



Developing a maintenance maturity model for prioritising water infrastructure maintenance in South Africa

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ABSTRACT

South Africa's water infrastructure is grappling with severe challenges, characterised by frequent breakdowns and systemic decline. National assessments such as the South African Institution of Civil Engineering's fourth infrastructure report and the Department of Water and Sanitation's drop reports highlight that much of this deterioration stems from inadequately structured and overly rigid maintenance strategies that fail to ensure sustainable asset performance. A key issue emerging from these evaluations is the lack of structured, progressive mechanisms for assessing and enhancing institutional maintenance capabilities. This gap significantly limits the ability of water authorities and utilities to move beyond short-term, reactive interventions and develop resilient, future-oriented maintenance regimes.

To respond to this critical deficiency, this study proposes the adoption of a maintenance maturity model (MMM). Maturity models are established tools across various sectors, providing structured frameworks for evaluating organisational capabilities across defined developmental stages. When applied to maintenance, an MMM enables systematic assessment of current practices, identification of process and system deficiencies, and guidance for strategic improvements. By supporting the evolution from reactive maintenance toward more proactive approaches, the MMM acts as a catalyst for building resilient, cost-effective, and sustainable infrastructure management systems. In doing so, this study offers both a practical and strategic solution to the persistent maintenance challenges confronting South Africa's water sector.

To ensure the model addressed the identified challenges, this research was situated within the design science research (DSR) approach, utilising the elaborated action design research (eADR) method. The study was limited to the diagnosis and design stages. It commenced with problem diagnosis, underpinned by a comprehensive literature review, which revealed a significant misalignment between existing maintenance policies and actual practices; largely characterised by reactive approaches. Additionally, a review of maintenance prioritisation approaches revealed limited adoption, particularly in developing regions such as South Africa, where significant infrastructure deficits persist. Among the key barriers identified, a lack of technical capacity emerged as a dominant concern; contributing to the widespread inadequacies in maintenance practices.

Following problem diagnosis, the design phase focused on establishing model requirements and ensuring contextual fit. Design requirements were defined, and a gap analysis of existing maturity models was conducted to ensure the model's relevance and applicability. The development process was further guided by Maier and Beckers' model development guidelines to ensure methodological rigour and practical utility.

To assess the model's robustness and relevance, validation was conducted through a Delphi study, which reached expert consensus by the second round. The resulting MMM is a validated decision-support tool that enables water utilities to effectively prioritise maintenance activities. By guiding organisations toward more proactive maintenance strategies, the model enhances infrastructure reliability and ensures the sustainable delivery of services.

The MMM also serves as a tool for raising awareness of the critical role of maintenance in sustaining infrastructure reliability. Furthermore, it can be used as a structured guide for training and developing maintenance teams, equipping them with the necessary capacity and competencies to support the organisation's transition to more mature maintenance practices.

While the model presents a validated framework, its real-world application was beyond the scope of this study. Future research should explore piloting the model within operational water utilities to evaluate its practical applicability, effectiveness, and impact on maintenance outcomes.

Keywords: Maintenance maturity model, water infrastructure, asset management, maintenance prioritisation, maintenance strategies, elaborated action design research, Delphi technique.

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"If I have seen further, it is by standing on the shoulders of giants." — Isaac Newton

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CHAPTER 1: INTRODUCTION

1.1 Introduction

Water infrastructure is fundamental to ensuring sustainable water supply and sanitation services, particularly in municipal settings (Laolang et al., 2022). However, in developing economies such as South Africa, small and resource-constrained municipalities continue to experience persistent maintenance challenges (Dighade et al., 2014, SAICE, 2022). These challenges often manifest as operational inefficiencies, escalating maintenance costs, and recurrent service delivery disruptions. Given these constraints, there is a critical need for an organised and logical approach to prioritise water infrastructure maintenance to optimise resource allocation and improve service reliability.

This study responds to this need by proposing a tailored framework to enhance the prioritisation of water infrastructure maintenance within such municipalities. Chapter 1 provides an overview of the study detailing its background and context, defining the research problem, and clearly stating the aim and objectives. It also outlines the scope and delimitations of the study, as well as its significance and potential contribution to the field.

1.2 Background of the study

Effective maintenance of water infrastructure is essential to guarantee sustainable access to clean water, particularly in regions facing resource constraints and service delivery challenges. In the water sector, where access to clean water is essential for upholding human dignity and a key driver of socio-economic development, the challenge of effective maintenance is increasingly urgent (Amis and Lugogo, 2018). This issue is particularly pronounced in South Africa, where the government has committed to achieving the 17 United Nations Sustainable Development Goals (SDGs), with SDG 6 focusing on the sustainable management of water and sanitation for all (Toxopeüs, 2019).

The South African Constitution and the Water Services Act recognise access to water as a fundamental human right, placing a responsibility on municipalities to ensure sustainable water and sanitation services. However, most South African municipalities are grappling with widespread dissatisfaction from residents, caused by frequent water service interruptions (Bikam and Chakwizira, 2021). Water infrastructure, consisting of pipes, reservoirs, pump stations, and treatment plants (Grigg, 2019), deteriorates over time and requires tailored maintenance

strategies to remain functional. Municipalities must adopt proactive strategies to manage wear and tear as infrastructure ages and address the critical issues contributing to recurrent breakdowns.

Inadequate maintenance and delayed responses to deteriorating water infrastructure have been identified as significant barriers to achieving universal access to clean water (Bikam and Chakwizira, 2021, Hoffman and Nkadimeng, 2016, Miya and Grobbelaar, 2015). According to the SAICE (2022) infrastructure report, a significant portion of South Africa's water supply systems, including pipelines and treatment facilities, have surpassed their intended lifespans, placing them at high risk of failure. Furthermore, SAICE (2022) reported that, in the same year, the Department of Water and Sanitation (DWS) indicated that at least 403 water supply systems were at high to critical risk of catastrophe, highlighting the urgent need to address persistent maintenance challenges.

Despite extensive research on the dire effects of equipment downtime (Fernández and Márquez, 2012, Patil et al., 2022), many water utilities continue to face challenges in effectively prioritising maintenance tasks. This difficulty often stems from a predominant reliance on reactive maintenance strategies, which focus on addressing immediate failures rather than identifying and mitigating the underlying causes of equipment breakdowns (SAICE, 2022). Consequently, these organisations experience recurrent failures, escalating operational costs, and decreased infrastructure reliability over time (SAICE, 2022, Raspati et al., 2022).

To effectively address these challenges, institutional innovations play a critical role in facilitating the adoption of systematic asset management approaches. Rather than relying on politically driven decision-making, municipalities must establish strategic frameworks that integrate both reactive and proactive maintenance to ensure sustainable infrastructure management (Amoah and Mazele, 2021, Chigangacha et al., 2021a). Municipalities can achieve sustainable water supply services by evaluating asset-specific needs and aligning strategies with operational priorities.

Despite the availability of various maintenance prioritisation techniques, most do not consider an organisation's maturity level in its maintenance capabilities. Maintenance maturity models offer a structured approach to assessing an organisation's capability to plan, manage, and improve maintenance practices systematically (Machado and Carvalho, 2021, Chemweno et al., 2015). Unfortunately, limited research exists on integrating these models into maintenance prioritisation frameworks, particularly in the context of water infrastructure in South African municipalities.

A maturity-based approach could provide municipalities with the tools to assess their current maintenance practices, identify weaknesses, and develop a guideline for improvement. When applied to water infrastructure, this approach could guide municipalities in prioritising maintenance tasks based on asset-specific needs, operational priorities, and resource availability. The goal is to reduce operational disruptions, extend asset lifecycles, and ensure reliable service delivery, all of which are significant to achieving sustainable water supply and sanitation services.

1.3 Problem statement

Frequent water infrastructure breakdowns, caused by inadequately structured and adaptable maintenance plans and strategies, significantly hinder uninterrupted service delivery. These challenges are worsened by a lack of structured and systematic frameworks that assess and improve maintenance practices (Laolang et al., 2022, Muller, 2024), leading to reactive approaches, escalating costs, and reduced infrastructure reliability.

1.4 Research aim

This study aims to develop a maintenance maturity model (MMM) tailored for prioritising water infrastructure maintenance in South Africa.

1.5 Research objectives

To accomplish the study's aim, the following objectives are established:

- a. to perform a systematic literature review on asset maintenance prioritisation approaches relevant to water infrastructure,
- b. to analyse current maintenance practices in and the state of water infrastructure management in South African municipalities,
- c. to identify and analyse the key factors influencing maintenance prioritisation decisions in water utilities,
- d. to develop a maintenance maturity model.
- e. to validate the proposed maintenance maturity model through expert consultations.

1.6 Central theoretical statement

This research is underpinned by the central theoretical premise that:

A systematically developed maintenance maturity model (MMM) can effectively assess and differentiate the maintenance capabilities of water infrastructure entities in South Africa, thereby enabling the prioritisation of maintenance interventions that enhance asset reliability and improve service delivery outcomes.

This premise draws upon the theoretical foundations of maturity modelling theory, asset management frameworks (such as ISO 55000), and the principles of continuous improvement (e.g., the Deming Cycle and Lean Six Sigma). It posits that the structured evaluation of maintenance capabilities—through a context-specific maturity framework—can function as both a diagnostic tool for assessing existing practices and a developmental mechanism for guiding the systematic advancement of organisational capability across defined maturity levels. Such a framework enables the transition from reactive to strategically optimised maintenance practices, ultimately supporting more effective, resilient, and sustainable infrastructure management.

By capturing the progression of maintenance practices across defined maturity levels, the model facilitates the alignment of maintenance efforts with asset criticality, operational context, and resource availability. This enables municipalities to transition from reactive, fragmented approaches to data-informed, risk-based, and strategically prioritised maintenance planning. Ultimately, the model is intended to foster greater sustainability, resilience, and reliability in water infrastructure service delivery across South African municipalities.

1.7 Study significance

This study presents the maintenance maturity model (MMM) as a structured and adaptable framework designed to prioritise maintenance in asset-intensive sectors, with a particular emphasis on water infrastructure. In the South African context, where municipalities and water utilities face mounting challenges, including ageing infrastructure, inadequate funding and human resources, and frequent service delivery disruptions, the relevance and utility of the MMM are especially critical.

The MMM serves as both a diagnostic and strategic tool. It enables infrastructure managers to systematically assess current maintenance practices, identify and prioritise critical interventions, and implement sustainable, efficiency-driven improvements. By doing so, the model enhances operational resilience and contributes to more reliable and consistent water service delivery.

A key contribution of the model lies in raising organisational awareness of maintenance as not just a supportive role, but as a fundamental operational and strategic activity. It bridges the gap

between an organisation's maturity level and maintenance prioritisation practices by aligning maintenance activities with the institution's capacity to execute them effectively. This alignment facilitates a shift from ad-hoc, reactive approaches to structured, strategic, and data-informed maintenance management. The MMM thus offers a practical roadmap for progressive capability development, supporting realistic and impactful step-by-step improvement.

The study holds dual significance. Academically, it enriches the maintenance management field by providing a validated framework that integrates maturity assessment with prioritisation strategies, paving the way for future research. Practically, it equips water utilities with a benchmarking tool to identify performance gaps and guide targeted improvements. Ultimately, the MMM can foster more reliable service delivery, improved asset performance, and greater long-term infrastructure resilience.

1.8 Scope of the study

This study is focused on developing and validating a maintenance maturity model (MMM) to enhance the prioritisation of maintenance activities within South Africa's municipal water infrastructure sector. It seeks to establish a structured framework that enables systematic assessment of current practices and guides progressive improvement, particularly in response to persistent breakdowns and service delivery disruptions. The focus is on municipal water infrastructure assets, including treatment plants, distribution pipelines, pumping stations, storage reservoirs, and related facilities. Priority is given to resource-constrained municipalities, which face acute financial, technical, and institutional limitations that undermine effective maintenance delivery.

The study concentrates solely on the maintenance management phase and does not address other asset lifecycle stages, such as design, procurement, construction, or decommissioning. While the MMM may inform broader asset management goals, its specific purpose is to improve decision-making around maintenance interventions, especially where resources are limited. Notably, the study does not include pilot testing or field implementation of the model. However, it is designed to be practically applicable, providing a foundation for future deployment in collaboration with water service authorities and infrastructure stakeholders. The primary output will be a context-specific MMM featuring defined maturity levels, key functional domains, and appropriate maintenance strategies. Its development is informed by relevant literature, best

practices, and expert input, strongly emphasising addressing the challenges and capacities unique to local infrastructure environments.

1.9 Research outline

The elaborated Action Design Research (eADR) framework underpins this study, guiding the research process and structure. As illustrated in Table 1, the research is divided into two main stages: diagnosis and design. These stages reflect a logical progression from understanding existing maintenance practices to developing and validating a Maintenance Maturity Model (MMM) tailored for water infrastructure maintenance. The chapters are organised to systematically address specific research objectives within each phase, ultimately culminating in formulating practical recommendations that can be applied in maintenance practices and infrastructure management. While Table 1 presents an overview of the research stages in alignment with the eADR approach, a detailed discussion of the research design within the eADR paradigm is provided in Chapter 2 and the results presented in Chapter 3. The overall organisation of the thesis has been deliberately aligned with the eADR phases to ensure conceptual and methodological coherence throughout the study.

Table 1: Structured outline of research chapters

Chapter	Chapter title	Objective	Design stage
1	Introduction	N/A	N/A
2	Literature review	N/A	N/A
3	Research design	N/A	N/A
4	A systematic literature review on asset maintenance prioritisation approaches relevant to water infrastructure.	Objective a	Diagnosis
5	Current maintenance practices in and the state of water infrastructure management in South African municipalities	Objective b	Diagnosis
6	Key factors influencing maintenance prioritisation in the water industry	Objective c	Diagnosis
7	Maintenance maturity model design requirements	Objective d	Design
8	Development of a maintenance maturity model	Objective d	Design
9	Validating the maintenance maturity model: Delphi process	Objective e	Design
10	Conclusion	N/A	N/A

1.9 Conclusion

This chapter outlined the background of the study and clearly articulated the problem addressed in the study. It also presented the research aim and objectives that directed the investigation and discussed the study's significance. The next chapter explores the extensive body of literature that underpins key themes and concepts related to contemporary maintenance practices and the current state of water infrastructure management in South African municipalities, providing a broader understanding of the problem under investigation.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter aims to explore and critically analyse the relevant literature that underpins the theoretical framework and context of this research study. Asset management principles are examined as the foundational strategy for effectively managing infrastructure throughout its lifecycle. Maintenance, as a critical subset of asset management, is emphasised as an essential operational function that directly impacts the reliability, performance, and longevity of assets. Furthermore, the chapter investigates the concept of maturity models as evaluation tools, providing structured approaches to assess and improve maintenance practices and decision-making processes. By integrating literature from these interconnected domains, this chapter establishes the foundation for a deeper understanding of the maintenance challenges faced by water infrastructure systems and how maturity models can be utilised to optimise maintenance strategies and practices

2.2 Water infrastructure

Water infrastructure is a complex system that manages water to meet both societal and environmental needs (Grigg, 2019). According to the Global Water Partnership (GWP, 2009), it includes facilities for extracting, storing, treating, transporting, and distributing water, as well as managing wastewater through processes like sanitation, reuse, and recycling. These systems operate on different scales, from small rural networks to large urban and industrial infrastructures, supporting everything from domestic water supply to agriculture, industry, and ecosystems (GWP, 2009).

As demand for water grows and climate change brings added stress, managing these systems effectively requires a coordinated and sustainable approach (Mekonnen and Hoekstra, 2016, United Nations, 2021). This makes it clear that advanced maintenance strategies are needed to ensure these systems can perform reliably and efficiently for years to come.

Maintenance is key to ensuring that water infrastructure stays reliable, services continue smoothly, and assets last longer (Fernández and Márquez, 2012). When done well, it also helps prevent health hazards and reduces emergency repair costs (Emily and Muyengwa, 2021, Aiyetan and Das, 2021). Unfortunately, many utilities still rely heavily on reactive maintenance;

waiting for breakdowns before taking action, which often leads to higher costs and unplanned outages, making it unsustainable for critical systems (Miya and Grobbelaar, 2015, SAICE, 2022).

Hence, shifting to preventive maintenance can enhance system resilience, lower costs, and ensure consistent service by addressing problems before they become bigger issues (Stip et al., 2019). This proactive approach is essential for maintaining long-term water service delivery.

Recent studies strongly support adopting these advanced maintenance practices. Sarfaraz et al. (2023) and George-Williams et al. (2024) highlight the benefits of comprehensive maintenance models that improve performance and resilience. Tlabu et al. (2022) also, stress how effective maintenance reduces downtime, leakage, and service interruptions. These practices are vital for ensuring that South Africa's water infrastructure can meet growing demands and adapt to environmental challenges.

2.3 The strategic importance of asset management in water infrastructure

Asset management has become a critical discipline for ensuring the sustainability, efficiency, and resilience of infrastructure, particularly within the water sector. As global infrastructure systems age and service demands rise, the need for structured asset lifecycle management has intensified. The International Organization for Standardisation (ISO, 2014) defines asset management as the “coordinated activity of an organisation to realize value from assets,” emphasizing the strategic integration of asset-related activities with organisational objectives to optimise performance and reduce risk.

In the context of water infrastructure—comprising essential assets such as pipelines, treatment plants, and control systems—asset management is not merely a technical function but a multidisciplinary enabler. It aligns engineering, finance, risk management, and long-term planning to support informed decision-making and efficient resource allocation (Diop et al., 2021). This broad strategic role extends beyond maintenance to encompass capital investment planning, lifecycle costing, and stakeholder engagement, thereby enhancing regulatory compliance, cost-effectiveness, and service reliability (Mohammadi and Amador Jimenez, 2022).

To support such comprehensive asset stewardship, several international frameworks such as ISO 55000, the Infrastructure Asset Management (IAM) framework, and PAS 55; offer guidance on governance, risk, and performance optimisation (ISO, 2014, IAM, 2015, Msongole et al., 2022). However, while these frameworks provide valuable high-level principles, they often fall short in

offering operational guidance tailored to transitioning from basic to advanced maintenance maturity levels. This limits their practical utility in sectors where reactive maintenance remains prevalent (Woodhouse, 2014).

The challenges facing the water sector, such as aging infrastructure, constrained budgets, and growing service demands, make the adoption of robust asset management practices particularly urgent. Without structured lifecycle strategies, utilities are increasingly exposed to unplanned failures, environmental risks, and rising operational costs (Pathirana et al., 2021, ASCE, 2021). Despite the strategic merits of asset management, a persistent gap exists between conceptual ambitions and practical implementation, especially in maintenance planning and execution (SAICE, 2022). Many utilities remain locked in reactive cycles due to the lack of clear pathways to more proactive approaches, such as preventive or predictive maintenance (Errandonea et al., 2022a). Bridging this gap requires detailed, context-specific guidance that addresses the unique challenges of infrastructure-heavy sectors; a role well-suited for a maintenance maturity model, which offers a structured pathway to assess, prioritise, and systematically improve maintenance practices (Errandonea et al., 2022a). Bridging this gap requires detailed, context-specific guidance that addresses the unique challenges of infrastructure-heavy sectors; a role well-suited for a maintenance maturity model, which offers a structured pathway to assess, prioritise, and systematically improve maintenance practices

Furthermore, addressing this strategic-operational divide requires an integrated framework that combines the principles of infrastructure asset management (IAM), lifecycle management (LCM), and strategic maintenance. IAM provides a foundation for aligning maintenance with long-term objectives, incorporating risk prioritisation, and advancing sustainability goals (Too, 2010, Hastings, 2015, Talab, 2023). LCM further strengthens this by encompassing all asset phases from acquisition to disposal, highlighting the critical importance of maintenance during the operational life of assets (Hastings, 2015, Pickshaus et al., 2016). However, implementation challenges persist, particularly in adapting LCM to operational realities within water utilities, which often lack the capacity or tools to embed proactive maintenance and condition-based monitoring strategies (Crespo Marquez et al., 2009, Guedes Soares et al., 2010).

Recent advances in digital technologies like the Internet of Things (IoT), intelligent systems and predictive analytics are reshaping asset management by enabling real-time monitoring, intelligent maintenance scheduling, and data-driven decision-making (Delnaz et al., 2023, Humnabadkar et al., 2024). These technologies support infrastructure resilience and sustainability by reducing

waste, improving responsiveness, and facilitating targeted resource allocation (Tlabu et al., 2022, Omotayo and Telukdarie, 2020).

In sum, embedding maintenance within the strategic fabric of asset management is crucial for improving water infrastructure reliability. Yet, without practical mechanisms such as maturity-based models that facilitate the translation of strategy into practice, the full potential of asset management remains unrealised. This study seeks to address this critical gap by proposing and validating a structured maintenance maturity framework tailored to the water sector, thereby enabling more consistent, sustainable, and uninterrupted service delivery.

2.4 Maintenance: A strategic function in asset management

Maintenance, as defined by the European Standard EN 13306, encompasses all technical, administrative, and managerial actions undertaken throughout an asset's lifecycle to sustain or restore its ability to perform its intended function (DIN EN-13306, 2018). Within this context, maintenance policies provide structured guidelines that inform the development of maintenance strategies. These strategies include core interventions such as corrective maintenance (CM), preventive maintenance (PM), and condition-based maintenance (CBM), which serve as the foundation for more advanced, targeted maintenance approaches (Velmurugan and Dhingra, 2015).

Effective execution of maintenance requires a well-defined management plan, as poor maintenance practices lead to increased asset failures, extended downtimes, and rising costs, all of which undermine operational efficiency (Gackowiec, 2019). Maintenance management, as outlined by Coanda et al. (2020) and Crespo Marquez and Gupta (2006), encompasses the activities that establish maintenance objectives, define strategies and responsibilities, and ensure their implementation through systematic planning, control, and continuous improvement. In asset-intensive industries, such as water infrastructure, maintenance management is vital for ensuring operational efficiency, asset longevity, and service reliability.

