanced new customer requests with old customer requests, with the lead time of the team tending to be higher when older PBIs were closed, and lower when newer PBIs were closed. This indicates how well a team manages the scope of work in the team.

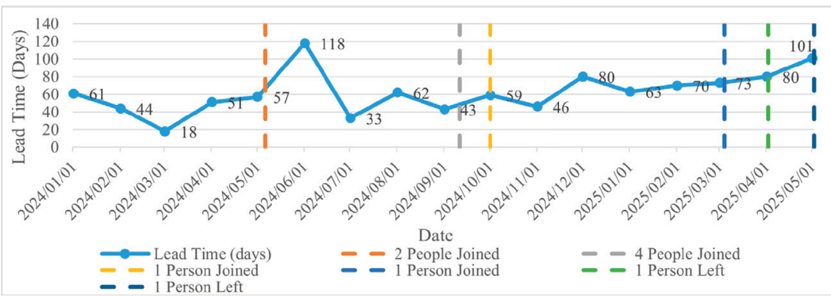

Figure 7: Average PBI lead time for AT1

In AT1, changes to the team dynamic when new members were added to the team generally benefited the team over time. During the period of new members being added to the team (two new team members joining in May 2024 and four joining in September 2024), AT1 closed more of the older PBIs, as indicated by a decrease in lead time in the following month, and thus improved performance on resolving PBIs timeously.

The increase in lead time in December 2024 was also expected as that month was classified as a feature freeze month, meaning that no new features or changes to software operations could be released, except for major problems or bugs in the system. During this period, team members who did not take leave usually worked on issues that were not prioritised throughout the year, such as older and smaller PBIs and requests. The effect of this can be seen by a significant increase in the team's lead time for December, which correctly represents the true performance and actions of the team. The increase in lead time in February did, however, correspond with the slight decrease in performance at the beginning of the year, related to the new member being onboarded in March 2025 and team members leaving in April 2025 and May 2025. Lead time thus accurately represents the performance of a team. While a distinct change in lead time could be due to a change in the sprint planning of the team, it could also be due to a change in the dynamics of the team, resulting in the team following a different structure to close customer requests and PBIs.

When investigating two prominent points in the lead time of AT1, further discussion is needed. In March 2024, the lead time of the team was quite low, which would usually be desirable behaviour if it did not correspond with a throughput and velocity decrease in the team. This could indicate that the team may have been struggling to complete all issues in the sprint, and that,therefore, more help was needed in the team. The dramatic increase in lead time in June 2024 also indicates that many issues that had been requested by customers a long time before had been closed. This change indicates that the increase in team performance, with two new members added in May 2024, led to an increase in older issues being closed, with the velocity and throughput of the team also increasing significantly during this time. Since the comparison of these metrics adds depth to the discussion, the correlation between different metrics is investigated further in the next section.

4.2 Validating correlation between individual MASTeP metrics and interpretation guidance

The MASTeP metrics were used to indicate whether an apparent improvement in team performance was a true reflection of a team's prowess, and, furthermore, to show the effects of changes in team dynamics on team performance. In addition, the possible existence of relationships between metrics needed to be taken into consideration to enhance the insights gained from the metrics. To reliably validate the existence of relationships between metrics, consistent and isolate time slots needed to be identified, during which team dynamics remained unchanged for a substantial period of time. This would ensure valid comparison and evaluation of the metrics, because changes in team dynamics can affect the performance of a team and thus also affect the metrics of a team, as indicated by Katikireddy and Veereddy [12]. To ensure a valid comparison, the performance of the team, assessed according to the relationship between metrics, was only evaluated during times when no external changes were reported, as external changes in the team dynamics could have had undue influence on the metrics being compared, skewing the results.

The time slot into which these metrics were divided was January 2024 to April 2024, when the team consistently had 12 people in the team, referred to as Period 1. The second period selected was from May 2024 to August 2024, which is directly after two additional team members joined and the team consistently had 14 people, referred to as Period 2. The third period selected because of limited change in team dynamics is referred to as Period 3, and is the period fromOctober 2024 to February 2025, when, despite a number of team members being on leave, there were, nevertheless, limited changes in the team dynamics. The relationship between the MASTeP metrics monitored during these times and the work hours in the team as well as other metrics are further discussed in the sections that follow. The aspects of correlation and the nature of the relationships between metrics is the main focus in the evaluation. The intention, therefore, is not to show causation, but rather to validate the relationships.