The shift from reactive to proactive and predictive maintenance strategies aligns maintenance with long-term strategic goals, including competitiveness, sustainability, and resilience (Mostafa et al., 2015, Opocenska and Hammer, 2016, Patil et al., 2022). As a result, maintenance is increasingly recognized as a strategic enabler of business continuity and operational excellence rather than merely a technical function. This growing recognition highlights the importance of structured maintenance programs that extend the functional lifespan of assets, enhance reliability,

and improve service delivery capacity (GFAM, 2021). Moreover, well-designed maintenance and rehabilitation programs improve asset safety and ensure compliance with regulatory requirements (Raspati et al., 2022).

Despite its critical role, maintenance remains a significant financial burden, with inefficiencies in planning and resource allocation contributing to rising costs. Studies suggest that one-third of maintenance expenditures are due to inadequate planning, leading to operational uncertainties and resource wastage (Fouladgar et al., 2012, Lucantoni et al., 2019, Rastegari and Salonen, 2015). To mitigate these challenges, maintenance must be integrated with broader organisational functions to optimise operational efficiency. Velmurugan and Dhingra (2015) stressed that aligning maintenance with business objectives ensures that it supports organisational goals, rather than disrupting them. A data-driven approach to maintenance is essential for minimising asset failures, optimising performance, and enhancing long-term outcomes, with strategic decision-making influencing asset reliability and overall maintenance effectiveness (Rastegari and Salonen, 2015).

However, as Velmurugan and Dhingra (2015) noted, quantifying the impact of maintenance strategies within broader management systems remains a challenge. The evolving nature of maintenance has also led to terminological ambiguities, with concepts such as maintenance strategy, maintenance type, and maintenance approach often used interchangeably in both academic literature and industry practice (Velmurugan and Dhingra, 2015, Manchadi et al., 2023). This lack of clarity underscores the need for precise definitions and classifications to ensure consistency in maintenance management frameworks.

The following section will address these distinctions, providing a structured understanding of their application in this study.

2.4.1 Maintenance types, approaches, and strategies

The distinction between maintenance types, approaches, and strategies is often unclear due to their interconnected nature. Velmurugan and Dhingra (2015) noted that terms such as maintenance strategy, maintenance policy, maintenance tactics/approaches, and maintenance concepts are often used inconsistently. Clarifying these distinctions is essential for developing effective maintenance frameworks.

Maintenance types

Maintenance types are categorised based on the specific tasks involved and the objectives they aim to achieve. While no universally accepted classification exists, common categorizations include preventive, reactive, and proactive maintenance. According to the European standard EN 13306, maintenance types are broadly classified into preventive and reactive maintenance (DIN EN-13306, 2018). However, various scholars expand this classification. For instance, Coanda et al. (2020) distinguish between reactive and proactive maintenance, while Khayal (2024) adds predictive maintenance to the mix. Each maintenance type has its own set of advantages and challenges, with the selection depending on operational context, asset criticality, and available resources.

Maintenance Approaches

The Oxford English Dictionary defines the term approach as "a way of considering or handling something, especially a problem." This definition underscores the distinction between maintenance types, representing broad maintenance objectives and approaches focusing on the practical execution of maintenance activities. Maintenance approaches, sometimes referred to as maintenance tactics, define the specific methodologies employed to sustain asset performance and reliability (Velmurugan and Dhingra, 2015).

Broadly, maintenance approaches can be categorised into two fundamental types (Velmurugan and Dhingra, 2015, Gandhare and Akarte, 2012): corrective maintenance and preventive maintenance. The selection and execution of these approaches depend on their alignment with the broader maintenance strategy and the technological and organisational capabilities available to support their execution. (Gandhare and Akarte, 2012).

Maintenance strategies

Unlike maintenance approaches, which focus on execution, maintenance strategies provide a structured, organisation-wide framework for optimising asset performance (Velmurugan and Dhingra, 2015). A maintenance strategy is a systematic plan for asset upkeep that varies depending on an organisation's facilities, operational environment, and business objectives (Gandhare and Akarte, 2012). Pinjala et al. (2006) define it as a "coherent, unifying, and integrative pattern of decisions in different maintenance strategy elements, aligning with corporate and business-level strategies."

A well-defined maintenance strategy incorporates research, planning, and execution, encompassing activities such as repairs, replacements, and inspections (Gackowiec, 2019, Gandhare and Akarte, 2012). These strategies must remain adaptable to evolving operational environments while maintaining alignment with overarching business goals. However, despite their strategic significance, scholars continue to debate their precise definition (Rastegari and Salonen, 2015).

2.4.2 Maintenance strategies

Maintenance strategies serve as a critical link between operational efficiency and corporate objectives. Crespo Marquez and Gupta (2006) emphasise that these strategies must be structured to align with corporate goals, ensuring that maintenance investments contribute to overall organisational success. Similarly, Zaim et al. (2012) stress the importance of adaptability in maintenance strategies, particularly in response to technological advancements and industrial transformations.

As organisations transition toward Industry 4.0, the adoption of data-driven maintenance approaches such as predictive and prescriptive maintenance have increasingly become relevant (Rastegari and Salonen, 2015, Molęda et al., 2023). This shift underscores the need to continuously refine maintenance strategies to leverage emerging technologies, enhance decision-making, and optimise asset performance in an evolving industrial landscape. Given this dynamic environment, examining various documented maintenance strategies from existing literature is essential.

2.4.2.1 Maintenance pyramid

The maintenance pyramid, illustrated in Figure 1, presents a structured framework for understanding the progressive evolution of maintenance strategies. It outlines the transition from reactive approaches to advanced predictive and prescriptive techniques, emphasising the increasing sophistication, investment, and efficiency of maintenance practices.

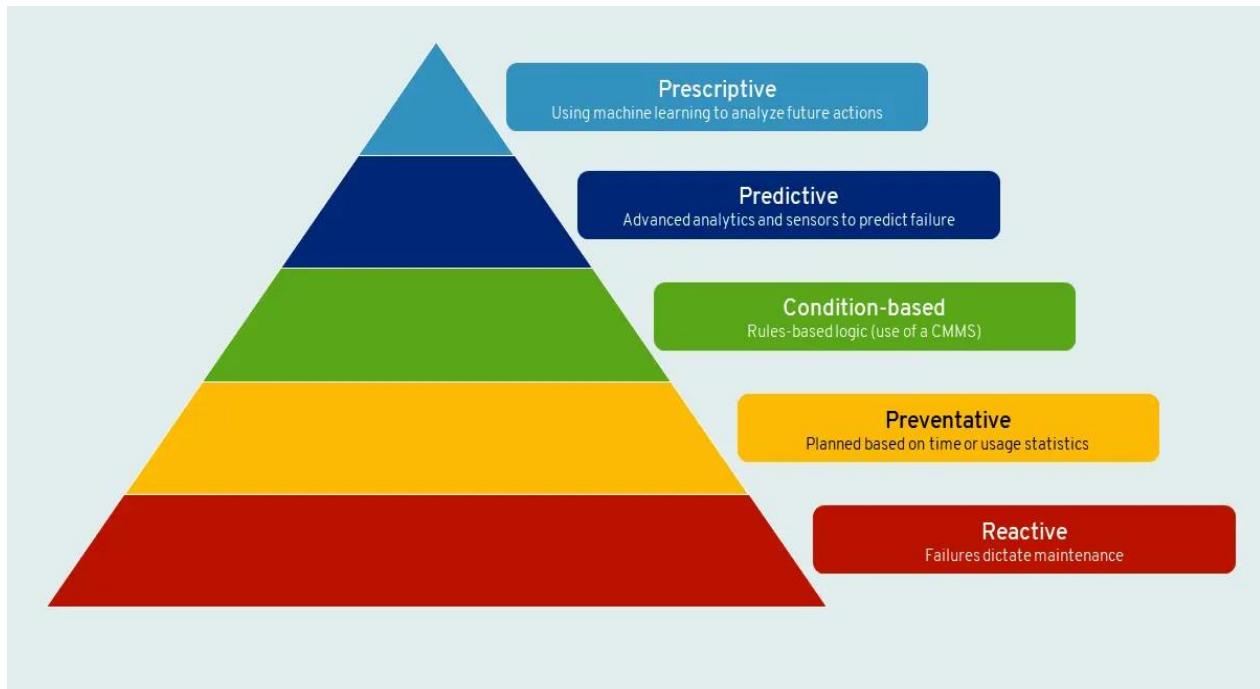


Figure 1: Maintenance pyramid adapted from Peterson (2023)

Each pyramid tier represents a distinct paradigm, reflecting the shift from failure-driven maintenance to proactive, data-driven decision-making. As organisations advance through these levels, maintenance strategies become more systematic, leveraging technological innovations and analytical capabilities to optimise asset performance and reliability. This hierarchical progression highlights the crucial role played by strategic maintenance planning in improving operational efficiency and minimising downtime.

a. Reactive/corrective maintenance: The traditional approach

According to the DIN EN 13306 standard, corrective maintenance is defined as: the maintenance carried out after fault recognition that is intended to put an item into a state in which it can perform a required function (DIN EN-13306, 2018). Also known as reactive or “run-to-failure” maintenance, this strategy addresses asset failures only after they occur (Velmurugan and Dhingra, 2015).

While simple and widely applied, particularly in water utilities, this approach is costly and risky, especially for critical assets (Merkt, 2019). As highlighted in national infrastructure reports, the unpredictability of failures often leads to frequent service disruptions, water losses, environmental hazards, and expensive emergency repairs. These shortcomings have prompted a shift towards more proactive strategies (Molęda et al., 2023).

b. Preventive maintenance: Proactively reducing failures

The DIN EN 13306 standard defines preventive maintenance as: the maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item (DIN EN-13306, 2018). This approach enhances reliability and minimises emergency repairs, but may result in over-maintenance and misallocated resources if not tailored to asset condition or criticality (Merkt, 2019, Velmurugan and Dhingra, 2015). Optimisation is crucial to avoid unnecessary interventions in the context of ageing infrastructure and constrained budgets.

c. Condition-based maintenance (CBM): Monitoring asset health in real-time

CBM is a form of preventive maintenance that relies on condition monitoring, inspections, and analysis to trigger interventions based on the actual state of assets (DIN EN-13306, 2018). Technologies such as pressure sensors, flow meters, and SCADA systems enable real-time assessments, extending asset life and reducing downtime. However, its full adoption within water utilities is often hindered by gaps in digital infrastructure, unreliable data, and shortages in skilled personnel.

d. Predictive Maintenance: Data-driven decision making

The DIN EN 13306 standard defines predictive maintenance as condition-based maintenance performed following a forecast derived from repeated analysis or known characteristics and the evaluation of significant parameters indicating asset degradation (DIN EN-13306, 2018). It uses real-time data and advanced algorithms to predict potential failures before they occur.

This approach improves efficiency and enables a proactive maintenance posture. In the water industry, the strategy has been used to solve inadequate resources, poor system maintenance, and insufficient measuring of performance data and monitoring systems (Tlabu et al., 2022). Nonetheless, fragmented asset data and low digital maturity are common in many water utilities, limiting their effective implementation.

e. Prescriptive maintenance: Optimising maintenance decisions through advanced analytics

Prescriptive maintenance, the most advanced strategy, predicts failures and recommends specific actions to prevent them (TRACTIAN, 2023). Nemeth et al. (2018) emphasised that prescriptive maintenance addresses the question, “How can we make it happen?”; or more

specifically, “How can we control the occurrence of a specific event?”; by providing actionable recommendations to prevent failures. This approach yields tailored, high-value outcomes, making it ideal for digitally mature organisations. However, successful implementation requires seamless integration of IT and operational technology and organisational readiness (Errandonea et al., 2022b) conditions often lacking in the water sector.

To clearly differentiate the evolution and characteristics of each maintenance strategy, from reactive to prescriptive, a comparative overview is provided in Table 2.

Table 2: Comparative overview of maintenance strategies

Maintenance strategy	Trigger	Use case	Tools	Strengths	Weaknesses	References
Reactive/Corrective Maintenance	After failure	Low-risk, non-critical assets	None or basic repair tools	Simple, low initial cost	High unplanned downtime, expensive for critical assets	(DIN EN-13306, 2018, Velmurugan and Dhingra, 2015, Merkt, 2019)
Preventive Maintenance	Fixed intervals or usage	Moderate-risk, moderately critical assets with predictable failure patterns	Manual checks, time-based schedules	Predictable, extends asset life	May cause over-maintenance, not condition-sensitive	(Merkt, 2019, DIN EN-13306, 2018, Patil et al., 2022)
Condition-Based Maintenance (CBM)	Actual asset condition	High-value or critical assets where failure can be prevented through real-time condition monitoring	Sensors, diagnostic tools	Avoids unnecessary work, improves reliability	Requires monitoring systems, initial investment	(DIN EN-13306, 2018, Guillén et al., 2016, Li et al., 2020, Merkt, 2019)

Maintenance strategy	Trigger	Use case	Tools	Strengths	Weaknesses	References
Predictive Maintenance (PdM)	Forecast based on data trends	Highly critical, expensive, or complex assets with failure patterns detectable through data analytics	IoT, AI, ML, data analytics	Proactive, cost-efficient, fewer disruptions	Requires high-quality data and technical skills	(Merkt, 2019, DIN EN-13306, 2018, Tlabu et al., 2022, Ran et al., 2019)
Prescriptive Maintenance	AI-driven actionable insights	Mission-critical assets in complex, data-rich environments requiring optimal, context-specific decisions	AI, digital twins, simulation engines	Optimised decisions, minimal waste, highest ROI	Complexity, costly to implement, data management burdens	(Nemeth et al., 2018, TRACTIAN, 2023, Errandonea et al., 2022b, Selvarajan, 2021)

These strategies reflect a broader transition towards proactive, data-informed maintenance. However, technology and frequency alone do not ensure success. Effectiveness hinges on alignment with an organisation's culture, processes, and capabilities. This is where the maintenance maturity model (MMM) becomes vital. The MMM addresses these challenges by offering a structured pathway for organisations to evaluate and improve their maintenance capabilities across key dimensions. Rather than promoting a one-size-fits-all strategy, the MMM recognises that effective maintenance is contingent upon organisational maturity.

2.4.2.2 Total productive maintenance (TPM),

Beyond the structured hierarchy of the maintenance pyramid, alternative strategies such as total productive maintenance (TPM) offer holistic approaches to enhancing asset performance and operational efficiency. TPM integrates maintenance into daily operations by encouraging proactive involvement across all organisational levels (Kumar et al., 2013, Molęda et al., 2023). This strategy is grounded in principles of continuous improvement, employee empowerment, and the systematic elimination of inefficiencies to maximise overall equipment effectiveness (Lundgren et al., 2018). By aligning maintenance activities with broader organisational objectives, TPM cultivates a culture of shared responsibility, leading to increased productivity and reduced downtime (Molęda et al., 2023). This approach is particularly effective in industries where

production efficiency and equipment availability are paramount, such as manufacturing, automotive, and process industries (Sahib, 2016). Unlike traditional top-down strategies, TPM emphasises bottom-up engagement, focusing operational efforts on optimising equipment performance at the (Crespo Marquez and Gupta, 2006).

2.4.2.3 Risk-based maintenance (RBM)

Risk-based maintenance (RBM) adopts a systematic and analytical approach by prioritising maintenance work based on the possibility of equipment failure and the potential impact of those failures on operational performance (Sibanda et al., 2024). RBM enables organisations to allocate resources effectively by focusing on assets with the highest operational risks. By so doing, this strategy enhances reliability while optimising maintenance costs, ensuring that critical systems receive the attention they require without unnecessary expenditures on less critical assets (Lucantoni et al., 2019). RBM is particularly beneficial in industries where safety, environmental concerns, and operational continuity are critical, such as water infrastructure, gas, power generation, and critical infrastructure sectors (Miya and Grobbelaar, 2015). Ultimately, RBM contributes to improved system performance, heightened safety outcomes, and reduced lifecycle costs through a structured and risk-aware maintenance strategy.

2.4.2.4 Reliability-centred maintenance (RCM)

Reliability-Centred Maintenance (RCM) is a structured method/approach that tailors maintenance strategies based on asset functions, failure modes, and the operational consequences of failures (Opocenska and Hammer, 2016). By systematically analysing potential failure risks and their associated impacts, RCM ensures that maintenance actions are both targeted and justified, aligning with safety, performance, and cost-effectiveness objectives (Opocenska and Hammer, 2016, Molęda et al., 2023). This approach is especially critical in asset-intensive and safety-critical industries such as aviation, power generation, and manufacturing, where high reliability is imperative for operational continuity and risk mitigation (Geisbush and Ariaratnam, 2022, Sajaradj et al., 2019).

RCM plays a pivotal role at both strategic and tactical levels by guiding the development of maintenance programs that uphold equipment reliability and system integrity (Crespo Marquez and Gupta, 2006, Crespo Marquez et al., 2009). The RCM framework is grounded in four core principles: (1) preserving asset functions, (2) identifying failure modes that could compromise those functions, (3) prioritising functions based on their criticality, and (4) selecting effective

preventive maintenance tasks accordingly (Lundgren et al., 2018). Additionally, RCM supports the proactive elimination or reduction of failure risks by enabling the ranking and prioritisation of failure modes that may be designed out during asset improvement or redesign initiatives.

2.4.3 The importance of maintenance prioritisation in asset-intensive industries

Beyond selection of maintenance strategies, effective maintenance prioritisation is essential for optimising resource allocation, minimising downtime, and maximising asset performance (Chong et al., 2019). Maintenance prioritisation is critical in asset-intensive industries, ensuring infrastructure sustainability, reliability, and efficiency. Given the constraints of limited resources and competing operational demands, organisations must strategically identify critical assets and failure risks to optimise maintenance efforts (Wing et al., 2016, Chong et al., 2019).

A key factor in maintenance prioritisation is asset criticality, which evaluates the consequences of failure on operations, safety, and regulatory compliance (Petersdorff and Vlok, 2014). By adopting a risk-based approach, organisations can allocate resources more effectively, focusing on assets whose failure would have the most significant impact. This ensures the continuity of essential functions while minimising operational disruptions.

While maintenance prioritisation is essential across various industries, its complexity varies depending on the operational context (Petersdorff and Vlok, 2014). Both public and private sector organisations encounter asset management challenges, yet their approaches differ due to distinct regulatory frameworks, decision-making processes, and resource allocation strategies. Public-sector entities, particularly those responsible for critical services such as water supply and treatment, must balance cost-effective maintenance with regulatory compliance and service reliability (Da Silva et al., 2021, Carpitella et al., 2017). Conversely, private-sector operators prioritise return on investment (ROI) and cost-efficiency in their maintenance strategies (Tam and Price, 2008). Despite these contextual differences, both sectors converge on enhancing asset performance, minimising operational costs, and reducing risk exposure.

Organisations have turned to diverse maintenance prioritisation frameworks that integrate qualitative judgment and quantitative analysis to navigate the increasing complexity of asset portfolios and evolving operational challenges (Fernández and Márquez, 2012). Among the most prominent approaches are reliability-centred maintenance (RCM), failure modes and effects analysis (FMEA), asset criticality analysis (ACA), and multi-criteria decision-making (MCDM) methods (Geisbush and Ariaratnam, 2022, Mezhoud et al., 2022, Salman, 2024, Chambel et al.,

2023). When applied in isolation, these methods may offer limited perspectives. Hence, their integration fosters a more comprehensive and strategic maintenance prioritisation framework that balances technical, operational, and risk-based considerations for improving reliability, efficiency, and sustainability.

2.5 Maturity model (MM)

Maturity models have emerged as essential frameworks for systematically assessing and enhancing organisational capabilities, processes, and systems across various domains. Becker et al. (2009) define maturity models as conceptual frameworks that outline an evolutionary path toward maturity. These models enable organisations to assess their current practices (as-is situations) against desired target requirements, facilitating the identification and prioritisation of improvement measures (Becker et al., 2009, Poeppelbuss and Roeglinger, 2011, Richard Caralli et al., 2012). In the context of design science research, Becker et al. (2009) viewed maturity models as artifacts that contribute to organisational learning and development.

Rooted in continuous improvement principles, maturity models guide organisations in evaluating their current state, identifying critical gaps, and implementing strategies to reach higher performance levels (Wendler, 2012, Linhart et al., 2017). By advancing through staged maturity levels, organisations transition from unstructured processes to standardised, optimised practices. This evolution ensures that improvements are systematic, sustainable, and aligned with long-term strategic objectives.

The origins of maturity models trace back to the capability maturity model (CMM), developed by the Software Engineering Institute (SEI) in the late 1980s to assess software development processes. Over time, the CMM evolved into the capability maturity model integration (CMMI), extending its application to broader organisational processes (Paulk et al., 1993). Central to the maturity model framework is staged progression, where organisations move through levels, each representing increased standardisation, optimisation, and innovation (Reis et al., 2017). This structured progression enables organisations to systematically enhance capabilities while mitigating inefficiencies and risks.

The theoretical foundations of maturity models align with established process improvement methodologies, such as total quality management (TQM) and lean six sigma. These methodologies emphasise measurable criteria, benchmarking, and continuous improvement as drivers of organisational excellence (Kohlegger et al., 2009, Reis et al., 2017). Moreover, maturity

models incorporate principles from organisational learning and knowledge management, recognizing that sustained improvement requires both structural and cultural transformation (Reis et al., 2017). By combining these theoretical perspectives, maturity models serve as comprehensive tools for process refinement and fostering a learning-oriented organisational culture.

In the context of maintenance, maturity models potentially play a crucial role in optimising resource allocation, improving strategies, and reducing failure risks. By assessing their current maturity, organisations can develop structured maintenance schedules, improve asset reliability, and enhance overall efficiency (Wendler, 2012, Chemweno et al., 2015). This demonstrates the versatility of maturity models, as they support continuous improvement and strategic decision-making across diverse industries and operational contexts.

2.5.1 Classification of maturity models

Maturity models are typically categorized into three types: progression models, capability models, and hybrid models (Richard Caralli et al., 2012):

- **Progression models:** These are structured around the idea of development over time, where entities evolve through a set sequence of stages. Each stage represents a level of maturity that builds upon the previous one.
- **Capability models:** These focus on assessing and enhancing specific abilities within an organisation. Instead of following a linear path, capability models emphasise achieving excellence in distinct areas or functions. The aim is to heighten competencies, with each capability assessed independently of others, allowing for targeted improvements in specific domains.
- **Hybrid models:** These combine elements of both progression and capability models. They recognise the value of sequential development and the need to build particular competencies simultaneously. Hybrid models offer more flexibility, allowing organisations to advance through maturity stages while developing critical capabilities tailored to specific business needs.

2.5.2 Typical purposes of use for maturity models

Maturity models can be used for various purposes based on their scope and focus (Poeppelbuss and Roeglinger, 2011):

- **Descriptive models:** These models define different maturity levels without prescribing specific improvements. They serve as assessment tools (e.g., CMMI, ISO 55000 for asset management) (Salhie and Alswaer, 2022).
- **Prescriptive models:** These not only define maturity levels but also suggest actions for improvement at each stage (e.g., Business process maturity model) (Becker et al., 2009).
- **Comparative models:** These models benchmark an organisation's maturity against industry standards or best practices (e.g., Gartner's digital maturity model).

2.5.3 Key components and structure of maturity models

Maturity models typically consist of the following components (Poeppelbuss and Roeglinger, 2011):

- **Maturity levels:** A hierarchical set of stages (e.g., initial, managed, defined, optimised) that represent increasing levels of capability.
- **Dimensions or domains:** Specific areas of focus, such as processes, technology, people, and governance, which are assessed independently.
- **Assessment criteria/ attributes:** Defined metrics or indicators used to evaluate performance within each dimension.
- **Improvement roadmap:** Guidance on how to progress from one level to the next.

2.5.4 Significance and contributions

Maturity models have garnered significant attention in academic research due to their potential to bridge theory and practice. Key contributions include:

- **Framework development:** Scholars have developed and refined maturity models for specific domains, manufacturing (Macchi and Fumagalli, 2013a), railway industry (Holomisa et al., 2024a) and cybersecurity (Caralli et al., 2010).
- **Empirical validation:** Research has focused on validating the effectiveness of maturity models through case studies and empirical analysis (Wendler, 2012).

Despite their widespread use, maturity models have also been critiqued and some criticisms include:

- **Rigidity and oversimplification:** Many models assume linear progression, whereas real-world organisational development is often non-linear and context-dependent (Wendler, 2012). In response to these limitations, the maintenance maturity model (MMM) has been intentionally designed to be flexible and non-linear. While it retains clearly defined maturity levels, the MMM does not prescribe a sequential path through them. Instead, it enables domain-specific assessments, recognising that an organisation may demonstrate a high level of maturity, such as 'Managed' in one domain (e.g., Maintenance Work Management), while remaining at a foundational level, such as 'Ad-hoc' in another (e.g., Human Resources). This modular architecture acknowledges the heterogeneous nature of organisational capabilities and supports the development of tailored, domain-focused improvement strategies, rather than enforcing uniform progression across all areas.
- **Lack of empirical validation:** Some maturity models are based on expert opinions rather than empirical data, raising concerns about their reliability and applicability (Poeppelbuss and Roeglinger, 2011). The maintenance maturity model (MMM) explicitly addresses this limitation by incorporating a Delphi study as a core component of its validation process. Involving practitioners, academics, and industry specialists from asset-intensive sectors (e.g., water infrastructure, mining, public works) ensured the model is not only theoretically sound but empirically informed.
- **Adaptability issues:** Generic models may not fully capture the complexities of industry-specific challenges, necessitating customisation for different organisational needs. This has led to scholarly calls for more flexible, adaptable, and context-sensitive models that reflect cultural, environmental, and sector-specific dynamics (Poeppelbuss and Roeglinger, 2011). In response to these concerns, the MMM promotes organisational self-assessment and contextual adaptation. It enables organisations beyond water utilities to tailor the model by prioritising domains that are most critical to their operational goals, strategic objectives, and regulatory requirements, thus enhancing the model's relevance and applicability across varied industry settings.

2.6 Methodologies

This section outlines the research methodologies employed in this study, namely Design Science Research (DSR), Action Design Research (ADR), and the elaborated Action Design Research (eADR) framework. These methodologies are particularly suited for the development, evaluation,

and refinement of artefacts in complex real-world contexts such as addressing the identified research problem.

2.6.1 Design science research (DSR)

Design Science Research (DSR) has emerged as a pivotal paradigm in problem-solving and innovation-driven disciplines such as information systems, engineering, and industrial management (Vom Brocke et al., 2020). Unlike purely descriptive research approaches, DSR emphasises the development and assessment of artefacts (e.g models, methods and constructs) that aim to solve practical problems while also enriching theoretical understanding.(Hevner et al., 2004). This approach provides a structured framework for developing and validating solutions to complex, practice-oriented challenges.

Operating at the intersection of pragmatism and constructivism, DSR emphasises the creation of functional solutions alongside the generation of new knowledge through iterative experimentation (Gregor and Hevner, 2013). This dual purpose distinguishes DSR from traditional empirical research, which primarily aims to explain or predict phenomena. By integrating both behavioural and design science paradigms, DSR facilitates a comprehensive understanding of system development, its implementation, and its assessment, while also considering the research environment and contributing to the body of knowledge (Hevner et al., 2004). In practice, DSR's framework allows for a continuous cycle of artefact development, evaluation, and refinement, ensuring that solutions are both effective and grounded in a robust theoretical context, as shown in Figure 2. This iterative process enhances the rigour and relevance of the research, making DSR a powerful tool for addressing practical problems while advancing academic knowledge.

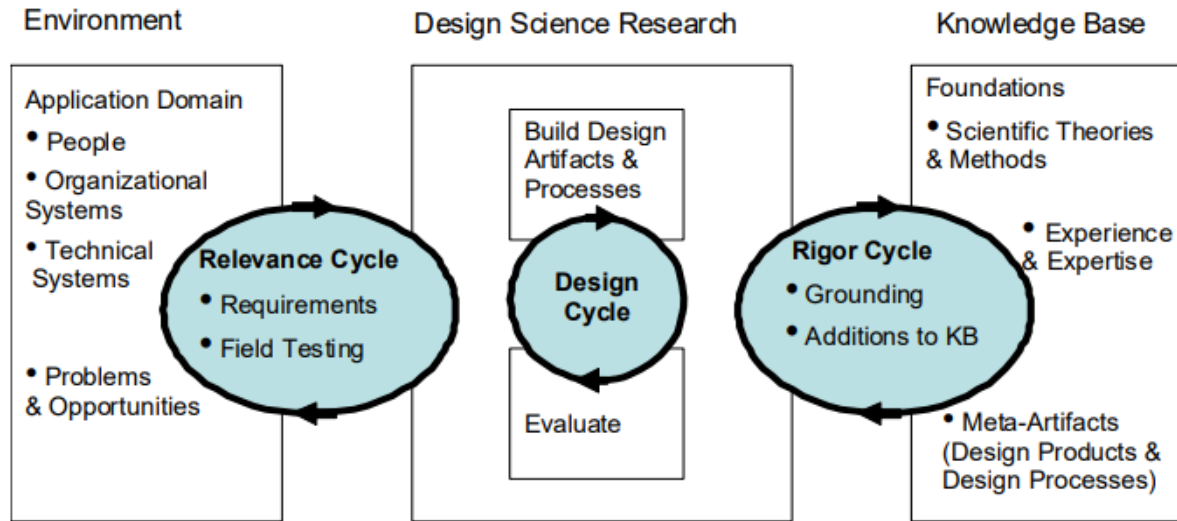


Figure 2: Design science research cycles (Hevner, 2007)

Within the design science research (DSR) paradigm, two widely recognised methodological approaches are the design science research methodology (DSRM) and action design research (ADR) (Sein and Rossi, 2019). DSRM offers a structured yet adaptable process model that permits entry at various stages depending on the nature and context of the research (Peffers et al., 2007, Vom Brocke et al., 2020, Mullarkey and Hevner, 2015). In contrast, ADR is situated within the broader DSR framework but is distinguished by its singular, problem-driven entry point. It emphasises close collaboration with practitioners to iteratively design, implement, and evaluate artefacts within real-world organisational settings (Sein et al., 2011). While both methodologies align with DSR's core principles, ADR adopts a more practice-oriented stance, directly integrating problem-solving with artefact development.

Building on this foundation, the present study adopts the elaborated ADR approach, which was introduced by Mullarkey and Hevner (2019) to direct the development of the MMM. The eADR approach refines and extends the original ADR framework by introducing a more detailed and adaptable process structure that accommodates evolving problem and solution spaces, while retaining the iterative rigour and dual focus on relevance and rigour that underpin DSR. Figure 3 illustrates the relationship between the DSR paradigm and the eADR methodology employed in this research.

The research began with problem diagnosis, consistent with the fundamental principles of Action Design Research as articulated by Sein and Rossi (2019), an approach also employed by Maisiri

(2021), Mangaroo-Pillay (2022), and Coetzee (2019). Further elaboration of ADR principles is provided in section 2.6.2 and section 2.6.3 discusses the details of the eADR method.

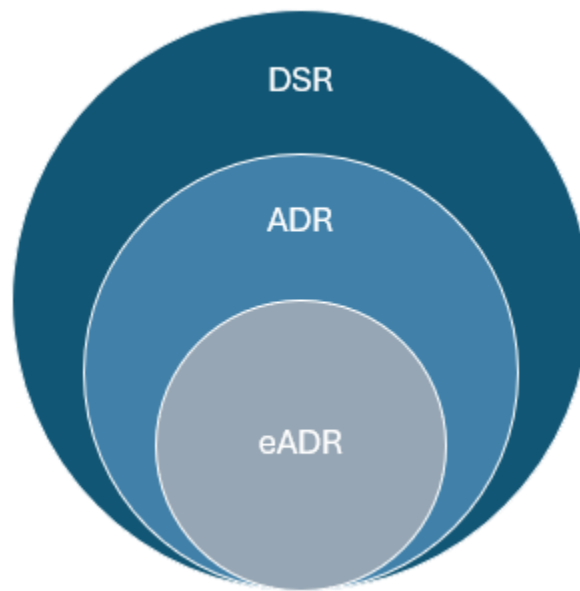


Figure 3: Onion model of the relationship between DSR, ADR and eADR

2.6.2 Action design research (ADR)

Action design research is a methodology that combines the principles of design research (DR) and action research (AR) to create and evaluate innovative IT artefacts within organisational contexts (Sein et al., 2011). Initially introduced by Sein et al. (2011), ADR focuses on addressing real-life challenges while simultaneously advancing scholarly understanding. Unlike traditional DSR, which primarily emphasises artefact creation, ADR extends this approach by incorporating organisational interventions, continuous refinements, and iterative cycles to ensure the artefact's relevance and rigour (Sein et al., 2011). This dual focus guarantees that the artefacts developed are both scientifically valid and practically useful in real-world applications.

The methodology emphasises ongoing engagement with the organisational context, allowing researchers to refine and adapt the artefact based on real-time feedback and emerging insights. Figure 4 illustrates the relationship between these stages and principles, highlighting how ADR provides a dynamic and flexible framework for both solving practical challenges and advancing theoretical knowledge.

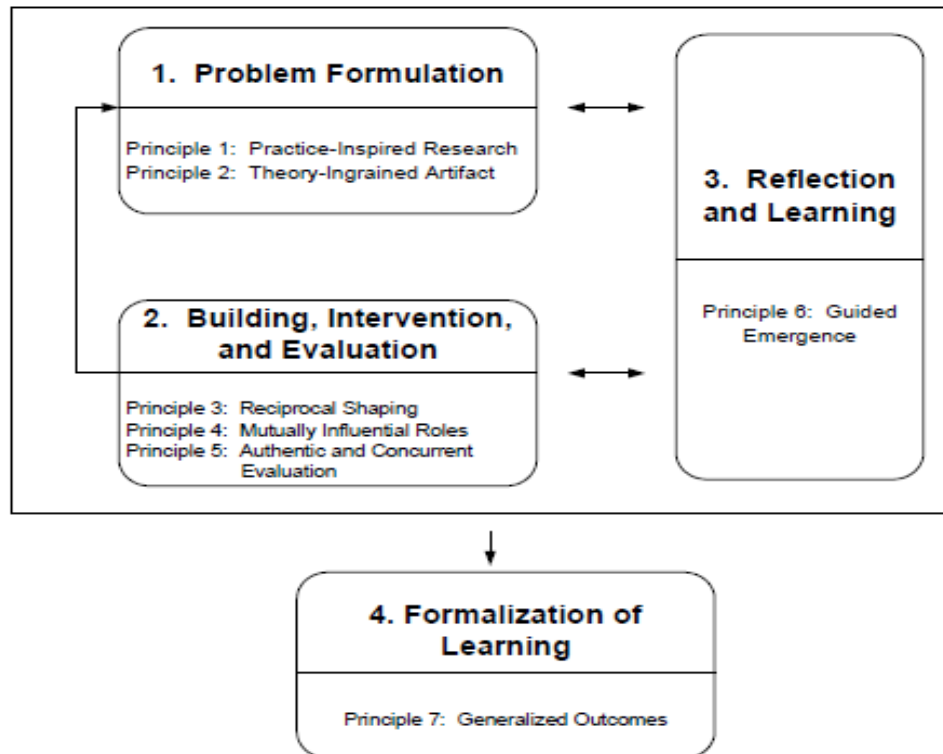


Figure 4: ADR method: stages and principles (Sein et al., 2011)

2.6.3 Elaborated action design research (eADR)

The elaborated Action Design Research (eADR) methodology, introduced by Mullarkey and Hevner (2015), extends the foundational ADR framework proposed by Sein et al. (2011) to accommodate research contexts in which no initial artefact exists. While traditional ADR assumes a predefined artefact and a linear progression through problem formulation, building, intervention, and evaluation (BIE) (Mullarkey and Hevner, 2015), eADR introduces a more flexible and inclusive structure. It incorporates a dedicated entry point for artefact identification and divides problem formulation into two distinct phases: diagnosing, which establishes a comprehensive understanding of the problem domain, and concept design, where an initial artefact concept is developed based on theoretical grounding. Furthermore, eADR embeds intervention, evaluation, and structured reflection across all stages of the research process, thereby supporting continuous learning and alignment between problem understanding and artefact evolution (Mullarkey and Hevner, 2015).

In its refined form, as articulated by Mullarkey and Hevner (2019), eADR comprises four iterative and overlapping stages: diagnosing, design, implementation, and evolution. This updated

framework reinforces design research's dynamic and adaptive nature by integrating action planning and reflection into each phase. The diagnosing stage focuses on the development of artefacts such as problem models, requirements, and specifications; design emphasises the conceptualisation of solutions through frameworks, design principles, or architectures; implementation involves the deployment and testing of the artefact in real-world settings; and evolution addresses the need for continual adaptation as organisational needs and environmental contexts shift (Mullarkey and Hevner, 2019).

Each phase of the eADR framework is underpinned by action planning, reflection, and learning, which enhance the methodology's responsiveness to real-world complexities (Sein and Rossi, 2019). This ongoing process of refinement ensures that the resulting artefact maintains both practical relevance and theoretical rigour. Notably, the framework's inherent flexibility allows researchers to contribute knowledge even before the artefact is fully developed, rendering eADR particularly suitable for addressing challenges in complex and dynamic environments. Figure 5 presents the eADR framework, highlighting its iterative cycles and the central role of sustained learning throughout the research lifecycle.

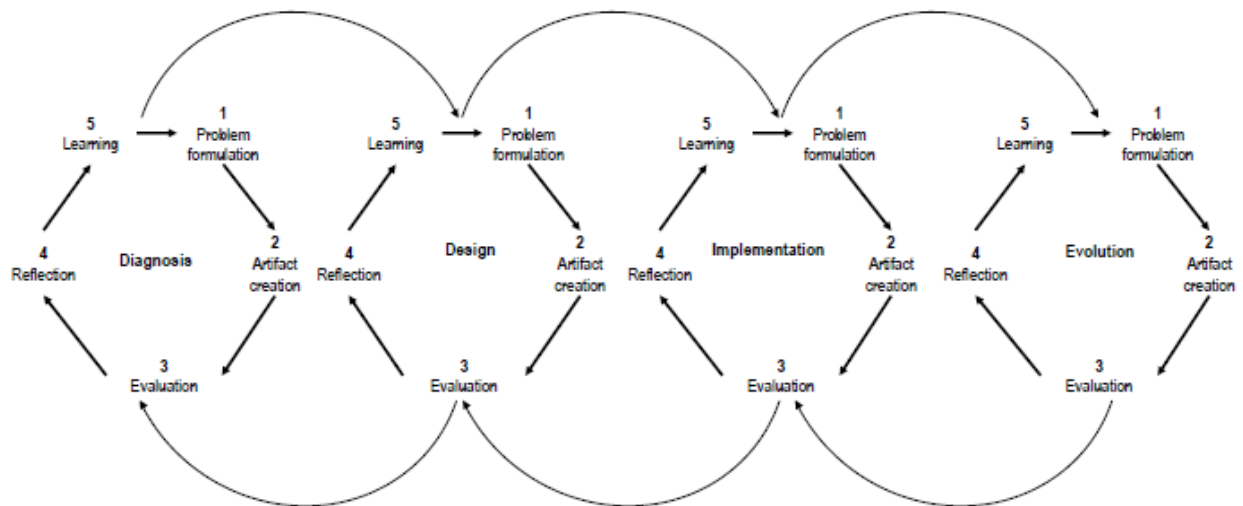


Figure 5: Elaborate action design science cycles - adapted from Mullarkey and Hevner (2019) as applied by Maisiri (2021)

2.7 Chapter summary

This chapter explored the key concepts that form the study's theoretical foundation. Examining relevant theories and frameworks established a conceptual basis that aligns with the overarching objectives of the research. The discussion in this chapter provided the necessary context for

understanding the variables and relationships that underpin the study's analytical framework. Chapter 3 presents the research design adopted for this dissertation and how it was applied-

CHAPTER 3: RESEARCH DESIGN

3.1 Introduction

This chapter presents the research design adopted for the study, guided by the Design Science Research (DSR) paradigm, which emphasises the development of innovative artefacts that address complex practical problems while contributing to academic knowledge (Gregor and Hevner, 2013). Within this paradigm, the study employed the elaborated Action Design Research (eADR) method, which integrates cycles of artefact design, evaluation, and refinement in close collaboration with practitioners (Mullarkey and Hevner, 2019). This iterative approach ensures that the developed artefact is both theoretically sound and practically relevant.

To ensure the rigour, credibility, and applicability of the artefact, the Delphi technique was incorporated as a systematic method for expert evaluation and validation. The Delphi process allowed for structured feedback and consensus-building among a panel of knowledgeable participants.

The remainder of this chapter is structured as follows:

- Section 3.2 provides an overview of the research design and its relevance to the study.
- Section 3.3 discusses the diagnosis stage synopsis.
- Section 3.4 discusses the design stage synopsis.
- Section 3.5 concludes the chapter.

Through this design, the study ensures methodological rigour while responding to real-world needs with a validated and actionable solution.

3.2 Research Design

This research aims to develop a maintenance maturity model (MMM) customised to support the prioritisation of water infrastructure maintenance in South Africa. Situated within the DSR paradigm, this research adopts the first two stages of the elaborated ADR methodology, as articulated by Mullarkey and Hevner (2019). These stages: diagnosis (stage 1) and design (stage 2); provide a structured, iterative framework for identifying complex, real-world problems and designing suitable artefacts in response.

The eADR approach has been successfully applied in related research contexts, including those of Coetzee (2019), Maisiri (2021), and Mangaroo-Pillay (2022), where it supported the development of artefacts addressing similarly complex, domain-specific challenges. These precedents affirm the methodological suitability of eADR for this study.

A key strength of eADR lies in its flexibility, allowing researchers to initiate or conclude at different stages depending on the context (Mullarkey and Hevner, 2019). Given the multifaceted and systemic nature of water infrastructure maintenance issues in South Africa, this flexibility is particularly advantageous. Accordingly, the present study begins at the diagnosis stage, which involves a comprehensive exploration of the current maintenance landscape, identifying inefficiencies, systemic gaps, and areas for improvement. Insights gained during this stage informed the subsequent design stage, which focused on conceptualising and developing the proposed MMM.

An overview of the research design, including the iterative nature of the methodology and the outputs of each phase, is presented in Figure 6. Each iteration is carefully documented to capture the evolution of understanding and design, thereby enhancing the transparency and replicability of the research process.