4.2.1 Velocity in practice

The evidence to indicate the existence of a possible relationship between velocity and hours worked was investigated for Period 1, shown in Figure 8, with a large positive correlation evident between the number of hours worked in the team and the velocity of the team. The trend indicates that as work hours increase, the velocity of the team also increases. The correlation coefficient is a statistical measure used to indicate the degree of association of two variables, with 1 being the maximum positive correlation, -1 being the maximum negative correlation, and 0 indicating no association between the two variables [33]. The correlation coefficient *r* between velocity and *hours worked* for Period 1 is $r = 0.852$, which indicates a strong positive relationship, suggesting that the more worked hours in a sprint, the greater the increase in the number of story points completed.

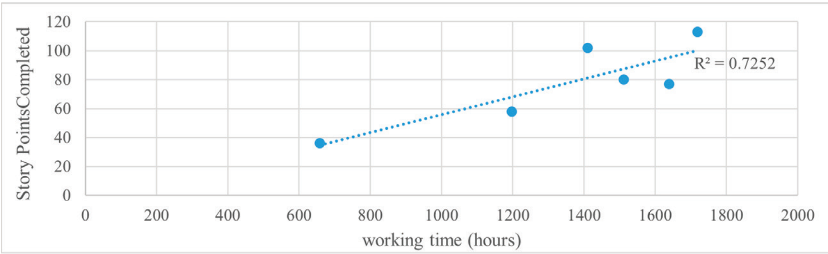

Figure 8: Velocity vs work hours for AT1 from January to April 2024

The regression test is another statistical measure that analyses the relationship between metrics and can be used to indicate the predictability of the variables being measured [34]. This value is represented by in Figure 8 and is the square of the correlation coefficient, with = 0.725 for Period 1. A regression coefficient of = 0.725 is, however, not seen as reliable enough for predictability as often only values greater than 0.9 are seen as reliable enough for predictability [34]. Therefore, while velocity and working hours have a strong correlation, story points estimated for a team are not reliable enough to be used to predict the working hours for a team. As suggested in the MASTeP, story points should thus be decided upon by a team in the sprint planning for predictability and planning, rather than used as a time estimate derived for the team. When evaluating team performance, the plan should be measured against the actual output of the team. This can be done by comparing the number of story point (SP) commitments by the team, that is, SPs planned for completion, against the number of SPs completed by the team. The comparison is shown in Figure 9, demonstrating team performance according to the available data.

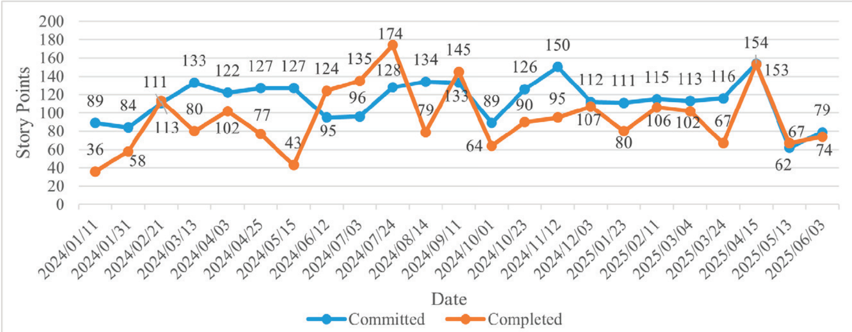

Figure 9: AT1 committed story points and completed story points over time

When comparing the completed and committed SPs of AT1, the goals of the team remained relatively consistent. While the team struggled to meet the sprint goals at the beginning of the year, once the new members were added to the team, AT1 began to meet its goals more consistently. The team also maintained a balance between performance improvements, such as taking risks and striving to complete more tasks, and being cautious and not overcommitting to story points. This behaviour is evident when looking at the target velocity, or goal, of the team and actual velocity of the team, as the team had an average sprint commitment reliability of 83%. This means that 83% of the SPs committed to in a sprint were completed in the sprint, which aligns well with the guidelines of Downey and Sutherland [35], which recommend that estimation accuracy, or commitment reliability in this case, should be maintained between 72% to 88%. Commitment reliability refers to the success rate of completion of issues scoped for a sprint. An accuracy exceeding 88% suggests risk aversions in a team, with accuracy below 72% indicating poor understanding of requirements. To further analyse the reliability of the team's task completion, the throughput of a team should be monitored in relation to the other metrics.