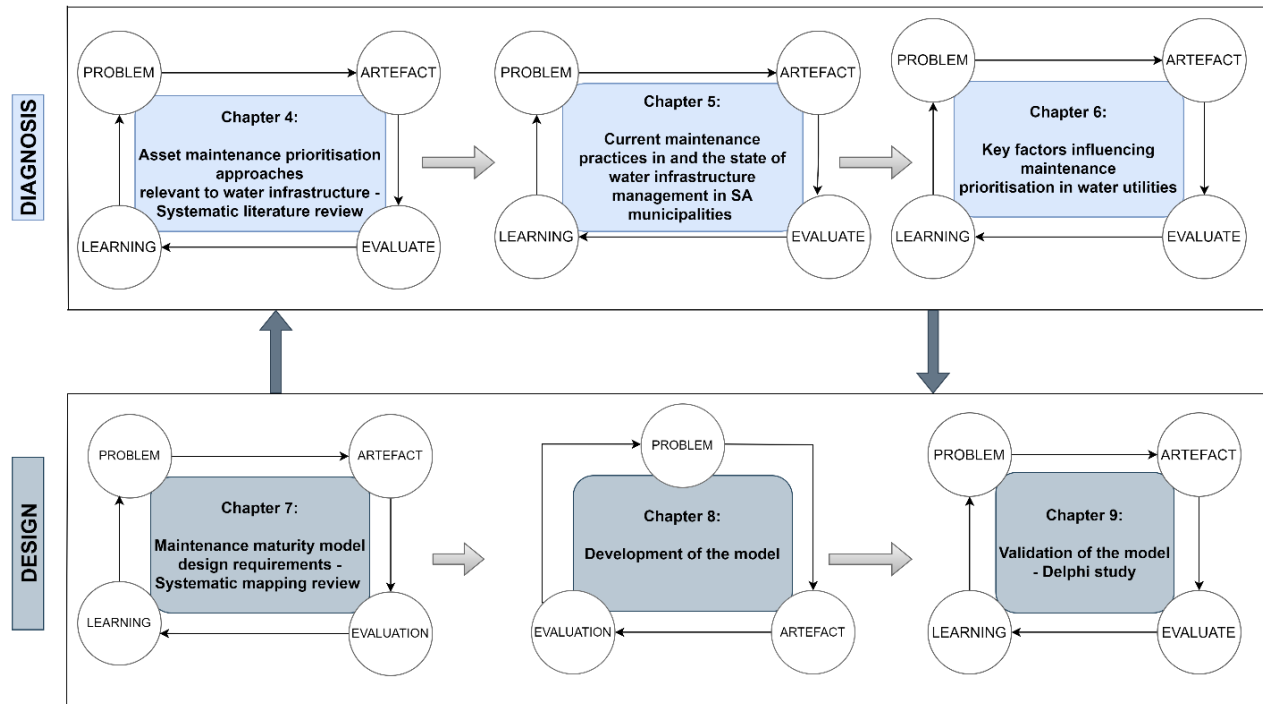


Figure 6: Research design overview

3.3 Diagnosis stage synopsis

The diagnosis stage was dedicated to the structured articulation and validation of the research problem in water infrastructure maintenance, as initially outlined in Chapter 1. This stage progressed through three iterations aimed at deepening the understanding of the problem context and refining the research focus. The details of these iterations are provided in Sections 3.3.1 to 3.3.3.

3.3.1 Current maintenance practices in and the state of water infrastructure management in South African municipalities

- Problem definition** - South African municipalities face persistent challenges in maintaining water infrastructure, leading to service delivery inefficiencies, frequent breakdowns, and deteriorating infrastructure conditions. The study addresses the gap in understanding how current maintenance practices contribute to these issues and seeks to identify areas for improvement.
- Artefact** - The study produced a comprehensive literature summary that critically examined the deep-seated challenges affecting water infrastructure maintenance. It also

identified potential areas for improvement, offering a structured understanding of existing maintenance practices and gaps that need to be addressed for sustainable infrastructure management

- c. **Evaluation** - Experienced academic peers independently reviewed the methodology and findings to ensure alignment with scholarly standards and the study's research objectives.
- d. **Learning** - By assessing existing maintenance practices and infrastructure challenges in South African municipalities, it became evident that the sector lacks prioritised, proactive maintenance strategies. These insights guided the design of the subsequent SLR to identify and evaluate global and local maintenance prioritisation approaches that could be adapted to improve water infrastructure management in South Africa's resource-constrained municipal settings

3.3.2 SLR of asset maintenance prioritisation approaches relevant to water infrastructure management.

- a. **Problem definition** - This study addresses the inadequate insights into current, more effective practices and tailored approaches for maintenance prioritisation in water infrastructure management. This gap limits the ability of asset managers to make informed, data-driven decisions for effective maintenance prioritisation
- b. **Artefact** - The artefact was presented as a conference paper at the 34th annual conference of the Southern African Institute for Industrial Engineering (SAIIE), highlighting its relevance to contemporary maintenance management challenges. See Appendix H
- c. **Evaluation** - The study employs a systematic literature review (SLR) as its evaluation method to analyse and synthesise relevant research rigorously.
- d. **Learning** - The paper synthesised global and regional trends in maintenance prioritisation, highlighting a lack of integrated, adaptable frameworks for water infrastructure in the global south. Presenting at SAIIE provided valuable feedback from academics and practitioners. Key points included the need to contextualise prioritisation models to South Africa's unique socio-technical and operational environment.

3.3.3 Key factors influencing maintenance prioritisation in water utilities

- a. **Problem definition** - The lack of structured prioritisation frameworks hinders efficient maintenance management, making it challenging to allocate resources and address critical issues proactively

- b. **Artefact** - A catalogue Key factors that influence maintenance prioritisation decisions in water utilities, ensuring that limited resources are allocated to maximise operational efficiency and service reliability.
- c. **Evaluation** - An independent evaluation of the findings was conducted by my academic supervisor, who provided critical feedback.
- d. **Learning** - The learning from this study involved a deeper understanding of how maintenance prioritisation frameworks can be designed and implemented within water utilities, considering various competing factors as discussed in Chapter 6.

3.4 Design stage synopsis

The design stage of this study consisted of three key phases: (1) establishing design requirements, (2) developing the maintenance maturity model (MMM), and (3) validating the developed model. These phases were carefully executed to ensure the model's effectiveness, applicability, and alignment with industry best practices. Chapter 7 discusses the establishment of design requirements and gap analysis, providing the foundational criteria for the model. Chapter 8 discusses the MMM development process, detailing the model's conceptualisation and formulation. Finally, chapter 9 focuses on the validation phase, where the model's applicability and robustness were tested and refined through expert consensus. Each phase was integral in ensuring that the final model addressed the identified challenges and met the study's objectives.

3.4.1 A systematic mapping review of maintenance maturity model design requirements

- a. **Problem definition** - There was no predefined set of design requirements to guide the development of a maintenance maturity model that is both academically rigorous and practically applicable in industry
- b. **Artefact** - Maintenance maturity model design requirements
- c. **Evaluation** - The design requirements formulated in this study were evaluated and validated by industry experts using the Delphi technique, as detailed in Chapter 9
- d. **Learning** – Chapter 7 outlined the refined design requirements which were further validated in chapter 9

3.4.2 Development of the model

- a. **Problem definition** -There is a lack of maintenance maturity models specifically tailored for water infrastructure maintenance challenges

- b. **Artefact** - Maintenance maturity model
- c. **Evaluation** - The Delphi technique was employed, and expert consensus on the sufficiency of the MMM structure was achieved within two rounds. Chapter 9 discusses the whole process.

3.4.3 Validation of the MMM

Phase three of the design stage focused on validating and refining the structure of the Maintenance Maturity Model (MMM) through an expert validation process.

- a. **Problem definition** - The lack of robust validation for the maintenance maturity model, particularly in ensuring its alignment with industry standards and its reliability and accuracy in evaluating maintenance practices.
- b. **Artefact** - A refined maintenance maturity model, validated through expert feedback, that offers a structured framework to evaluate and improve maintenance practices within asset-intensive industries.
- c. **Evaluation** - The Delphi technique was employed to validate the model by seeking consensus among a panel of experts through successive rounds of structured questionnaires.
- d. **Learning** - Formalised the model structure

3.5 Conclusion

This chapter outlined the design and methodology employed in developing the maintenance maturity model, with a particular focus on the use of elaborated action design research. The discussion provided an overview of the process followed, highlighting the key steps undertaken to ensure a systematic and rigorous approach. The subsequent chapters will provide a detailed examination of each stage as outlined in section 1.9, offering in-depth insights into the development and validation of the model. The next chapter delves into a systematic literature review of maintenance prioritisation approaches tailored to water infrastructure

CHAPTER 4: A SYSTEMATIC LITERATURE REVIEW ON ASSET MAINTENANCE PRIORITISATION APPROACHES RELEVANT TO WATER INFRASTRUCTURE

4.1 Introduction

This chapter investigates the maintenance prioritisation approaches widely used in the management of municipal water-related infrastructure and identifies and examines knowledge deficiencies and leading practices within the current body of knowledge. The findings provide valuable insights into current maintenance decision-making and uncover areas for improvement in the management of water sector infrastructure.

4.2 Systematic Literature Review method

The SLR assessed and interpreted relevant research on asset maintenance prioritisation strategies relevant to water infrastructure in line with Kitchenham (2004) and Siddaway et al. (2019)'s approach and guided by Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Page et al., 2021).

4.2.1 Research protocol

Table 3 provides a detailed account of the protocol followed in this chapter, which includes information on the purpose of the SLR, research questions, inclusion criteria, exclusion criteria, databases searched, keywords used and quality assessment criteria employed.

Table 3: Research protocol

Purpose of the study	To investigate the maintenance prioritisation approaches commonly applied to water infrastructure assets
Research questions	RQ1: What are the prevalent water infrastructure asset maintenance prioritisation strategies in literature? RQ2: What are the key factors influencing the selection of maintenance prioritisation strategies in managing water infrastructure?
Inclusion criteria	• The paper discusses maintenance prioritisation being applied to water infrastructure management. • The research paper focuses on asset management in water infrastructure.

Exclusion criteria	• The paper is a duplicate publication. • The full text of the paper is not in English except for the title. • There is no access to the full text of the paper. • The research paper loosely uses terms and synonyms related to maintenance and prioritisation. • The research paper focuses solely on maintenance prioritisation outside the context of water infrastructure. • The research papers that are unrelated to the primary focus of the study.
Search Database	Scopus
Keywords	“water infrastructure” and “asset management” and “maintenance prioritisation”
Quality assessment criteria	• All duplicate literature must be removed. • Correct scientific methods must be used throughout the research study. • The overall methodology should be described in a manner that allows the study to be replicated. • Recovered literature should be checked for relevance and credibility. • Proper grammar, syntax, and terminology should be used to ensure the reader fully understands the research's intentions and outcomes.

4.2.2 Search strategy

The primary approach used to gather data involved searching the Scopus databases for articles using specific keywords related to “maintenance prioritisation”, “asset management”, and “water infrastructure”. Search terms were carefully selected to reflect the main themes presented in the research questions while considering spelling variation, synonyms and usage differences. The approach followed increases the chances of identifying relevant studies (Siddaway et al., 2019).

Table 4 presents alternative terms used to encompass any potential differences in spellings or usage of synonyms.

Table 4: Search terms (alternative terms included)

Search terms	Alternative search words
Water infrastructure	
Asset management	Infrastructure management
Maintenance prioritisation	Maintenance prioritization, maintenance priority, maintenance management, maintenance priority setting, maintenance planning, maintenance scheduling, reliability-centred maintenance (RCM), priority setting methods, maintenance strategy selection

4.2.3 Search scope

The SLR review was conducted on the Scopus database, and only papers published in the last ten years, i.e. from January 2014 to December 2023, were reviewed to advance the existing research. The Scopus database was chosen for its extensive repository of peer-reviewed literature, providing a significant range of research contributions relevant to our research questions. The search returned a total of 442 studies which underwent scrutiny and evaluation following the PRISMA guidelines.

4.2.4 Study selection

Guidelines for selecting papers in this SLR adhered to the exclusion and inclusion criteria outlined in Table 3. The screening process involved a thorough examination of each paper's title, abstract, and full text. This comprehensive evaluation aimed to determine the potential relevance of each paper to the research objectives and adherence to the specified criteria. Literature studies that did not meet these criteria (described in Table 3) were excluded from the review. Despite retrieving many articles, many were not directly related to water infrastructure due to their abstract nature. Each article's abstract was carefully examined, and those considered relevant were further explored.

Ambiguous abstracts led to a review of the conclusion sections or a rapid assessment starting from the introduction to determine relevance. Articles that remained unclear were ultimately disregarded.

Figure 7 summarises the selection stages followed in this SLR which included the removal of articles that were duplicated (DP), non-English studies (LC), studies that did not allow full access (NF), unrelated to the SLR's primary focus (NR) and studies that are casually related to this review. This led to the remaining 14 eligible articles which were further analysed.

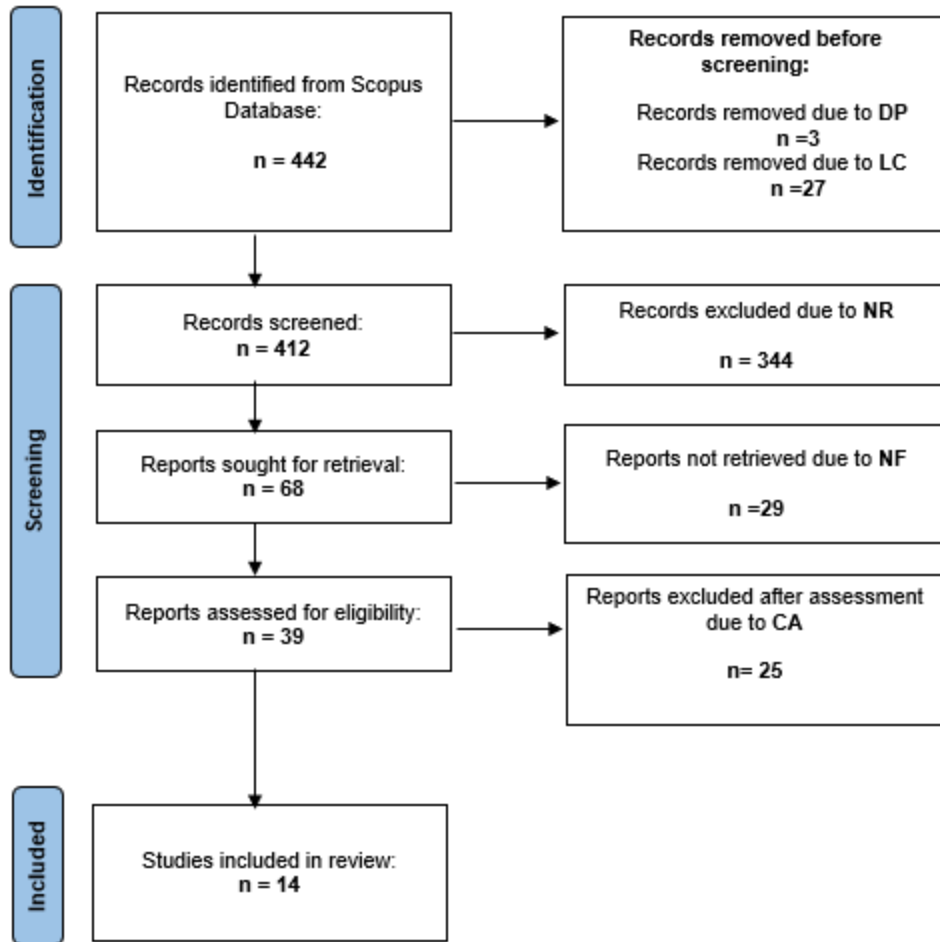


Figure 7: PRISMA flow diagram for systematic reviews (Page et al., 2021)

4.2.5 Quality assessment for relevant studies

The quality of relevant literature was evaluated by thoroughly reading the articles. The retrieved studies were examined to determine their relevance to maintenance prioritisation in water infrastructure asset management and the factors they addressed. Evaluation criteria included language use, writing credibility, and reputable scientific research methods used in the literature.

4.2.6 Data analysis

To address the research questions outlined in Table 3, a total of 14 articles were selected for in-depth review. The data collection and review process were intentionally open-ended, permitting exploration of various aspects related to maintenance prioritisation without imposing predefined categories or biases. This approach facilitated a comprehensive examination of the topic.

The extracted data encompass diverse elements of maintenance prioritisation, including various methods, models, factors, algorithms, frameworks, tools, and decision-making processes. These elements form the basis for further analysis and synthesis aimed at effectively addressing the research questions and objectives of the SLR.

A qualitative analysis was employed to interpret the collected data, specifically through the application of descriptive coding. This method was chosen to identify the maintenance prioritisation strategies utilised in addressing water infrastructure maintenance issues and to determine the factors influencing these prioritisation decisions. Table 5 provides a summary of the literature included in the SLR, listing relevant references and offering a brief overview of each article's content.

Table 5: Summary of the studies included in the review

Author	Factors considered	Prioritisation approaches	Results
(Tornyeviadzi et al., 2022)	Asset criticality, impact on service delivery	Segment criticality Measure/assessment/analysis	Framework for scheduling maintenance routine
(Mazumder et al., 2021)	Risk, asset criticality	Risk analysis + Complex network theory analysis.	Risk-informed decision support framework for integrated water and road infrastructure asset management.
(Chu et al., 2022)	Condition - economic cost, network reliability, and network health	Non-dominated Sorting Genetic Algorithm	A life cycle oriented multi-objective optimal maintenance model for water distribution
(Al-Attar et al., 2021)	Asset condition, risk, budget constraints	Fuzzy-Failure mode effect analysis (FFM-EA) - Risk Priority Index and the Total Intensity (TI)-AHP, FMRPI-FMTI Risk diagram	Fuzzy-based multi-criteria decision support system for maintenance of wastewater treatment plants
(Meijer et al., 2021)	Asset criticality, impact on service delivery	Graph theory method	A method of Identifying critical elements in drinking water distribution networks
(Ramos-Salgado et al., 2021)	Risk, asset criticality, proximity, budget constraints, asset condition	Multi-objective genetic algorithm (MOGA)	A decision support system to design water supply and sewer pipe replacement intervention programs
(Marlim et al., 2019)	Asset criticality	Element-based simulation approach Criticality index	A methodology to Identify Critical Pipes Using a Criticality index
(Srivastava et al., 2019)	Risk, asset condition	Fuzzy-FMEA	A risk-based method of identifying and prioritising causes of failure for maintenance planning

Author	Factors considered	Prioritisation approaches	Results
(Phan et al., 2019)	Risk	Risk analysis/assessment) Risk map	Framework for risk assessment of pipes in a WDN for maintenance prioritisation
(Masud et al., 2019b)	Asset condition, risk, budget constraint	Risk assessment - risk rating matrix; Life Cycle Costs analysis	Risk-based approach to develop a maintenance strategy
(Pereira et al., 2020)	Asset criticality, asset condition	Strategic Options Development and Analysis (SODA), Elimination and Choice Translating Reality (ELECTRE TRI-nC) method,	A methodological framework for sorting the water distribution network areas for the maintenance plan.
(Meijer et al., 2018)	Asset criticality	Graph theory method	A method of identifying the most critical elements in a network with respect to malfunctioning of the whole system.
(Maryati and Romdoni, 2017)	Environmental impact, risk	AHP-fuzzy model	An AHP-fuzzy model to determine maintenance priority based on environmental factors
(Katheeri et al., 2015a)	Asset condition, asset criticality, risk	Failure mode effect analysis Asset Criticality analysis Life cycle cost analysis	Water asset replacement maintenance prioritisation procedure

4.3 Systematic literature review findings

4.3.1 Literature overview

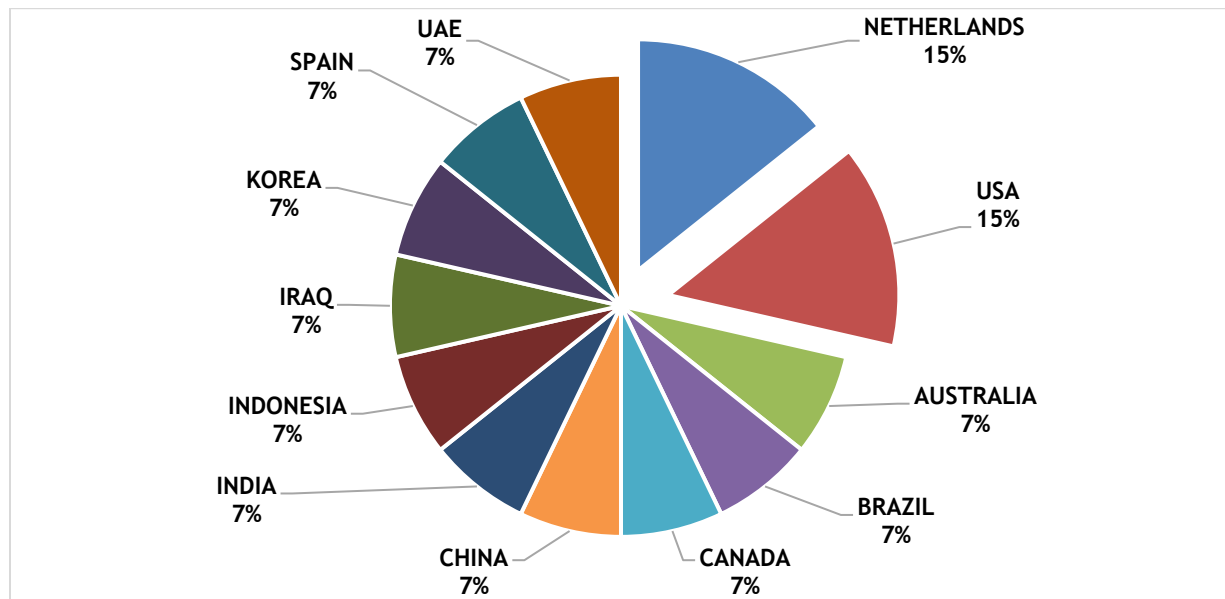


Figure 8: Countries in the reviewed studies

Figure 8 above illustrates the distribution of studies on water infrastructure maintenance by country, revealing a notable lack of contribution from developing countries. The majority of studies were conducted in the Netherlands and the USA, constituting 30% of the reviewed journal articles and conference papers.

The water distribution and wastewater infrastructure are essential elements of urban systems, ensuring access to clean water and proper wastewater management. However, research exhibit a notable maintenance priorities discrepancy between these two infrastructural types, as depicted in Figure 9. Literature predominantly emphasises maintenance of water distribution infrastructure pipeline networks.

The emphasis on pipeline networks in both water distribution and wastewater infrastructure is justified by their essential role as the backbone of these systems, facilitating water transportation. Their critical function, susceptibility to deterioration, and significant economic implications underscore the focus on pipeline maintenance. Any disruptions in these pipelines can lead to severe consequences, highlighting the need for prioritised maintenance efforts.

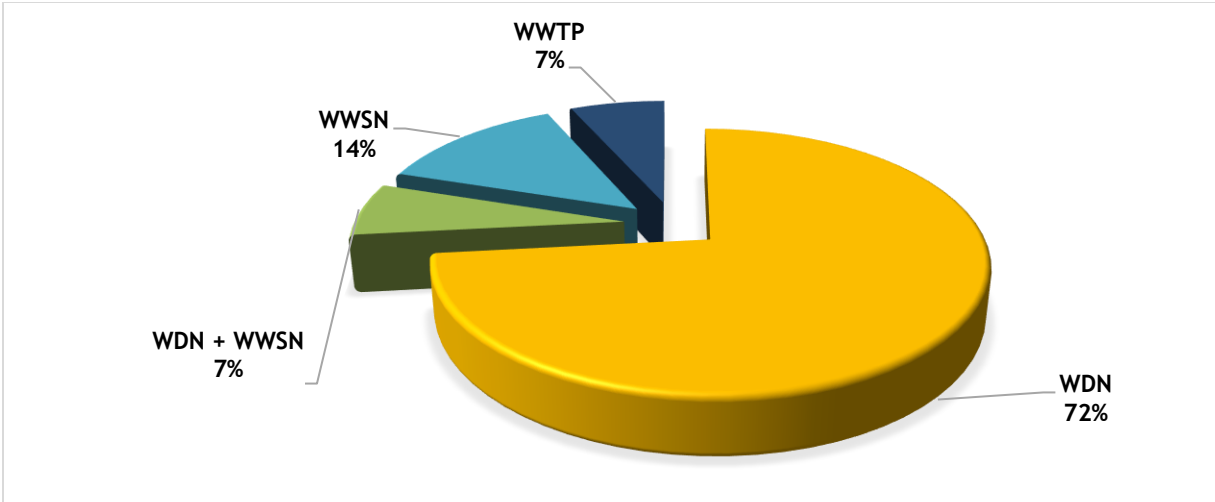


Figure 9: Application context of the reviewed studies (wastewater sewage network (WWSN), wastewater treatment plant (WWTP), water distribution network(WDN))

4.3.2 Prevalent maintenance prioritisation strategies

Table 6 provides a summary of common maintenance prioritisation strategies used in the water infrastructure sector, identified through a systematic literature review. The summary categorises the strategies, techniques, or methods employed, along with corresponding references from eligible articles meeting the inclusion criteria.

Table 6: Maintenance prioritisation strategies

Strategy/Approach	Method/ Technique	Reference
Risk-based	• Risk analysis + Complex network theory analysis • Fuzzy-FMEA • Risk analysis/assessment) + Risk map • Risk assessment • AHP-fuzzy model • FMECA + Life cycle cost analysis • Risk assessment	(Mazumder et al., 2021, Phan et al., 2019, Srivastava et al., 2019, Masud et al., 2019b, Maryati and Romdoni, 2017, Katheeri et al., 2015a)
Asset criticality analysis	• Segment Measure/assessment/analysis Criticality • Graph theory method • Element-based simulation approach + Critical index • Graph theory	(Tornyeviadzi et al., 2022, Meijer et al., 2021, Meijer et al., 2018, Marlim et al., 2019)

Optimisation	• Non-dominated Sorting Genetic Algorithm • Multi-Objective Genetic Algorithm	(Chu et al., 2022, Ramos-Salgado et al., 2021)
Multi-Criteria Decision Analysis (MCDA)	• FFM-EA + FMRPI-FMTI Risk diagram • Strategic Options Development and Analysis + ELECTRE TRI-nC method	(Al-Attar et al., 2021, Pereira et al., 2020)

Figure 10 shows that 43% of the analysed studies employed a risk-based strategy to prioritise maintenance activities based on the likelihood and consequences of asset failure.

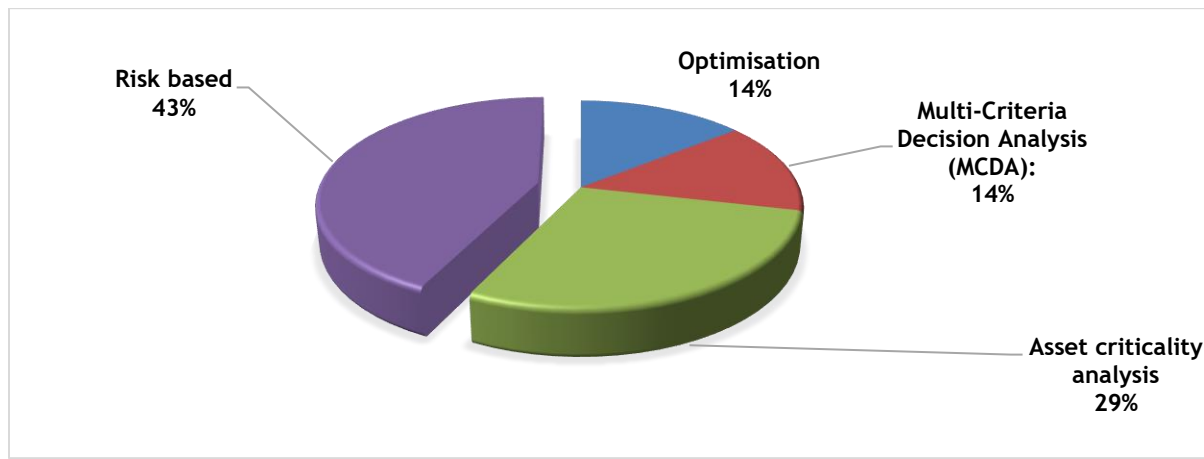


Figure 10: Application of maintenance prioritisation approaches

Given the substantial impacts of water infrastructure malfunctions on public health and environmental safety, this approach is crucial. The widespread use of risk-based methods underscores their effectiveness in providing proactive maintenance for vital assets and in mitigating long-term expenses by preventing significant failures.

The importance of risk management techniques in maintenance prioritisation extends beyond identifying high-risk areas within water infrastructure networks. Maintenance practitioners not only address these high-risk areas to prevent potential failures that could endanger public health, safety, and the environment, but also utilise risk assessments to inform resource allocation decisions (Mazumder et al., 2021, Phan et al., 2019, Srivastava et al., 2019).

In addition, risk assessment is essential for ensuring regulatory compliance in water infrastructure management. Non-compliance with regulatory standards, such as pipeline leakages or deteriorating wastewater treatment plants, can lead to contamination or poor water quality,

violating water utilities' obligations to provide safe and continuous clean water (Masud et al., 2019b).

Asset criticality analysis, comprising 29% of reviewed articles, ranks as the second most dominant approach, as shown in Figure 10. This analysis evaluates each asset in the water infrastructure network to determine its significance. Assets deemed crucial, either due to their key role in the system or their potentially severe impact if disrupted, are given top priority in maintenance operations. A study by Tornyeviadzi et al. (2022), employed segment criticality analysis to identify specific segments within the water distribution network (WDN) that can undergo maintenance without causing operational disruptions or hindering service delivery.

Incorporating asset criticality analysis emphasises the importance of maintaining high-priority components within water infrastructure and enables effective resource allocation by establishing priorities necessary for optimal functionality and uninterrupted service delivery across all networks involved.

Given the necessity to balance multiple objectives and navigate conflicting constraints during decision-making, multi-criteria decision analysis (MCDA) methods offer a comprehensive approach to assessing maintenance priorities aligned with organisational goals and stakeholder preferences (Al-Attar et al., 2021, Pereira et al., 2020, Katheeri et al., 2015a). Figure 10 shows that MCDA approaches account for 14% of the studies. Multi-criteria decision analysis involves the use of multiple criteria to evaluate and prioritise maintenance activities. These criteria can include risk, cost, asset criticality, and other relevant factors (Katheeri et al., 2015a). This approach provides a structured framework to balance various competing factors. The adoption of MCDA indicates the recognition of the complexity involved in asset management decision-making and the multifaceted nature of maintenance prioritisation in water infrastructure.

Although potentially powerful, multi-criteria optimisation is the least common approach in the reviewed literature (Figure 10). It employs mathematical and computational techniques to determine efficient resource allocation and maintenance schedules with specific objectives like cost minimisation or asset reliability maximisation. For instance, in a study conducted by Chu et al. (2022), the genetic algorithm was utilised to optimise maintenance schedules by exploring trade-offs between conflicting objectives, such as minimising risks and maintenance costs while maximising system reliability, all within the constraints of available resources or system limitations. Chu et al. (2022) asserted that genetic algorithms help decision-makers identify

maintenance strategies that effectively balance multiple goals by generating various pareto-optimal solutions to enhance operational efficiency, reduce costs, and prolong asset lifespan.

In summary, SLR findings indicate that a balanced approach, which involves considering both technical and practical factors, is essential for effective maintenance prioritisation in water infrastructure. By integrating these diverse factors and strategies, maintenance practitioners can develop comprehensive maintenance strategies that improve water infrastructure resilience, optimise resource use, and ensure continuous service delivery.

4.4 Discussion

4.4.1 Discussion of the SLR

The systematic literature review (SLR) identified a consistent theme of risk consideration and the implementation of risk-based strategies, demonstrating the effectiveness of risk management techniques in the maintenance prioritisation of water infrastructure systems.

Tools such as risk assessment, risk matrices, failure mode effect analysis (FMEA), failure mode effect and critical analysis (FMECA), and risk maps augment the decision-making process aimed at mitigating the associated risks. By identifying critical failure modes and assessing risks, decision-makers can optimise maintenance planning, allocate resources efficiently, and enhance the overall reliability of water infrastructure systems. Risk assessments prioritise maintenance efforts on critical assets to prevent potential issues and improve practices. However, the SLR revealed that due to resource constraints, maintenance practitioners tend to focus primarily on addressing maintenance risks that pose the greatest threat to their business objectives.

The success of a decision-making system relies heavily on amassing sufficient and relevant data (Al-Attar et al., 2021). Limited access to asset data poses significant challenges, hindering effective infrastructure monitoring and problem resolution. Reliable data is fundamental to understanding the current condition of assets, predicting future performance, and formulating appropriate maintenance and management strategies. The SLR revealed the difficulty of conducting thorough risk assessments with inadequate data, underscoring the necessity of robust data collection strategies to enhance asset condition monitoring and evaluation. Chu et al. (2022), further proposed that dependable data collection and model validation are crucial for scientifically managing water distribution networks.

Multi-criteria decision analysis (MCDA) approaches effectively incorporate qualitative factors into decision-making processes, particularly when information or analytic resources are scarce. MCDA supports maintenance decisions involving multiple factors, constraints and adapts as more data becomes available. However, selecting the appropriate MCDA technique for resource allocation remains challenging. Techniques such as the analytic hierarchy process (AHP), failure mode effect analysis (FMEA) and others have inherent strengths and weaknesses that must be evaluated to determine their suitability in specific context, as demonstrated by Pereira et al. (2020) and Maryati and Romdoni (2017). These techniques can be complex and require specialised knowledge, which may not be available in some municipalities.

Life cycle-oriented, multi-objective optimisation and multicriteria decision models are important for balancing objectives such as cost, reliability, and service level in comprehensive maintenance management. Optimisation techniques can significantly reduce operational costs and enhance service delivery, which is increasingly important as water utilities aim to improve financial sustainability and operational efficiency. While promising, these approaches are less widely adopted due to complexity and resource demands.

Advanced analytical techniques, fuzzy logic, and decision support models are prevalent, yet there is a need for customised models to handle uncertainty and complexity in maintenance decision-making. Life cycle cost (LCC) analysis for budget allocation and asset replacement/renewal decisions as noted by Katheeri et al. (2015a). However, there is a lack of comprehensive discussion on the practical implementation of LCC analysis in the reviewed studies.

In summary, the literature indicates the need for adaptable maintenance prioritisation strategies that incorporate structured decision-making methods, consider resource constraints, and employ advanced analytical techniques.

4.4.2 Knowledge gaps and suggested areas for scholarly inquiry

A notable research gap exists regarding the economic consequences of maintenance decisions, particularly in water infrastructure management. This gap hinders effective collaboration between technical and financial teams, potentially leading to misalignment between technical decisions and financial constraints, resulting in suboptimal resource allocation and inefficiencies.

There is an identifiable gap in the literature regarding the development of tailored solutions and strategies for managing water infrastructure, particularly in the developing countries of Southern Africa.

Currently, while many existing research studies offer valuable insights into maintenance prioritisation, they often adopt a narrow focus on specific asset types or isolated operational contexts. Although beneficial in some scenarios, this asset-specific lens tends to produce fragmented approaches that overlook the interdependencies within broader infrastructure systems. As a result, practitioners frequently encounter difficulties when attempting to generalise or scale these findings across diverse asset portfolios. This lack of a holistic strategy underscores a critical gap in the literature—namely, the need to understand maintenance prioritisation from a system-wide perspective that accounts for the complexity and interconnectedness of infrastructure networks.

In addressing this gap, the subsequent chapter focuses on identifying and analysing the key factors influencing maintenance prioritisation decisions within the water industry. By adopting a comprehensive lens, the chapter informs decision makers on how to move beyond isolated asset considerations, providing a more integrated understanding that supports scalable and context-responsive maintenance strategies.

4.4.3 Contribution of the SLR

The SLR consolidates and analyses existing research on maintenance prioritisation for water infrastructure assets, providing a holistic view and comprehensive understanding that is often missing in individual studies. The SLR identified and compiled commonly used maintenance practices and effective strategies from various sources, offering a clear guide for maintenance practitioners to adopt proven approaches in the water industry. By effectively prioritising maintenance, water infrastructure managers can optimise resource allocation, reduce downtime, and extend the lifespan of critical assets.

By examining the breadth of existing literature, the SLR identified areas needing further exploration, thus acting as a guide for future research by pinpointing unexplored areas, emerging trends, and technologies in the maintenance of water infrastructure assets. The review allows for a comparative analysis of different maintenance prioritisation strategies, highlighting their applicability to various contexts within water infrastructure.

4.4.4 Limitations of the SLR

This SLR was based on publications from 2014 to 2023. The SLR exclusively considered English-language publications, potentially excluding significant studies published in other languages. The

SLR solely reviewed research indexed in the Scopus database, thereby leaving out pertinent studies published elsewhere. Additionally, the SLR did not include grey literature, even though these sources can sometimes offer valuable insights and data. This exclusion was because grey literature is often not peer-reviewed and may lack the rigorous quality control and academic validation that peer-reviewed journal articles and conference papers provide. This decision was made to ensure the reliability and credibility of the data included in our systematic review. The wide variety of research goals and methodologies among the reviewed studies created substantial heterogeneity, precluding the possibility of conducting a meta-analysis.

4.5 Conclusion

This chapter presented a systematic literature review (SLR) of maintenance prioritisation strategies within the water infrastructure sector. It provided a comprehensive understanding of current practices and highlighted dominant approaches, particularly the widespread use of risk-based and criticality analyses, which account for 72% of identified strategies (Section 4.3.2). While these methods offer structured and defensible decision-making frameworks, the review reveals a critical gap in adopting more integrated and data-informed approaches that address the sector's increasing complexity and dynamic operating environment.

The findings underscore the urgent need to evolve beyond conventional methodologies toward holistic prioritisation models that are adaptable, data-driven, and capable of responding to emerging risks and long-term infrastructure sustainability demands. Such an evolution is essential for supporting the resilience and long-term performance of critical water infrastructure systems.

The following chapter builds on this foundation by examining the current maintenance practices and the state of water infrastructure management in South African municipalities. Through this contextual exploration, the study seeks to assess how existing operational realities align with or diverge from the trends and gaps identified in global literature, thereby framing the relevance and applicability of proposed prioritisation strategies within the South African context.

CHAPTER 5: CURRENT MAINTENANCE PRACTICES AND THE STATE OF WATER INFRASTRUCTURE MANAGEMENT IN SOUTH AFRICAN MUNICIPALITIES

5.1 Introduction

The water infrastructure management in South African municipalities is a critical concern, given the increasing demand for reliable water services and the persistent challenges related to infrastructure degradation. This chapter presents an analysis of the current state of water infrastructure in South Africa and evaluates existing maintenance management practices, their implementation, and their effectiveness. The analysis identified key deficiencies, inefficiencies, and best practices within municipal maintenance frameworks. The study's findings contributed to an in-depth comprehension of the research problem presented in Chapter 1 and established a foundational basis for developing a maintenance maturity model (MMM).

5.2 Overview of the water sector in South Africa

Water infrastructure is fundamental to modern society, ensuring access to potable water, sanitation, and supporting economic activities (Makhari, 2016). However, maintaining reliable and efficient water systems in South African municipalities remains a significant challenge. Reports such as the SAICE Infrastructure report scorecard (IRC) and the Department of Water and Sanitation's (DWS) Blue Drop and Green Drop assessments indicate that many municipal water and wastewater systems are in deteriorating condition (SAICE, 2022, DWS, 2023b, DWS, 2023a). Frequent pipe bursts, wastewater leaks, and prolonged service interruptions reflect systemic deficiencies in maintenance practices, resulting in infrastructure failures, service disruptions, and heightened public health risks (Muinamia, 2015, Wall and Rust, 2017).

A key contributor to these challenges is the inadequacy of maintenance practices within municipalities (Stats SA, 2024). Many local governments operate under severe financial constraints and lack the technical expertise required to implement structured maintenance programs (Luyaba et al., 2024). Historically, underinvestment in infrastructure maintenance and rehabilitation has resulted in a growing backlog of urgent repairs (Boshoff, 2009). Additionally, the absence of comprehensive asset management plans hinders effective maintenance prioritisation and execution (Le Gat et al., 2023, Mazele and Amoah, 2022). Consequently, municipalities often

adopt a reactive maintenance approach, addressing breakdowns only after they escalate into major failures. This short-term strategy leads to higher long-term costs, increased service disruptions, and accelerated infrastructure deterioration (Muller, 2024).

Despite ongoing government investments in infrastructure, outcomes frequently fall short of expectations, as reflected in the Auditor General of South Africa (AGSA)'s reports (AGSA, 2023, AGSA, 2020), where concerns regarding inadequate maintenance have been consistently highlighted. This is consistent with the findings of the SAICE Infrastructure Report Cards (2006-2022), yet progress in addressing the root causes remains limited.

The consequences of poor maintenance extend beyond technical failures, impacting service quality and governance (AGSA, 2023). The absence of standardised maintenance protocols impedes knowledge sharing and the adoption of best practices, further undermining the municipal capacity to sustain infrastructure performance (Boshoff, 2009, Petrus and Ruiters, 2014). Moreover, regulatory frameworks tend to emphasise compliance and service delivery mandates over proactive infrastructure management, resulting in inconsistent maintenance practices and accelerating infrastructure (Bikam and Chakwizira, 2021)

To address these issues, a structured, proactive maintenance approach integrated within the broader regulatory and governance framework is imperative. Bikam and Chakwizira (2021) emphasised that strengthening maintenance management through improved planning, resource allocation, and performance monitoring can enhance service reliability, reduce long-term costs, and guarantee sustainable municipal water infrastructure

5.3 Current state of water infrastructure in South Africa

South Africa's water infrastructure, encompassing dams, reservoirs, rivers, and groundwater systems, is vital for meeting the nation's water demands. However, the deteriorating condition of this infrastructure poses a significant challenge to national development, public health, and the delivery of essential services. For example, residents in some regions still rely on manual water collection from makeshift supply points due to unreliable or a lack of piped water systems, as illustrated in Figure 11.



Figure 11: A man fills containers from a mobile water supply unit (SABC NEWS, 2024)

Ageing infrastructure is among the primary drivers of service disruptions in South Africa's water sector (Omotayo and Telukdarie, 2020). Compounding these challenges are the country's significant non-revenue water (NRW) losses, primarily driven by leaks, theft, vandalism and operational inefficiencies. According to the DWS (2022a), approximately 41% of treated water is lost to NRW, far exceeding the global best practice threshold of 15%. This substantial water loss worsens existing shortages and places additional strain on already fragile infrastructure, making the need for proactive maintenance strategies even more urgent.

Beyond physical infrastructure failures, ineffective maintenance practices further reduce the sector's reliability. Research by Mokgobu et al. (2023) and Vyas-Doorgapersad and Masibigiri (2022) underscores the interconnectedness of outdated infrastructure, inadequate maintenance regimes, governance challenges, and corruption. These systemic issues create a cycle of deterioration, where delayed maintenance leads to more frequent failures, increasing repair costs, and further weakening municipal service delivery.

Despite various government-led initiatives, South Africa's water infrastructure continues to deteriorate, exposing persistent governance, planning, and maintenance deficiencies. Approximately 30% of the country's water infrastructure requires urgent rehabilitation, with rural areas facing an even greater backlog of 35% (Ruiters and Amadi-Echendu, 2022a). Local municipalities such as Mopani District have long exemplified these challenges, struggling with

outdated infrastructure and chronic resource constraints (Maake and Holtzhausen, 2015). Likewise, the Elias Motsoaledi Local Municipality has experienced recurring service disruptions in areas like Motetema, largely due to delayed maintenance and unstable infrastructure systems (Hoffman and Nkadimeng, 2016). These cases underscore the pressing need for improved infrastructure management, particularly in resource-limited and rural contexts where the impact of neglect has the gravest outcomes.

The impact of this deterioration extends beyond service reliability, posing significant public health risks. Inadequate maintenance often results in water leaks, contamination, and exposure to waterborne diseases including cholera, dysentery, and typhoid fever (Malima et al., 2022, Mokgobu, 2017, Xaba, 2020). These risks are particularly pronounced in smaller municipalities and rural communities, where limited access to sanitation and healthcare amplifies the vulnerability of already marginalised populations.