4.2.2 Throughput in practice

The throughput of a team helps to monitor the effectiveness of the team's actions in a sprint, with throughput only increasing if a PBI is completed and closed, no matter the size. When comparing the velocity of a team and

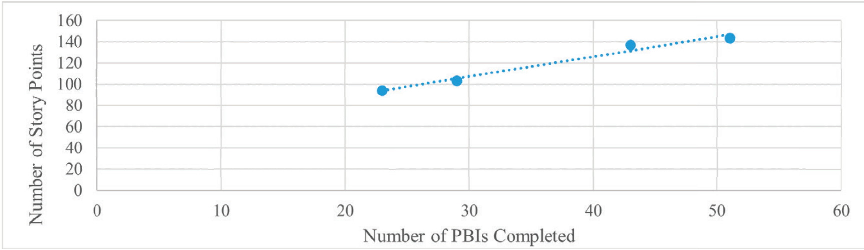

Figure 10: AT1 velocity over throughput per month in Period 1

When analysing the correlation between throughput and velocity, the correlation coefficient is shown to be $r = 0.987$, which is a very strong positive correlation. This means that there is a strong relationship and linking between these two metrics, which is to be expected since each PBI closed has a number of story points assigned to the issue, and thus if more PBIs are closed, more story points will be completed in the sprint. The average size of PBIs for AT1 is 2.67 story points per issue. This indicates that the team is more comfortable with addressing many smaller issues that are clearly defined, rather than a larger issue with many unknowns. This helps to inform how to best help the team address other problems in ASD, such as defects that occur in operations.

4.2.3 Defect density in operations

When monitoring the defect density of a team, insights can be gained as to how effectively a team develops new code without sacrificing quality of effort. Since defect data is only recorded for AT1 from July 2025, Period 3 was analysed to compare the relationship between velocity and defect density, with the data plotted in Figure 11.

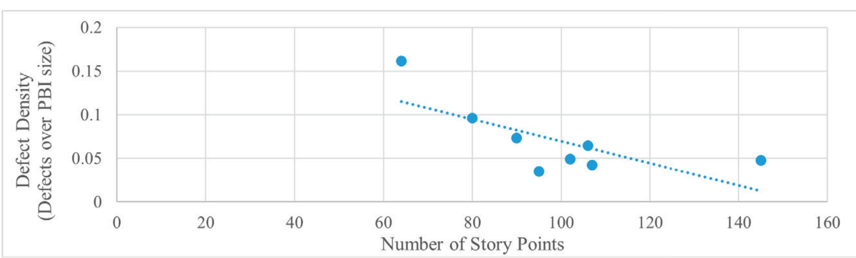

Figure 11: AT1 defect density over velocity for Period 3

The data indicates a strong negative correlation between the defect density and the velocity of the team, with the correlation coefficient r = - 0.718. This negative correlation indicates that as the velocity of a team increases, the defect density of the team will also decrease. This is understandable, as defect density is calculated by the number of defects over the size of the PBI measured in story points, and thus if an increasing number of issues are being developed in a sprint with the sprint backlog thus increasing, the defect density denominator will greatly decrease in size.

When considering the data for Period 3, the relationship between throughput and defect density, the opposite association can be seen by the trendline in Figure 12. As with velocity, there appears to be a negative correlation between throughput and defect density in operations, with the correlation coefficient being weak and negative at r = -0.22. This then shows that there is a weak relationship between throughput and defect density and that if one metric increases, such as throughput, it does not necessarily mean that more defects will be produced during development.

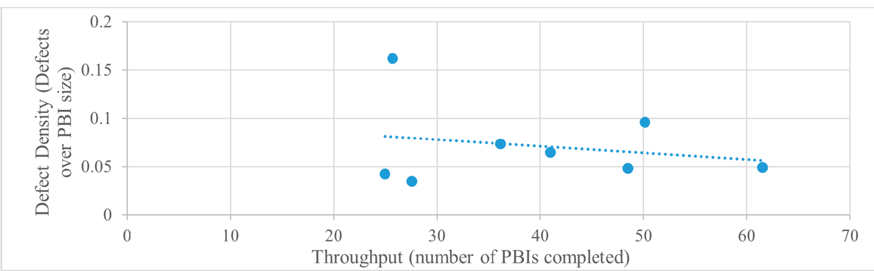

Figure 12: AT1 defect density vs throughput for Period 3

Since there is a slight negative correlation, it will be fair to say that when driving a performance increase in a team and focusing on improving productivity in code, it does not mean that more defects will naturally be produced. As the work requirements in the team increase, along with the backlog size, defect density helps to show how effectively the team is addressing issues and closing PBIs without causing more defects, even when work requirements increase. Therefore, a decrease in the defect density shows continuous improvement in the team, as, with fewer defects being produced in relation to the number of the other PBIs needing to be addressed in development, the team usually closes more issues with fewer defects. This continuous improvement, consequently, leads to an increase in the efficiency of the team.