A striking example is the 2023 cholera outbreak in Hammanskraal, where failures in the water treatment system led to widespread contamination (Chagopa, 2023). In informal settlements, deteriorating wastewater systems further escalate public health threats by allowing untreated sewage to infiltrate water sources, heightening the risk of disease outbreaks (Bazaanah and Mothapo, 2024). These cases demonstrate how poor maintenance not only disrupts services but also directly endangers community health.

Beyond human health, failing infrastructure has profound environmental implications. The degradation of wastewater treatment facilities has severely polluted key water systems such as the Vaal River, triggering ecological damage including algal blooms, fish die-offs, and disruption of aquatic biodiversity (Evans, 2021, Dzwauro et al., 2010). These environmental consequences reinforce the need for systematic maintenance strategies that preserve both public and ecological well-being.

In urban contexts, inadequate stormwater infrastructure intensifies vulnerability to climate-related events. The 2022 Durban floods, which caused approximately R38 billion in damages, were exacerbated by poorly maintained drainage systems (MISA, 2023). This example highlights the cascading risks of infrastructure neglect, where maintenance failures compound the effects of extreme weather events, increasing socio-economic and environmental losses.

Underlying many of these issues is a critical deficiency in data and information systems. As Odeku (2018) observed, many municipalities lack the capacity for comprehensive data collection and

analysis, impeding informed decision-making. The South African Local Government Association (SALGA) further noted that the absence of robust maintenance policies, audits, and tracking systems makes it difficult to monitor asset conditions or implement preventative measures (SALGA, 2021). This data gap has been widely recognised by both the World Bank Group (2022) and the National Treasury (2021) as a major obstacle to sustainable water infrastructure management.

Moreover, disparities between urban and rural municipalities further complicate infrastructure maintenance management. Metropolitan municipalities, such as Johannesburg, Cape Town, and Durban, benefit from stronger financial backing and established asset management systems, ensuring more reliable water services (Ngobese, 2018, Malima et al., 2022). In contrast, rural municipalities in provinces like the Eastern Cape and Limpopo suffer from frequent infrastructure failures due to outdated systems, insufficient funding, and poor governance (Bikam and Chakwizira, 2021, Adom et al., 2023). The study by Emily and Muyengwa (2021) stressed how neglecting proactive maintenance in rural areas accelerates infrastructure degradation.

To address these disparities and challenges, the Department of Water and Sanitation implemented the Blue Drop and Green Drop water quality regulation systems, which monitor both potable water and wastewater management (DWS, 2023e). These initiatives provide a framework for improving water infrastructure management at both the municipal and national levels, helping identify areas in need of immediate attention.

The Blue Drop, Green Drop, and SAICE Infrastructure report cards collectively offer valuable insights into the state of South Africa's water systems. These reports consistently call for improved maintenance practices, better governance, and more strategic investments in infrastructure rehabilitation.

5.3.1 Infrastructure Report Card

The Infrastructure Report Card (IRC) serves as a critical benchmarking tool for assessing the condition and performance of South Africa's infrastructure. It provides a structured evaluation that informs policymakers, academics, civil society organisations, and governmental agencies, aiding in evidence-based decision-making and strategic planning (SAICE, 2022). By systematically analysing infrastructure trends, the IRC highlights key deficiencies and areas requiring intervention, thereby guiding resource allocation and policy formulation. The scorecard grades are classified as outlined in Table 7 (SAICE, 2022, SAICE, 2011, SAICE, 2017):

Table 7: IRC grading index definitions

Grades	Definition	Description
A	World-class	Infrastructure is comparable to the best internationally in every respect. It is in excellent condition and well maintained, with the capacity to endure pressure from unusual events.
B	Fit for the future	The infrastructure is in good condition and properly maintained. It satisfies current demands and is sufficiently robust to deal with minor incidents.
C	Satisfactory for now	Infrastructure condition is acceptable although stressed at peak periods
D	At risk of failure	Infrastructure is not coping with normal demand and is poorly maintained
E	Unfit for purpose	Infrastructure has failed or is on the verge of failure, exposing the public to health and safety hazards. Immediate action is required.

Table 8 presents a detailed overview of the changes in water infrastructure grades from 2006 to 2022. Successive assessments by the SAICE have consistently highlighted the deteriorating state of municipal water infrastructure. Many water treatment plants and pipeline networks have been classified as being in decline or at critical failure levels, indicating significant deficiencies in maintenance and long-term asset management (SAICE, 2022).

Table 8: Comparison of water infrastructure grades: IRC 2006-2022 (SAICE, 2022, SAICE, 2017, SAICE, 2006, SAICE, 2011)

Category	2006	2011	2017	2022
Overall grade	D+	C-	D+	D
Water				
Bulk water resources	D+	D-	D-	D-
Supply in major urban areas	C+	C+	C+	C+
Supply in other areas	D-	D-	D-	D-
Sanitation				
Major urban areas	C-	C-	C-	C-
For all other areas	E	E-	E	E

The overall grading of South Africa's water infrastructure has declined from C- in 2011 to D in 2022, reflecting a marked deterioration in both quality and reliability. Moreover, the SAICE (2017) and SAICE (2022) IRC assessments reported no notable improvements in water and sanitation infrastructure, underscoring the persistent challenges facing the sector.

This decline aligns with broader concerns highlighted by Duvenage (2015), who asserted that South Africa's water and sanitation infrastructure is increasingly precarious, positioning it among the highest risk categories, warranting immediate attention. Tackling these challenges

necessitates a structured and forward-looking approach to maintenance planning, ensuring the long-term sustainability and resilience of the country's water infrastructure (SAICE, 2022).

The Department of Water and Sanitation (DWS) conducted its most recent Blue Drop, Green Drop, and No Drop audits in 2023 to assess municipal water and wastewater management. These audits offer valuable insights into the efficiency of maintenance activities and the overall condition of the water infrastructure.

Beyond serving as an evaluation tool, these audit reports play a crucial role in guiding policymakers, regulators, and stakeholders. By offering data-driven assessments, they enable informed decision-making and inform targeted strategies aimed at improving water infrastructure reliability and ensuring sustainable service provision.

5.3.2 Blue drop report (2023)

The Blue Drop report assesses the quality and management of drinking water supply systems, offering a diagnostic framework to assist water services institutions (WSIs) in improving their operations (DWS, 2023a). The evaluation is structured around a scorecard methodology, which measures performance across five key performance areas (KPA's), weighted according to national regulatory priorities (DWS, 2023a):

- Capacity management - 15%
- Drinking water quality risk management - 20%
- Financial management - 15%
- Technical management - 15%
- Drinking water quality compliance - 35%

A water supply system that attains a Blue Drop score of 95% or higher qualifies for Blue Drop certification, signifying excellence in water service delivery (DWS, 2023a). Conversely, systems scoring below 31% are deemed dysfunctional and are subject to regulatory interventions.

The DWS (2023a)'s assessment of 958 water supply systems revealed a significant deterioration in drinking water quality since the previous comprehensive evaluation, here only 26 systems achieved Blue Drop certification; indicating a substantial decline from 44 in 2014 while 277 systems were identified as critical. Microbiological water quality compliance has worsened markedly, with 46% of systems classified as poor or bad, compared to 5% in 2014. The DWS (2023a) acknowledged the existence of disparities where major metropolitan areas generally

maintained satisfactory water quality while rural and smaller municipalities exhibited severe performance deficiencies.

Key risk factors contributing to the declining scores include (DWS, 2023a):

- Infrastructure degradation - Widespread system vandalism, non-operational boreholes, and dysfunctional pumping and treatment facilities.
- Equipment failures - Frequent breakdowns due to inadequate maintenance and insufficient flow monitoring.
- Regulatory non-compliance - Elevated levels of drinking water contamination and failures to notify users about non-compliant water quality.

5.3.3 No drop report (2023): Water distribution efficiency

The No Drop Report examines non-revenue water (NRW), defined as the proportion of water lost through leaks, defective meters, or inadequate billing systems (DWS, 2023c). The 2023 findings indicate a sharp increase in NRW, rising from 37% in 2014 to 47% in 2023. This figure is significantly higher than the international benchmark, highlighting critical inefficiencies in South Africa's water distribution networks. Despite these challenges, only four water services authorities attained No Drop certification, demonstrating water loss levels below 10% and effective financial and technical management (DWS, 2023c). The report underscores the need for systematic infrastructure investment, improved metering accuracy, and proactive leak detection strategies to mitigate increasing water losses.

5.3.4 Green drop report (2023): Wastewater treatment performance

The Green Drop assessment report evaluates the operational efficiency and regulatory compliance of wastewater treatment works (WWTWs) (DWS, 2023b). The 2023 findings indicate a progressive decline in wastewater treatment performance, with 64% of WWTWs classified as high-risk or critical due to their failure to adequately treat and discharge effluent. This deterioration, compared to previous assessments, poses severe environmental and public health risks, as untreated wastewater contributes to water pollution, ecosystem degradation, and increased disease outbreaks.

5.4 Key challenges hindering effective maintenance

Several interrelated challenges continue to undermine maintenance effectiveness in municipalities, making it difficult to adequately perform essential maintenance activities. These challenges stem from financial constraints, worn-out infrastructure, skills shortages, inadequate planning, and policy shortcomings, all of which contribute to the deterioration of infrastructure and inefficiencies in service delivery.

5.4.1 Deteriorating infrastructure

Despite notable advancements in maintenance practices globally, the effective management of water infrastructure remains a persistent challenge, particularly in resource-constrained settings like South Africa. Much of the country's water supply and treatment infrastructure, constructed during the mid-20th century, has now exceeded its original design life and urgently requires rehabilitation or replacement (World Bank Group, 2022). Originally designed for lower demand and smaller populations, these ageing systems are now under immense pressure due to urbanisation, demographic expansion, and expanding industrial activities, all of which have severely diminished their reliability and operational efficiency (Mokgobu et al., 2023).

As infrastructure deteriorates, it becomes increasingly susceptible to mechanical failures, leaks, and contamination risks—conditions that escalate both water losses and the associated repair costs (Omotayo and Telukdarie, 2020). The situation is compounded by a significant technological mismatch: legacy infrastructure is often incompatible with modern maintenance tools and techniques. This disconnect is exacerbated by the widespread absence of reliable, up-to-date data on the condition and performance of critical water assets, posing a substantial obstacle to the implementation of advanced, data-driven maintenance strategies (Omotayo and Telukdarie, 2020).

This lack of integration between asset condition data and modern technologies severely limits the ability of municipalities and service providers to optimise maintenance activities (Humnabadkar et al., 2024). Hence, routine maintenance becomes more complex, and emergency response is hindered by an inability to accurately diagnose faults or apply cost-effective, timely interventions. In many instances, the inability to retrofit or adapt outdated systems restricts the scope for using predictive analytics, condition-based monitoring, or automation, thereby perpetuating a cycle of reactive and inefficient maintenance (Omotayo and Telukdarie, 2020, SAICE, 2022).

Tackling such multifaceted issues calls for concerted initiatives to invest in infrastructure renewal and to adopt contemporary asset management frameworks (Ruiters and Amadi-Echendu, 2022b). It also demands integrating technology-enabled maintenance approaches that can offer greater efficiency, reliability, and foresight. However, the financial realities of infrastructure management present an ongoing challenge: the escalating costs of maintenance and capital replacement often surpass the budgets allocated by local authorities, undermining both service sustainability and long-term system resilience (Laolang et al., 2022).

5.4.2 Financial constraints

Municipalities in South Africa face persistent and complex financial constraints that severely hinder effective water infrastructure maintenance (Ruiters and Amadi-Echendu, 2022a). Although the challenge is often framed as a lack of funding, this perspective oversimplifies the deeper structural and institutional issues at play. Budget allocations for maintenance are frequently inadequate, misallocated, or diverted to emergency repairs, undermining long-term sustainability planning (National Treasury, 2021). While funding is primarily sourced from national government grants, municipal revenue (through tariffs and property rates), and loans, these mechanisms are often insufficient to meet the growing maintenance demands, particularly in municipalities burdened with extensive infrastructure backlogs (Ruiters and Amadi-Echendu, 2022a).

However, this narrative oversimplifies the underlying issue, which extends beyond a mere lack of funding. Municipalities often return unspent capital budgets to the National Treasury, pointing to weak internal controls, bureaucratic bottlenecks, and a lack of technical capacity to plan and execute maintenance projects effectively (Mudzusi et al., 2024). For example, the DWS application to roll over R722.7 million in unspent funds from the 2022/23 to the 2023/24 financial year (DWS, 2023d). This case illustrates the complex interplay between fund availability, institutional capacity, and budget execution efficiency, demonstrating that underutilisation of available funds is often the result of misaligned priorities and poor strategic planning rather than an absolute lack of financial resources.

These inefficiencies reveal a critical gap in the strategic planning and execution capabilities of both municipalities and government departments. In this context, the failure to adopt modern maintenance practices such as predictive maintenance technologies or structured maintenance prioritisation frameworks can be attributed more to weak institutional capacity than to financial shortfalls alone. Consequently, financial constraints must be understood as symptomatic of

broader governance challenges, including fragmented planning, weak coordination, and procedural bottlenecks.

Compounding these financial challenges is the limited revenue-generating capacity of many municipalities. Low water tariffs, poor billing systems, high non-revenue water levels, and competing priorities—such as housing, education, and health—diminish the funds available for infrastructure upkeep (South African Cities Network, 2015). In economically disadvantaged areas, the situation is even more dire. Low collection rates, high levels of water theft, and aging infrastructure exacerbate financial stress and force municipalities to favour reactive maintenance approaches, which incur higher long-term costs and contribute to accelerated asset deterioration (Ruiters & Amadi-Echendu, 2022).

Political dynamics further complicate the issue. Infrastructure development projects that promise visible, short-term gains are often prioritised over less conspicuous maintenance activities. This leads to deferred maintenance, escalating future repair costs, and deepening infrastructure vulnerability (Dithebe et al., 2019, Aiyetan and Das, 2021). Although government grants and international funding exist, they are frequently earmarked for new infrastructure projects, leaving systemic and preventive maintenance requirements underfunded (SAICE, 2022, World Bank Group, 2022).

Moreover, over-reliance on conditional grants disrupts the continuity of maintenance planning and execution. When disbursement schedules do not align with maintenance cycles, timely interventions become difficult, increasing the risk of service interruptions and asset failures (MISA, 2023). These factors demonstrate the urgent need for sustainable financial models that prioritise maintenance, stabilise revenue streams, and align financial planning with long-term infrastructure goals.

In conclusion, addressing the financial constraints impeding South Africa's water infrastructure maintenance requires rethinking the issue not merely as a funding deficit, but recognising it as a strategic governance failure. Enhancing institutional capacity, streamlining procurement, improving budget utilisation, and embedding long-term financial planning into municipal governance frameworks are crucial steps.

5.4.3 Skills shortages

A critical challenge confronting South African municipalities is the acute shortage of expertise in strategic planning and maintenance management, which undermines the implementation of

sustainable infrastructure programs (SAICE, 2022, MISA, 2023). The integration of advanced technologies in water infrastructure maintenance demands specialised technical competencies (Omotayo & Telukdarie, 2020). However, many municipalities face persistent difficulties in attracting, developing, and retaining such skilled professionals, thereby impeding the adoption of modern, proactive maintenance strategies (Omotayo and Telukdarie, 2020, MISA, 2023). The ongoing migration of technical experts to the private sector and international markets further depletes the public sector talent pool (SAICE, 2022), exacerbating municipalities' dependence on reactive maintenance approaches (Omotayo and Telukdarie, 2020).

This skills gap is intensified by institutional capacity limitations, including high staff turnover, inadequate recruitment pipelines, and the absence of targeted professional development programs (Ndzelu, 2016, AGSA, 2023). Rural municipalities, in particular, struggle to compete for qualified personnel, often relying on external contractors to bridge internal competency gaps. While outsourcing can provide temporary operational support, it does not contribute to the development of internal expertise or institutional resilience (Luyaba et al., 2024).

Consequently, many municipalities adopt short-term, fragmented maintenance practices that lead to inefficient resource utilisation, accelerated infrastructure degradation, and frequent service disruptions. Addressing this systemic issue requires a comprehensive approach that includes structured training programs, capacity-building initiatives, and policy reforms aimed at attracting and retaining technical talent (AGSA, 2023, Luyaba et al., 2024). Such interventions are essential for building institutional capability and ensuring that municipal infrastructure systems remain reliable and sustainable over the long term.

5.4.4 Governance and policy gaps

Governance and policy deficiencies are key drivers of water infrastructure deterioration in South Africa (CIDB, 2007). A major obstacle is the fragmentation of responsibilities across various levels of government, departments, and agencies, which hampers effective coordination and the implementation of maintenance strategies (Dighade et al., 2014). This disjointed structure is compounded by governance failures, such as corruption and mismanagement, which divert resources from essential maintenance, deepening the backlog of repairs.

These governance challenges are further exacerbated by weaknesses in the regulatory framework for water infrastructure maintenance. While municipal policies mandate routine maintenance, the lack of strong enforcement mechanisms results in inconsistent compliance,

particularly at the municipal level (CIDB, 2007, McDonald et al., 2015). This leads to significant disparities in maintenance practices across municipalities, as evidenced by the stark variations in service delivery and infrastructure performance highlighted in the Blue Drop and Green Drop reports.

Tackling such matters requires establishing a more integrated and enforceable regulatory framework. Strengthened oversight mechanisms and enhanced institutional accountability are essential to ensure that water infrastructure maintenance is prioritised and resources are allocated effectively (AGSA, 2023).

5.4.5 Vandalism and theft

Vandalism and theft significantly threaten South Africa's water infrastructure, undermining municipalities' ability to deliver reliable services (Miya and Grobbelaar, 2015, Makhari, 2016, Malima et al., 2022, Bikam and Chakwizira, 2021). Criminals primarily target valuable components like pipes, valves, and electrical systems, with copper and brass being particularly sought after for resale. While driven by financial gain, these acts have broader consequences, disproportionately affecting vulnerable communities and worsening service delivery challenges.

Rural and peri-urban areas are particularly impacted due to socio-economic factors and limited resources for effective security (AGSA, 2023). For example, the Merafong City Local Municipality has faced operational disruptions in two Wastewater Treatment Works (Kokosi and Wedela) due to theft and vandalism, leaving both plants inoperative and classified as critical risk (DWS, 2023b). This highlights the growing vulnerability of water infrastructure in areas already facing resource constraints.

Underfunded municipalities often lack the financial means to implement adequate security, exacerbating infrastructure vulnerability (Mokgobu, 2017, Mokgobu et al., 2023). The result is prolonged water service interruptions, with repair costs diverting funds from essential upgrades and further hindering service improvements (Chauke, 2017).

Addressing this challenge requires enhanced security measures, community engagement, and policy interventions to curb the illicit trade in stolen infrastructure components (Mokgobu, 2017). In addition, strengthening municipal capacity to prevent and respond to these crimes is essential for safeguarding water infrastructure and ensuring sustainable service delivery.

5.5 Review of maintenance practices in South Africa’s water infrastructure

South African municipalities are accountable for managing and maintaining water supply and sanitation systems (DWS, 2023d). This section examines the policy and regulatory landscape governing municipal water infrastructure maintenance, municipal responsibilities and the predominant maintenance approaches employed.

5.5.1 Policy and regulatory framework for water infrastructure maintenance

The advent of democracy in 1994 represented a watershed moment in South Africa’s approach to water resource management, prompting a governmental shift towards principles of equity and sustainability (SAICE, 2017). In response, a comprehensive regulatory framework was established, encompassing legal instruments, policies, and strategic plans aimed at guiding the maintenance and development of water infrastructure. The governance of water and sanitation in South Africa is thus anchored in an integrated system of legislative, policy, and operational mechanisms that collectively shape the national landscape. These instruments operate at various levels of authority and function, forming a structured hierarchy as illustrated in Table 9 below (DWS, 2023e, DWA, 2014, DWA, 2021):

Table 9: Hierarchical overview of South African water and sanitation governance instruments

Category	Document/Instrument	Purpose/Description
Supreme law	Constitution of South Africa (1996) - Section 27(1)(b)	Guarantees the right to access sufficient water; obligates the state to take reasonable measures.
Primary legislation	National Water Act (Act 36 of 1998)	Legal grounds for water resource management, emphasising sustainability and service delivery.
	Water Services Act (Act 108 of 1997)	Assigns water and sanitation responsibilities to municipalities; introduces ‘free basic water’.
National policies	National Water Policy (2013)	Sets strategic direction for sustainable and equitable water access.
	National Sanitation Policy (2016)	Focuses on enhancing sanitation and promoting hygiene.
	National Water Resources Strategy (NWRS)	Guides sustainable and equitable use of water resources.
	National Water and Sanitation Master Plan (2019)	Prioritises sustainable water use, infrastructure development, and service delivery improvement.

Category	Document/Instrument	Purpose/Description
Operational & implementation strategies	National Water Services Infrastructure Asset Management Strategy	Promotes lifecycle asset management to minimise risk and optimise services.
	Government-Wide Immovable Asset Management Act (GIAMA)	Establishes guidelines for efficient public infrastructure asset management.
Monitoring & funding instruments	Blue Drop, No Drop & Green Drop certification programs	- Evaluate water and wastewater service quality, indirectly assessing maintenance strategies. - Assesses the quality of drinking water supplied by municipalities. - Evaluates wastewater treatment and compliance with environmental standards. - Measures water use efficiency and non-revenue water reduction by municipalities.
	Municipal Infrastructure Grant (MIG) Framework	Allocates funding for municipal infrastructure, but it is often insufficient for full maintenance needs.(National Treasury, 2021)

Despite these progressive frameworks and instruments, implementation remains uneven due to financial constraints, institutional inefficiencies, and a lack of technical capacity (Emily and Muyengwa, 2021). Governance challenges, corruption, and mismanagement further undermine maintenance efforts, with reports from the Helen Suzman Foundation (Toxopeüs, 2019) highlighting cases of misallocated maintenance funds, leading to infrastructure neglect and service delivery failures. Addressing these systemic challenges is essential to ensuring the long-term, sustainable, and effective maintenance of water infrastructure in South Africa.

5.5.2 Municipal responsibilities for water infrastructure maintenance

The maintenance of municipal water infrastructure falls under the mandate of local governments, as outlined in the National Water Act (1998) and the Municipal Systems Act (2000). These regulations emphasise the need for municipalities to develop and implement integrated maintenance plans to ensure sustainable service delivery. Municipalities are tasked with essential maintenance functions, including (DWS, 2023d):

- Routine inspections to identify infrastructure vulnerabilities.
- Scheduled maintenance of water treatment plants, reservoirs, and pipelines.
- Emergency repairs in response to infrastructure failures or service disruptions.
- Compliance monitoring to meet Blue Drop, No drop Green Drop water quality standards.

Despite these responsibilities, municipal maintenance efforts remain inadequate. Studies by the South African Institution of Civil Engineering (SAICE, 2022) and the Department of Water and Sanitation (DWS, 2023d) indicate that many municipalities lack the technical capacity to execute proactive maintenance strategies effectively. The DWS (2023d) reports that insufficient maintenance has led to severe infrastructure deterioration, requiring an estimated R12.5 billion in refurbishment costs. This growing financial burden underscores the urgent need for municipalities to transition from reactive maintenance to proactive, well-planned asset management strategies.

5.5.3 Predominant maintenance approaches

a) Reactive maintenance

Municipalities often rely on reactive and outdated approaches that fail to address the long-term sustainability of infrastructure (SAICE, 2022). Common reactive maintenance activities include emergency repairs of burst water pipes, pump failures, and other critical infrastructure breakdowns (Duvenage, 2015). This reactive approach is widespread in South African municipalities, primarily due to financial constraints and a lack of comprehensive long-term maintenance planning (Wall and Rust, 2017, Mothetho, 2018, Miya and Grobbelaar, 2015).

However Gandhare and Akarte (2012) argued that while reactive maintenance provides an immediate response to failures and requires lower initial investment, it is inherently unsustainable as it does not mitigate underlying asset deterioration. Consequently, it leads to escalating repair costs, frequent service disruptions, and increased levels of non-revenue water. For instance, a 2023 case in Tshwane illustrated the financial burden associated with extensive reliance on reactive maintenance, exacerbated by a skills deficit. According to the Auditor-General's report (AGSA, 2024), these challenges led to significant repair costs and service inefficiencies, underscoring the critical need for proactive maintenance strategies.

b) Preventive maintenance

Preventive maintenance is a widely adopted strategy across the globe, aiming to reduce unplanned downtime and prevent unexpected failures through scheduled interventions. These interventions include routine inspections, servicing of equipment, pipeline cleaning, and reservoir maintenance, all of which contribute to the longevity and efficiency of infrastructure (Duvenage, 2015).

Nonetheless, the adoption of preventive maintenance practices varies significantly across municipalities. Well-funded municipalities, such as Johannesburg and Cape Town, have the financial resources to invest in structured preventive maintenance programs (DWS, 2023d). In contrast, financially constrained municipalities often struggle to allocate sufficient funds for proactive maintenance and instead default to reactive approaches, addressing failures only after they occur (National Treasury, 2021). This disparity in maintenance strategies underscores the need for a more impartial distribution of resources, and strategic policy adjustments are essential to ensuring the sustainability of preventive maintenance practices across all municipalities.

Beyond preventive maintenance, predictive maintenance offers even greater potential to water infrastructure maintenance practitioners, by leveraging data analytics and technology to anticipate failures, optimise resource allocation, and extend asset life (Delnaz et al., 2023). However, its adoption in South African municipalities remains limited due to inadequate technological investment, insufficient funding, and a lack of capacity to manage and analyse data effectively (Omotayo and Telukdarie, 2020). Addressing these barriers through targeted investment and capacity-building initiatives could significantly enhance infrastructure resilience and service reliability.

5.6 Comparative analysis: South Africa vs. Global best practices

This comparative analysis seeks to unpack the primary distinctions between South Africa's existing methods for maintaining water infrastructure and the global best practices in essential areas, including policy and regulation, funding mechanisms, maintenance strategies, technology integration and workforce development. Table 10 presents a structured comparison of these areas to pinpoint where South Africa could enhance its approach by embracing international standards for better management of its water infrastructure.

South Africa's water infrastructure maintenance is largely reactive (SAICE, 2022), leading to frequent service disruptions and escalating repair costs. In contrast, global best practices emphasise proactive strategies—preventive, predictive, and condition-based maintenance—integrated into regulatory frameworks. Countries like the UK, Australia, and Singapore implement these strategies to extend asset longevity and minimise failures (OECD, 2015). The lack of adequate maintenance in South Africa (SAICE, 2022, Stats SA, 2024) underscores the need for a shift towards more sustainable approaches.

Table 10: Comparative analysis of water infrastructure maintenance management – South Africa vs. Global best practices

Category	South Africa	Global best practices
Policy & regulatory framework	- Regulated under the National Water Act (1998) and Water Services Act (1997). However, weak enforcement, financial mismanagement, and fragmented municipality responsibilities result in inadequate infrastructure maintenance. - Blue Drop/Green Drop certification assesses compliance but is inconsistently enforced. - Decentralised model, where municipalities are responsible for maintenance (DWS, 2023d)	- Countries such as the Netherlands, Australia, Singapore, and the USA employ stringent regulatory frameworks and compliance monitoring through independent water utilities, ensuring accountability, performance benchmarking, and proactive maintenance strategies (OECD, 2015, Blankesteyn and Pot, 2024). - EU Water Framework Directive mandates strict penalties for non-compliance (European Commission Directorate-General for Environment, 2014). - Centralised governance models, e.g. Netherlands, the Rijkswaterstaat
Maintenance strategies	- Maintenance practices are predominantly reactive, addressing failures after they occur rather than preventing them. - Limited implementation of preventive maintenance due to financial and technical resource constraints (SAICE, 2022).	Emphasis on predictive and prescriptive maintenance, utilising artificial intelligence (AI), smart sensors, and advanced asset condition monitoring to prevent failures before they occur
Funding & investment	- Severe underfunding, reliance on government subsidies, and inconsistent revenue collection systems contribute to poor infrastructure maintenance (Ruiters and Matji, 2015). - High levels of non-revenue water (NRW) due to leakage, illegal connections, and inefficient billing systems (Stats SA, 2024).	- Diverse financing models, including public-private partnerships (PPPs), green bonds, and tariff-based revenue streams, ensure sustainability (World Bank Group, 2024, Granata and Di Nunno, 2025). - Well-managed utilities maintain cost-recovery mechanisms, reducing financial deficits (Alegre et al., 2016).
Technology integration	- Limited implementation of Supervisory Control and Data Acquisition (SCADA) systems, Geographic Information Systems (GIS), and AI-driven analytics (Omotayo and Telukdarie, 2020). - Slow adoption of smart water metering and digital twins for asset management.	Widespread adoption of smart water grids, real-time monitoring systems, AI-powered leak detection, and digital twins to model and simulate infrastructure performance before failures occur (eawater, 2024, Humnabadkar et al., 2024).
Workforce & skills development	- Municipalities face a shortage of skilled engineers and maintenance professionals due to lack of capacity-building programs (SAICE, 2022). - Heavy reliance on short-term contractors leads to inconsistent infrastructure management.	Countries like Germany and Singapore invest in long-term workforce training initiatives, continuous professional development programs, university-industry collaborations, and the use of augmented reality (AR) and virtual simulations for maintenance training (EPA, 2021).

Effective maintenance relies heavily on strong governance. In countries like the Netherlands, centralised agencies standardise maintenance practices, facilitate efficient resource allocation, and ensure consistent investment (Blankesteyn and Pot, 2024). Similarly, Singapore has implemented a robust water governance framework through a comprehensive water management strategy that includes protecting and expanding water sources, wastewater reclamation, desalination, demand management, and public education initiatives (Octastefani and Kusuma, 2016). In contrast, South Africa's decentralised municipal governance systems lead to significant disparities among municipalities, where maintenance quality varies based on local capacity. Enhancing regional oversight and implementing standardised frameworks could improve coordination and resource distribution.

Funding mechanisms also play a crucial role in infrastructure sustainability. Advanced economies UK, Canada and the USA rely on full-cost recovery models and public-private partnerships to secure stable funding. For instance, the UK's Yorkshire Water has committed £850 million to infrastructure reliability through contracted service providers (World Construction Network, 2025). In contrast, South Africa struggles with poor revenue collection and overreliance on government grants (Ruiters, 2013, Ruiters and Amadi-Echendu, 2022b), resulting in underfunded maintenance programs. The Department of Water and Sanitation (DWS, 2018) recommended dedicated maintenance funds and performance-based budgeting to address these financial gaps. Integrating PPPs could further attract sustainable investment.

Beyond governance and financing, technological advancements significantly enhance maintenance efficiency. Leading nations such as Singapore and the US utilise AI-driven analytics, digital twins, and real-time monitoring to anticipate failures and optimise interventions (PUB, 2020). However, South Africa faces challenges in adopting these innovations due to financial and technical constraints (Omotayo and Telukdarie, 2020). While municipalities like Cape Town have real-time monitoring, following the real-time operational status of water and sanitation assets (ITWEB, 2024), these efforts remain fragmented. Scaling up smart water management initiatives with proper investment and training could improve maintenance outcomes (Luyaba et al., 2024).

To align with global best practices, South African municipalities must transition towards proactive maintenance practices, strengthen governance frameworks, secure dedicated funding, and integrate advanced technologies. While these reforms require substantial investment, they offer a clear path to sustainable and reliable water infrastructure management.

5.7 Conclusion

South Africa's water infrastructure is beset by systemic challenges in governance, financial constraints, and operational inefficiencies. While researchers and industry practitioners have actively introduced reliability-focused frameworks to enhance the management and performance of water infrastructure, many municipalities continue to rely on fragmented maintenance management practices predominantly centred around reactive strategies. This reactive approach eventually results in service disruptions, accelerates infrastructure deterioration, and undermines the long-term sustainability of critical water systems.

To overcome these challenges, a transformative approach towards proactive and predictive maintenance is crucial. Such an approach, underpinned by technological innovations and balanced funding allocations, offers a path toward more reliable and sustainable water infrastructure. Moreover, policy reforms should prioritise the integration of maintenance strategies into broader infrastructure planning. This would enable data-driven decision-making and foster resilient service delivery capable of adapting to evolving demands.

Chapter 6 builds on the insights gained from the literature and preceding chapters by identifying and analysing the key factors that influence maintenance prioritisation decisions in real-world utility contexts. This analysis will provide the empirical foundation necessary to inform the development of more robust and context-sensitive maintenance prioritisation frameworks.

CHAPTER 6: KEY FACTORS INFLUENCING MAINTENANCE PRIORITISATION IN THE WATER INDUSTRY

6.1 Introduction

The prioritisation of maintenance within water utilities and the broader water industry presents a multifaceted challenge, as discussed in chapter 5, shaped by the dynamic interplay of interrelated factors that influence decision-making processes. This chapter builds upon the findings of the preceding chapter, which critically examined the existing literature on maintenance prioritisation approaches for water infrastructure. Drawing on insights from the literature, the chapter identifies and categorises the influencing factors according to established frameworks proposed by Wing et al. (2016), Chong et al. (2019), and Karasneh and Moqbel (2024). These factors have been systematically organised into five principal domains: technical, financial, environmental, social, and operational, each representing a distinct yet interconnected dimension of the maintenance prioritisation landscape.

6.2 Technical factors

The term "technical factor" refers to the evaluation of an asset's performance and condition, as outlined by (Wing et al., 2016). These factors serve as the foundation for maintenance decision-making and prioritisation within the water industry by assessing asset conditions, failure risks, and the effectiveness of maintenance strategies. The reliability, efficiency, and overall lifespan of infrastructure components are heavily influenced by the technical aspects that guide maintenance decisions (Kumar et al., 2013). Table 11 summarises the primary technical factors influencing maintenance prioritisation within water infrastructure systems. Although not exhaustive, it captures the most critical considerations.

Table 11: Technical factors

Factor	Description	Examples
Asset criticality	- Asset criticality refers to the relative importance of infrastructure components in sustaining core service functions and the potential consequences of their failure (Katheeri et al., 2015b). - Supports maintenance prioritisation by identifying components that most affect reliability and performance (Meijer et al., 2021). - High-criticality assets—such as trunk mains, booster stations, and treatment facilities—are prioritised to prevent large-scale service disruptions (Pereira et al., 2020, Phan et al., 2019). - These assessments are particularly important for ageing infrastructure and interdependent systems that are increasingly vulnerable to failure - Criticality assessments inform not only operational maintenance scheduling but also long-term capital investment and renewal planning (Marlim et al., 2019, Mazumder et al., 2021),	- At the Abu Dhabi Distribution Company (ADDC), RCM was implemented to assess the criticality of water distribution assets. This led to targeted replacement plans, reduced unplanned outages, and facilitated a shift towards condition-based maintenance strategies (Katheeri et al., 2015b). - Asset criticality has been used to enable water utilities to focus limited maintenance resources on trunk mains that posed significant environmental and public health risks, improving service continuity during peak demand (Marlim et al., 2019, Mazumder et al., 2021).
Asset condition & age	- Considers the physical integrity and operational history of assets, including signs of deterioration, corrosion, or mechanical wear . - The age of infrastructure may indicate potential degradation, although it must be correlated with actual condition data . - Condition assessments may employ visual inspections, non-destructive testing, and sensor-based monitoring (Omotayo and Telukdarie, 2020, Le Gat et al., 2023). - Even newer infrastructure requires routine monitoring and maintenance, necessitating a shift from age-centred frameworks to integrated assessments that include real-time condition data (Bloetscher et al., 2023).	- In a metropolitan water utility, ageing cast iron pipelines are more prone to bursts due to corrosion and pressure fluctuations. A shift from age-based to condition-based prioritisation, using acoustic sensors and machine learning for leak detection, allows for early intervention and reduced repair costs. - Conversely, newly installed pipelines in areas with unstable soil conditions have exhibited premature joint failures. Regular condition monitoring helped identify the need for reinforcement, illustrating that asset age alone was not a reliable indicator of performance.

Factor	Description	Examples
Network coverage & population density	• Focuses on the geographical spread of infrastructure and the concentration of people it serves. • High-priority is given to assets supporting dense populations or those in strategically vital service corridors. • Regions with extensive network coverage require comprehensive asset monitoring due to the geographic spread and service complexity (Karasneh and Moqbel, 2024). • GIS and demographic data are often used in planning interventions (Kabir et al., 2015). • High population density intensifies asset utilisation, placing additional pressure on ageing infrastructure and accelerating wear and tear. • Maintenance interventions in densely populated areas tend to have broader socio-economic implications due to the larger number of end-users affected	• In a metropolitan city, a burst water main located in a central business district servicing over 500,000 residents is prioritised over a similar failure in a sparsely populated rural area. The urban failure would impact a larger number of users, cause traffic disruptions, and increase public health risks.
Hydraulic performance	• Hydraulic performance is a critical determinant of system reliability and a key input in maintenance prioritisation, as it directly affects water availability and pressure stability (Je Van Zyl, 2014). • Relates to the system's capacity to deliver water at the required flow rates and pressures under varying demand conditions. • Failures are not exclusively caused by corrosion; poor design and substandard construction are also significant contributors to hydraulic inefficiency and premature deterioration complexity (Karasneh and Moqbel, 2024). • Persistent hydraulic limitations increase lifecycle costs due to the need for reactive interventions and energy-intensive operations. • Adoption of hydraulic modelling and real-time monitoring enables utilities to identify emerging capacity constraints, prioritise assets for intervention, and plan proactive maintenance.	• In Egypt, Elkhartbotly et al. (2023) implemented hydraulic modelling within district-metered areas (DMAs) to develop a permanent monitoring system. This enabled the early detection of pressure anomalies and leaks, informing proactive maintenance schedules and improving service reliability.

Factor	Description	Examples
Technological capability	• Technological advancements have significantly reshaped maintenance practices in water infrastructure, enabling evolution from reactive to dynamic strategies (Je Van Zyl, 2014, Omotayo and Telukdarie, 2020, PUB, 2020, Mufor, 2021). • Supervisory Control and Data Acquisition (SCADA) systems, Geographic Information Systems (GIS), and real-time monitoring tools support data-driven, condition-based maintenance by providing continuous insights into asset performance (Omotayo and Telukdarie, 2020, Mufor, 2021). • Remote sensing technologies facilitate the non-invasive monitoring of inaccessible infrastructure components, reducing both risk and inspection costs (Mothetho, 2018, PUB, 2020). • Big data analytics and Artificial Intelligence (AI) enhance predictive maintenance by enabling early detection of anomalies and guiding timely intervention strategies (PUB, 2020). • Implementation challenges persist in contexts such as South Africa, where disparities in infrastructure investment, digital readiness, and skills development hinder widespread adoption (Omotayo and Telukdarie, 2020).	• Singapore's Public Utilities Board (PUB) employs the WaterWiSe system, which uses pressure transient and acoustic data analytics to detect pipeline leaks. Suspicious anomalies are verified via site inspections (PUB, 2020). • PUB has also implemented an AI-driven platform to monitor real-time data, provide early warnings of process deviations, and recommend corrective actions to pre-empt system failures (PUB, 2020).
Structural and material considerations	• The structural integrity and material composition of water distribution networks critically influence asset longevity and maintenance needs (Karasneh and Moqbel, 2024). • Encompasses design characteristics, construction materials, and their implications for durability and maintenance. • Material choice significantly affects corrosion resistance, mechanical strength, and performance under varying environmental conditions (Stip et al., 2019, Mazumder et al., 2021). • Assets built with outdated materials (e.g., asbestos cement) or poor design accessibility may be more prone to failure or harder to maintain. • Networks with older pipe materials and poor installation records often exhibit higher leak frequencies, prompting urgent maintenance and rehabilitation interventions. • Understanding deterioration patterns across material types is vital for data-driven maintenance prioritisation and resource optimisation (Hussein Farh et al., 2023).	• Cast iron pipes, commonly installed in the mid-20th century, are prone to corrosion-related failures, especially in areas with acidic or saline soils (Stip et al., 2019, Bloetscher et al., 2023).

6.3 Financial factors

Effective maintenance prioritisation in water infrastructure necessitates the alignment of financial resources with operational demands (Wing et al., 2016). A persistent challenge lies in reconciling fixed maintenance budgets with actual cost requirements, which encompass routine maintenance, recurring issues, asset failures, temporary service provisions, and the consequences of deferred maintenance (Chong et al., 2019). These costs typically involve labour, materials, equipment, and unplanned repairs. When financial allocations fail to match these requirements, maintenance may be postponed, resulting in increased service disruptions and higher long-term expenditures (Zeb, 2020). Financial and economic factors are therefore pivotal in guiding maintenance decisions, promoting cost-effectiveness, and safeguarding the long-term functionality of water infrastructure systems.

Table 12 summarises financial factors, followed by a discussion of the principal financial and economic considerations influencing maintenance prioritisation in the water sector.

Table 12: Summary of financial factors

Factor	Description	Example
Budget constraints	- Financial resources are a central determinant of maintenance prioritisation in water utilities, acting as both a limiting and enabling factor (Laolang et al., 2022). - Utilities typically operate within tight fiscal frameworks, requiring a balance between capital expenditure (CapEx) and operational expenditure (OpEx) (Pathirana et al., 2021, Imonikhe, 2020). - Limited financial resources reduce the frequency, scope, and quality of maintenance, undermining asset performance and long-term service reliability - In African municipalities, lack of structured maintenance planning is often linked to inadequate budgeting, leading to reactive, short-term fixes (Malima et al., 2022, Mokgobu et al., 2023). - Maintenance is frequently deprioritised in favour of politically visible or short-term service delivery goals, particularly where failures are not immediately apparent (Vinke-De Kruijf et al., 2024, Laolang et al., 2025). - Effective maintenance prioritisation requires integration of technical risk assessments with fiscal realities, ensuring that limited budgets are directed towards high-risk or high-impact assets (Bester, 2023).	Faced with limited funding, a district opts for borehole rehabilitation and tanker water delivery instead of scheduled maintenance of existing reticulation infrastructure.

Factor	Description	Example
Benefit analysis and return on investment (ROI)	- Water infrastructure is often publicly owned and non-revenue-generating, requiring government funding (Ratnaweera et al., 2020) underscoring the urgency of strategically justifying funding allocations, especially as water infrastructure competes with other essential public services for increasingly limited resources - Public budgets are limited and scrutinised, necessitating justification of maintenance expenditures, - Serves a dual function: as both a prioritisation mechanism (López-Serrano et al., 2023) and a cornerstone of evidence-based decision-making - Evaluates long-term economic, social, and environmental benefits relative to costs (Ratnaweera et al., 2020). - Helps justify funding allocations in public sectors with limited resources, - Advocates a life-cycle approach, highlighting risks of deferred maintenance (Farouk et al., 2023).	- CBA is applied to select maintenance strategies that maximise long-term returns, including reduced service disruptions and environmental protection. - Used to justify preventative maintenance funding by demonstrating long-term value (Granata and Di Nunno, 2025). - ROI analysis supports the prioritisation of maintenance activities that offer the best financial and operational returns, such as upgrading a water treatment plant to improve efficiency and reduce future repair costs.
Cost-benefit analysis	- Measures the return from maintenance investments relative to their cost. - Ensures strategic allocation of resources towards activities that yield the highest returns in reliability, sustainability, and public benefit (Farouk et al., 2023).	
Revenue and Economic Impact	- Some infrastructure components (e.g., metering systems, industrial pipelines) are key revenue generators (Short et al., 2012). - Failures (e.g., leaks, faulty calibration) in these assets can cause major economic losses and social/environmental harm. - Maintenance prioritisation increasingly includes economic risk assessment to protect assets tied to financial and operational continuity (Granata and Di Nunno, 2025).	- Prioritising calibration and maintenance of bulk water meters for large industrial users to prevent billing inaccuracies. - Fast-tracking pipeline repairs in zones supplying commercial districts to avoid service disruptions that may halt business operations.