4.2.4 Cycle time and lead time in operations

When monitoring the relationship between cycle time and other performance aspects in a team, an improvement in the cycle time of a team (with improvements being a decrease in the cycle time of issues) should generally indicate improved performance as the improvements come as a result of issues assigned to the team being addressed faster. Therefore if a team puts in more effort and works harder to improve the performance of the team, it is expected that the cycle time should also decrease. This relationship is evident when comparing the impact of the number of hours worked by the team on the cycle time of AT1, there is a clear positive trend in Period 2, as can be seen in Figure 13.

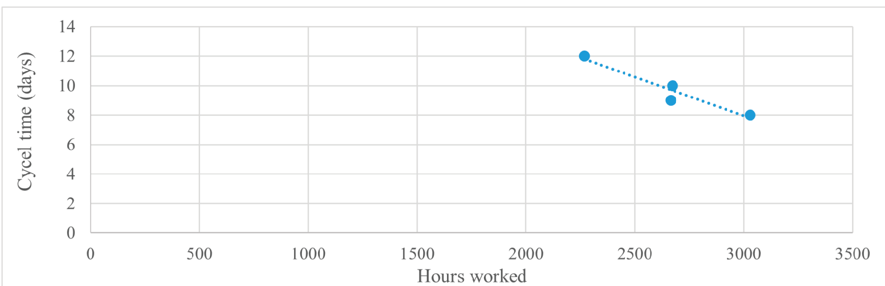

Figure 13: AT1 Cycle time and work hours per month for Period 2

The correlation coefficient for Period 1 and Period 2 indicates a strong negative correlation between the number of hours worked in the team and the decrease in cycle time, with *r1* = -0.826 and *r2* = -0.959 respectively. This indicates that when the team works more hours, the performance in the team improves. This is in line with the assertion by the Agile master that when the perceived performance of the team improves, the efficiency of the team also improves, and thus PBIs will be closed faster.

While AT1 improved in efficiency in closing PBIs faster, a true improvement in performance can only be claimed when considering the productivity increase in the team during the same time. When considering

Period 1, the velocity of the team is compared with the cycle time of the team, as shown in Figure 14. The correlation between velocity improvement and a corresponding decrease in cycle time gives validity to the observation that there was indeed a performance increase in Period 1.

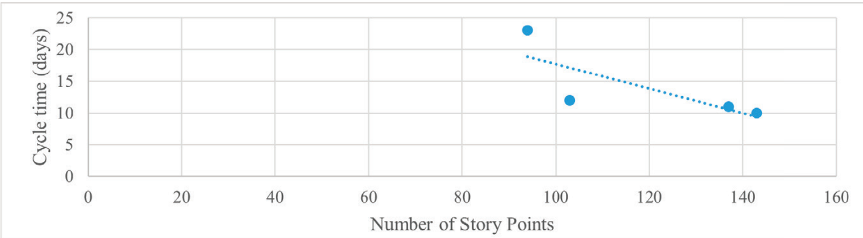

Figure 14: AT1 story points and cycle time per month for Period 1

Period 2 and Period 3 also had negative correlations between velocity and cycle time, with *r2* = -0.179, and *r3* = -0.572. Thus, while a weak correlation is visible, an increase in velocity should lead to a decrease in *cycle time* in a team if its performance has improved. As shown in Figure 15, this relationship is true for throughput and cycle time for *Period 1*.

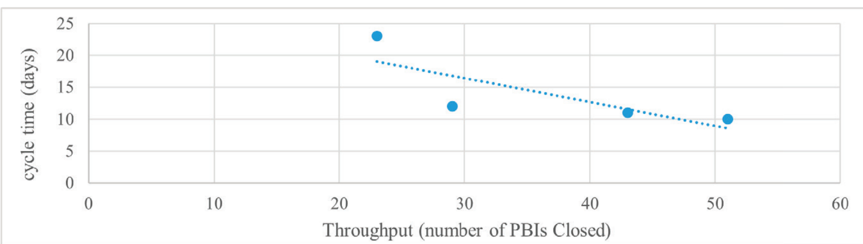

Figure 15: AT1 throughput and cycle time per month for Period 1

A strong negative correlation exists between throughput and cycle time, with *r* = -0.792, which indicates that, like velocity, as the number of PBIs closed in the month increases, there is a corresponding decrease in cycle time for the issues. This would seem to represent reality well, as to increase the number of PBIs closed in a month, PBIs will need to be worked on and closed faster. Likewise, this negative correlation is present in AT1 in Period 2 and Period 3, with *r2* = -0.356, and *r3* = -0.656, which indicates that an improvement in performance in the other sprints, which results in more PBIs being closed, should lead to a decrease in the cycle time.

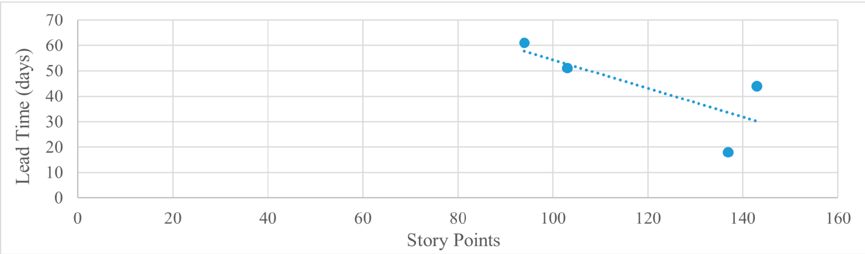

Figure 16: AT1 lead time and velocity for Period 1

The same negative correlation between cycle time and velocity is also true for lead time and velocity, as shown in Figure 16. As can be seen, there is a strong negative relationship between the two metrics, with *r1* = -0.748, which indicates that improvement in velocity should result in a decrease in the lead time of PBIs, and that customer requests should also decrease. If the team is, therefore, improving in efficiency and performance, customer requests should be addressed more promptly, with an increase in the number of story points completed, and also with a corresponding decrease in the lead time on PBIs.

5 CONCLUSION, LIMITATIONS AND RECOMMENDATIONS

In the initial stage of this study five key metrics were identified from literature to construct the Model for Agile Software Development Team Performance (MASTeP), namely velocity, throughput, defect density, cycle time, and lead time. Using historical operational data from an active team, this study validated that each metric represents a distinct aspect of ASD team performance and therefore justified their inclusion in the model. By analysing the changes in these five metrics over periods with significant changes in team dynamics which would have a clear impact on the performance of the team, such as people joining or leaving the team, each of the metrics correctly showed significant corresponding shifts.

This demonstrated that the metrics included in the MASTeP effectively monitors ASD team performance and can indicate whether a change in a team had a positive or negative effect on the team performance.

The validation of relationships and correlation between these metrics in this study also helped to provide clarification of the dynamics of the performance of an ASD team. Therefore, by standardising velocity, throughput, defect density, cycle time and lead time as performance metrics in an ASD team, the MASTeP provides insight into all aspects of team performance, and the different characteristics and facets that could affect team performance. The findings of this study are in line with Downey and Sutherland [35], namely that the success rate of completing issues committed to by the team in a sprint, or commitment reliability in this case, should be between 72% and 88%.

One of the limitations of this study was that the leave patterns and data of individual team members were not available. While it is normal for most South African employees to take a break over December, the exact data was not available in this instance. Further investigation into the period of leave of certain team members would help to explain or attribute specific changes in team performance. To keep the participants anonymous, specific investigation into the skill level and years of experience of each team member was not done. Further investigation into this aspect would benefit the explainability of performance changes in the team, but this data were not available at the time. The estimation of story points was kept consistent by using relative estimation, and referencing a set standard for the size and type of user story set by the team. While this improves the consistency of estimations, adjustment of user story points during a sprint was not allowed, in order to keep story points consistent with the set standard. Further investigation into the accuracy of this set reference standard, while not undertaken in this study, would improve the accuracy of claimed performance improvements and prevent distorted performance data due to scope creep. Future investigation into such a standard would also benefit the model by suggesting when adjustments to references need to be made. In addition, greater validity of findings could be gained if the study is extended to multiple teams, across different software development areas, over several years, and within different companies in the future. This was, however, not possible within the scope and time constraints of this study, but is strongly recommended for future work.

The real-world data gathered in the study validate the inclusion of these metrics for the MASTeP, which demonstrated how different metrics should be interpreted, and highlighted the effects of changing team dynamics. This study, however, only used data collected from one team in one company, with input provided by LaSC members. Additional real-world cases, where the five key metrics are used, would increase the generalisability of the artefact. A second data set, from a different enterprise, would also increase the credibility of the interpretation guidance and findings in the study. The LaSC requested a set of metrics that could be used to compare the performances of teams. This study validated the metrics related to a single team. In a further study, the data of two teams could be extracted, and the validity of the metrics and their interpretation evaluated when comparing the performance of the teams.

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