Factor	Description	Example
Available funding and financial support	- Water infrastructure maintenance is often financed through external sources like government grants, donor funds, PPPs, or infrastructure bonds (Granata and Di Nunno, 2025). - These funding mechanisms have predefined conditions—timelines, scope, and geographic focus—that influence prioritisation, - Debt financing is sometimes used to meet urgent or large-scale maintenance needs, but its terms (interest rates, repayment schedules) must be carefully managed to avoid compromising sustainability (SALGA, 2021, DWS, 2022b). - Funding is typically conditional on value-for-money, procurement compliance, and target outcomes (SALGA, 2021). - As a result, maintenance priorities are sometimes shaped by funding eligibility instead of actual criticality (Ruiters and Matji, 2015), neglecting the need to balance urgency, cost, and long-term goals	A municipality delays the replacement of an ageing water pipeline in a high-risk zone because the available donor funding prioritises rural expansion projects instead. Although the pipeline poses a higher failure risk, the repair is postponed due to ineligibility for immediate financial support under current funding criteria.
Lifecycle cost considerations	- represents the total cost of owning an asset over its entire life, including capital, maintenance, repair, and replacement costs (López-Serrano et al., 2023). - informs whether it is more cost-effective to maintain or replace ageing assets. - In water infrastructure, LCC supports strategic, evidence-based maintenance prioritisation (Schiller and Dirlich, 2015, Katheeri et al., 2015b). - Enables better allocation of maintenance resources over time, discouraging reactive approaches. - Can reveal when replacement is more viable than continuous maintenance due to lower future costs and technological efficiency (Fregonara, 2020). - Works best when integrated with tools like cost-benefit analysis (CBA) to align financial, social, and environmental goals (Farouk et al., 2023, Fregonara, 2020). - CBA addresses broader value; LCC focuses narrowly on cost over the asset life (Masud et al., 2019a).	- A municipality uses LCC to evaluate a 40-year-old water pipeline system. While repairs have grown increasingly expensive, the analysis shows that replacing the pipeline would reduce operational and repair costs significantly over the next 25 years. This leads to prioritising replacement over continued patch maintenance. - In the UAE, Katheeri et al. (2015b) applied LCC to decide between refurbishing existing pumping stations or investing in new, energy-efficient systems. The LCC approach supported the replacement decision based on long-term cost savings.

6.4 Environmental factors

The maintenance of water infrastructure is inherently complex due to its interaction with both human and environmental systems. Environmental considerations are increasingly shaping maintenance strategies in the water industry, as climate change and resource scarcity pose significant challenges (Howard et al., 2016, Borzì, 2025). Water conservation is a key priority, with

maintenance efforts focusing on leak prevention and efficient water distribution. Studies have shown that a significant percentage of treated water is lost due to pipeline leaks (Delnaz et al., 2023), underscoring the need for proactive maintenance interventions. This is particularly pertinent given the growing imperative to promote and uphold environmental sustainability in infrastructure management (Mezhoud et al., 2022). Table 13 outlines key descriptive insights and practical examples demonstrating how compliance requirements influence maintenance planning and resource allocation.

Table 13: Environmental factors

Factor	Description	Example
Climate change	• Extreme weather events such as heat waves droughts and floods are linked to infrastructure failures and service disruptions. • Rising temperatures and altered precipitation patterns accelerate asset degradation, impacting performance and capacity (Rathnayaka et al., 2023). • Maintenance prioritisation is shifting towards integrating climate data and projections (Fan et al., 2023). • Climate-informed failure prediction models are being adopted to improve maintenance planning and guide pipe material choices (Fan et al., 2023). • Extreme climate conditions also affect operational functions, increasing the risk of water treatment failure and contamination (Al-Attar et al., 2021). • The overarching goal is to ensure infrastructure resilience and continuity of service amidst climatic volatility.	• KwaZulu-Natal's 2022 floods caused extensive damage to stormwater infrastructure, prompting the government to prioritise upgrading drainage and flood management systems (MISA, 2023)
Environmental regulations and compliance considerations	• Environmental regulations set performance standards and impose penalties for non-compliance • In South Africa, the National Water Act (No. 36 of 1998) and the National Environmental Management Act (No. 107 of 1998) mandate pollution prevention and ecological protection (DWS, 2018, DWS, 2023e) • Regulations mandate risk assessments and structured maintenance schedules for effective planning (DWS, 2023e, MISA, 2023) • Compliance requires routine inspections, water quality testing, and structured reporting • Poorly maintained assets can result in leakages or effluent discharge, posing public health and ecological risks (Evans, 2021) • Maintenance is prioritised to avoid legal breaches resulting from deteriorating, ageing, or insufficient infrastructure.	• Vaal River Crisis: Wastewater plants discharged untreated sewage due to poor maintenance, violating environmental standards (Evans, 2021). • Green Drop Report (2023): Highlighted municipalities with failing wastewater systems needing urgent maintenance (DWS, 2023b). • Seoul (South-Korea) case study: Risk-based sewer inspection framework used to prioritise environmental threats while optimising investment (Lee et al., 2021).

6.5 Social factors

Maintenance prioritisation in the water sector is not merely a technical or economic decision but is deeply intertwined with the social context of the communities it serves. Increasingly, academics and practitioners recognise the importance of social dimensions in guiding infrastructure maintenance decisions. These factors emphasise equity, inclusivity, safety and health (Linneck et al., 2015), aligning with the United Nations' Sustainable Development Goal 6, which advocates for universal access to clean water and sanitation (United Nations, 2015). Social factors significantly influence maintenance management in the water sector, shaping operational and strategic decisions affecting service delivery. Table 14 summarises key social influences on maintenance prioritisation and practical examples drawn from current literature and sectoral practices.

Table 14: Social factors

Factor	Description	Example
Equity & inclusivity	- Ensures fair access to clean water for all communities. - Water access is a fundamental human right (United Nations, 2010) - Equity in service delivery is essential to meet SDG 6 targets (United Nations, 2015). - Maintenance failures disproportionately affect vulnerable communities, exacerbating social and economic inequalities (Linneck et al., 2015). - Prioritises maintenance in vulnerable regions to reduce disparities in service delivery (Linneck et al., 2015, United Nations, 2015).	- Prioritising water infrastructure maintenance in disadvantaged areas to uphold constitutional rights and promote inequality in South Africa (Toxopeüs, 2019). - Allocating emergency repair teams to rural villages consistently facing pipe bursts or water shortages. - In India, ageing infrastructure caused water shortages that disproportionately impacted marginalised populations, deepening poverty and inequality (Linneck et al., 2015).
Health & safety	- Poor maintenance can lead to unsafe water, increasing the risk of waterborne diseases (World Health Organisation, 2022). - In areas with deteriorating infrastructure, cases of waterborne diseases like cholera increase, and further burden healthcare system (Maluleke, 2024). - Maintenance focuses on preventing health crises and reducing strain on healthcare systems.	Prioritising water-treatment and leak repairs in areas with recent diarrhoeal disease outbreaks. A typical example is the Hammaskraal cholera outbreak which became a national crisis.

Factor	Description	Example
Customer satisfaction & social cohesion	- Customer satisfaction is influenced by water reliability, quality, and affordability. - Disruptions in water service lead to a loss of trust in institutions and social instability. - Reliable water services promote social stability and confidence in public institutions (Fenner, 2017). - Poor service leads to lack of trust in utilities and increases complaints, pressuring service providers - Maintenance responsiveness to complaints is essential (Je Van Zyl, 2014)	Resolving maintenance issues in township zones to prevent protests and civil unrest over unfair water supply. -Frequent water outages in South African communities increase tensions and inequality, leading to protests and social unrest (Bikam and Chakwizira, 2021).

Ultimately, prioritising maintenance is not solely a technical or economic exercise but a social responsibility. Decisions on where and how to invest in infrastructure upkeep must account for the lived realities of affected communities. By centring equity, inclusion, and human dignity in maintenance planning, governments and utilities can enhance service delivery, strengthen social cohesion, restore public trust, and uphold the fundamental right to water for all.

6.6 Operational factors

A robust understanding of operational factors begins with the foundational principles of operations management, which govern the transformation of inputs into outputs that create customer value. Thakar (2021) defined operations management as the administration of processes that convert inputs into goods and services. Wolniak (2020) further highlighted its pivotal role in organisational functionality, encompassing planning, scheduling, procurement, quality control, and inventory management. These core responsibilities render operations management central to business decision-making across sectors, including water utilities.

In the context of water infrastructure, prioritising maintenance necessitates a multidimensional perspective, integrating technical, financial, social, and environmental considerations discussed in sections 6.2 – 6.4. A holistic synthesis of these dimensions informs decisions that balance operational efficiency, sustainability, and public value. Table 15 summarises the critical operational factors affecting maintenance prioritisation, accompanied by practical examples.

Table 15: Operational factors

Factor	Description	Example
Asset performance monitoring	- Asset performance informs maintenance priorities (Laolang et al., 2022). - KPIs such as pressure, water quality, and continuity signal asset health (Karasneh and Moqbel, 2024). - Performance deviations trigger corrective actions to uphold reliability.	Low water pressure in a distribution zone indicates pipe deterioration; maintenance is scheduled to prevent service interruption and maintain user satisfaction.
Demand-responsive scheduling	- Maintenance is scheduled during low-demand periods to reduce disruption (Tornyeviadzi et al., 2022). - Informed by user consumption patterns and behavioural trends. - Aligns operations with public expectations and improves efficiency.	A municipality delays valve replacement until early morning hours when water demand is minimal, minimising inconvenience and revenue loss.
Risk-management	- Evaluates failure likelihood and consequence (Phan et al., 2019, Kheradmand et al., 2021, Cavaignac et al., 2020). - Critical assets (e.g., buried pipes, pump stations) prioritised to avoid cascading failures (Mazumder et al., 2021). - Strengthens system resilience.	A corroded pipeline near a hospital is prioritised for urgent repair due to its high failure consequence and impact on essential services.
Workforce capacity and readiness	- Effective execution depends on skilled personnel and coordination (George-Williams et al., 2024, Miya and Grobbelaar, 2015). - Poor coordination or staff shortages delay interventions.	A team with designated roles and adequate training promptly resolves a pump failure, avoiding prolonged downtime.
System redundancy	- Redundant systems allow planned maintenance without service disruption (Perelman & Fishbain, 2022). - Absence of redundancy increases operational risk and complexity in scheduling (Phan et al., 2019).	A backup pump enables the servicing of a primary pump without halting water supply to residential areas.
Service quality	- Maintenance is prioritised to meet quality standards and maintain public trust (Karasneh and Moqbel, 2024). - Operational factors ensure service continuity and user satisfaction.	Scheduled flushing of water mains ensures compliance with quality standards and reduces user complaints.
Operational-financial integration	- Financial constraints influence operational decisions (Wolniak, 2020). - Collaboration between operations and finance ensures alignment of priorities and cost-effectiveness. - Under tight or misallocated budgets, resources are allocated based on asset criticality and impact (Patience and Nel, 2021, Ruiters and Amadi-Echendu, 2022b)	A utility prioritises leak repairs in high-loss zones to maximise water savings within budget limits.

6.7 Key take-away: a multidimensional perspective

Maintenance prioritisation in the water industry is inherently complex, shaped by the dynamic interplay of technical, financial, environmental, social, and operational factors, as illustrated in Figure 12. Technical considerations such as infrastructure condition, asset criticality, and the integration of emerging technologies form the foundation of effective decision-making. However, the practical application of these technical ambitions is often limited by financial constraints, including budget limitations and competing capital priorities, which can delay infrastructure upgrades and inhibit the adoption of innovative solutions.

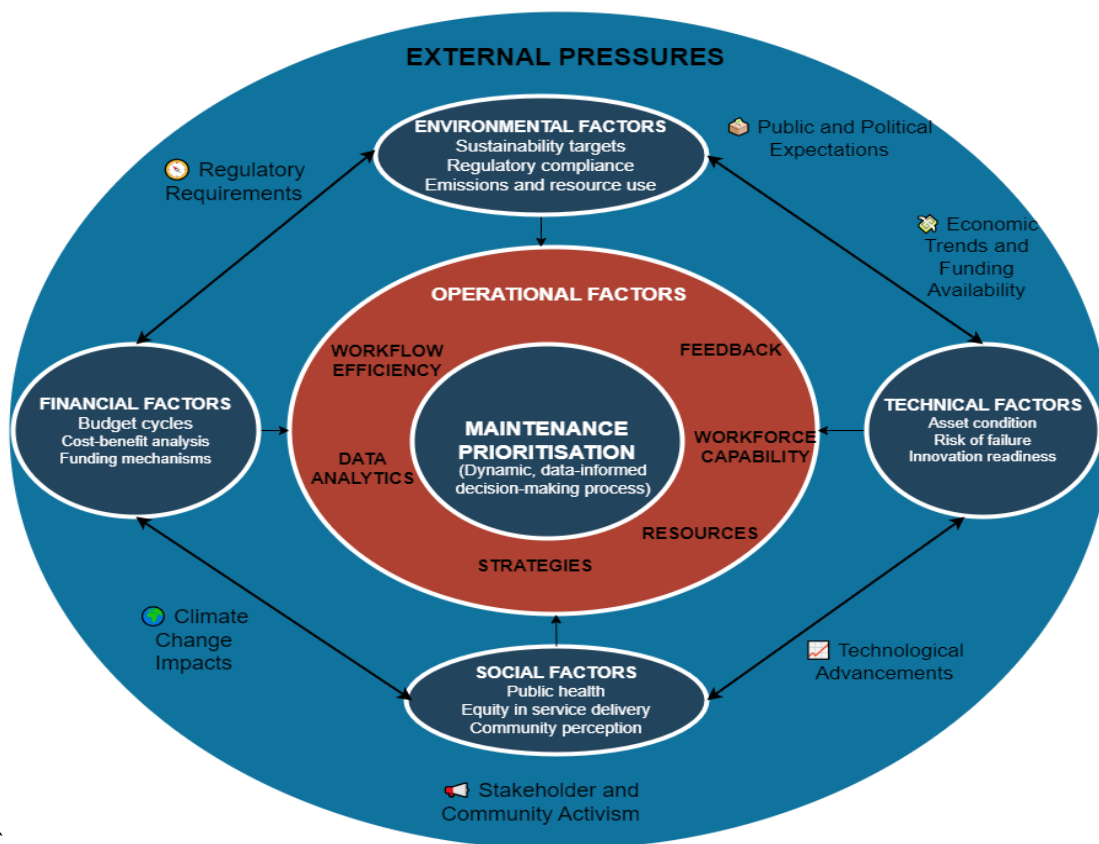


Figure 12: Decision making factors (Author representation)

Building on this, financial constraints do not only affect technical execution but also directly shape environmental outcomes. While sustainable technologies have the potential to reduce water loss and energy consumption significantly, their implementation frequently requires substantial upfront investment. This creates a fundamental tension between short-term fiscal feasibility and long-term environmental benefit. Furthermore, environmental sustainability has transcended

regulatory compliance to become a societal imperative. Communities are increasingly vocal in their demand for environmentally responsible water management, prompting utilities to integrate sustainability into their maintenance strategies.

In parallel, the social dimension introduces further complexity by foregrounding communities' lived realities and expectations. Public concerns regarding equitable service delivery, health risks, and responsiveness to service disruptions serve to prioritise specific maintenance interventions over others. In this way, stakeholder engagement becomes a critical input into the prioritisation process, helping to ensure that maintenance decisions are technically sound, environmentally responsible, and socially equitable.

Finally, operational considerations act as the integrative mechanism that harmonises these diverse domains. Through the application of real-time data, and asset performance monitoring, operational strategies can be dynamically adapted to accommodate evolving technical needs, financial pressures, environmental targets, and social expectations. Consequently, maintenance prioritisation emerges as a continuous, data-informed process that balances engineering precision with financial discipline, ecological stewardship, and community accountability.

6.8 Conclusion

This chapter highlighted the significant impact of multiple factors on shaping maintenance prioritisation within the water sector. These elements collectively support informed decision-making amidst resource constraints and escalating service demands.

Their interdependence reveals a complex system wherein decisions in one domain have cascading effects on others. While each factor is individually important, their collective impact highlights the need for a structured, multi-criteria decision-making framework. Operational strategies are essential in translating these interrelated priorities into actionable plans, enabling utilities to optimise resource use, enhance service delivery, and bolster infrastructure performance.

Building on these insights, the next phase of this research, the design stage, will concentrate on developing and validating a maintenance maturity mode specifically for water infrastructure. This stage will begin by establishing the design requirements that will guide the model's development. Chapter 7 builds upon this discussion by addressing these requirements comprehensively.

CHAPTER 7: MAINTENANCE MATURITY MODEL DESIGN REQUIREMENTS

7.1 Introduction

Chapter 7 begins by outlining the design requirements that will inform the development of the model, with a focus on ensuring theoretical robustness, methodological rigour, and practical applicability. A comprehensive review of existing maturity models is undertaken to strengthen the model's credibility. This review evaluates how these models meet the identified requirements and highlights limitations or gaps. The resulting gap analysis provides the rationale for developing a new or refined model that is grounded in existing literature and offers a substantive contribution to theory and practice.

7.2 Background

Maintenance practices are fundamental to achieving operational excellence across various asset-intensive industries, including manufacturing and water (Patil et al., 2022). The reliability, efficiency, and safety of physical assets are intrinsically linked to the effectiveness of maintenance strategies, which aim to minimise downtime, reduce operational costs, and extend asset lifespans (Gackowiec, 2019, Muchiri et al., 2017).

Within an increasingly complex global landscape, characterised by rapid technological innovation and stringent regulatory demands, maintenance is no longer viewed as a mere operational necessity. Instead, it is increasingly recognised as a strategic function that underpins organisational competitiveness and long-term sustainability (Patil et al., 2022). This evolving perception has catalysed the development of structured frameworks such as maintenance maturity models (MMMs), which provide a systematic methodology for assessing and enhancing maintenance capabilities across organisations (Holomisa et al., 2024b).

Despite this positive trajectory, the transition from rudimentary to advanced maintenance strategies remains a significant challenge for many organisations. One of the primary obstacles is the absence of robust decision-making frameworks to guide this evolution (Macchi and Fumagalli, 2013b). As noted by Chemweno et al. (2015), organisations often lack the structured guidance necessary to effectively progress through the stages of maintenance maturity. This gap frequently results in inefficient resource allocation, diminished asset lifespan, and suboptimal

operational performance. Maintenance maturity models offer a viable solution to this challenge by promoting evidence-based decision-making and facilitating performance benchmarking in alignment with industry best practices (Hellweg et al., 2021).

As both diagnostic instruments and strategic planning tools, MMMs allow organisations to assess their current maintenance maturity levels against predefined criteria (Chemweno et al., 2015). This process aids in identifying performance gaps and informing targeted improvement strategies (Franciosi et al., 2023). By supporting incremental capability development, Chemweno et al. (2015) emphasised that MMMs also serve as a mechanism for embedding continuous improvement within maintenance management systems.

The growing interest in MMMs has led to a proliferation of studies examining their implementation, organisational impact, and sector-specific applications (Reis et al., 2017). Despite this growing body of work, the literature remains fragmented. Existing models are characterised by divergent methodologies, case-specific findings, and varying conceptual underpinnings (Oliveira and Lopes, 2020, Chemweno et al., 2015). While certain models have shown effectiveness within particular contexts (Hellweg et al., 2021, Normann Andersen et al., 2020), there is no widely accepted consensus on the essential attributes of a universally applicable maturity model (Reis et al., 2017).

This lack of standardisation presents a considerable challenge. In the absence of a cohesive framework, organisations face difficulty in benchmarking their maintenance maturity or aligning with best practices. Consequently, they may struggle to justify investments in maintenance improvement initiatives or to develop strategic pathways for capability enhancement.

To address this gap, the chapter seeks to establish a systematic foundation for the development of a new model, underpinned by a rigorous and methodologically sound approach. Drawing upon the model design principles proposed by Poeppelbuss and Roeglinger (2011), a systematic mapping review was undertaken to identify prevailing practices and frameworks from both academic and industry literature. This was followed by a gap analysis to assess the extent to which existing models align with the established design requirements. The outcome of this chapter will inform the development of an MMM for water infrastructure in the South African context.

7.3 Maintenance maturity model design requirements

Maturity models are vital tools for organisational assessment and improvement, serving both descriptive and prescriptive purposes (Chemweno et al., 2015, Maier et al., 2012). When applied descriptively, maturity models help evaluate an organisation's current state by benchmarking it against predefined criteria (Poeppelbuss and Roeglinger, 2011). This evaluation enables organisations to identify their strengths and weaknesses across various domains, including project management, software development, and process optimisation (Cooke-Davies and Arzymanow, 2003, Paulk et al., 1993, Vanier et al., 2011). Such insights are critical for understanding operational capabilities and pinpointing areas that require improvement.

In contrast, the prescriptive application of maturity models provides a structured pathway for progression (Otto et al., 2020, de Almeida Santos et al., 2020, Becker et al., 2009). These models offer step-by-step guidelines to support organisations progress from their current level of maturity to a more advanced and desirable state. This guidance is essential for strategic planning, as it sets clear objectives and actionable steps that organisations can follow to systematically enhance their performance and achieve sustained growth (Otto et al., 2020).

The dual functionality of maturity models, as both evaluative and developmental instruments, makes them indispensable tools for continuous improvement. As Volker et al. (2011) noted, organisations that leverage these models can effectively navigate their maturity journey and strive for operational excellence.

7.3.1 Principles guiding maturity model design

When developing a maintenance maturity model, it is essential to establish both descriptive and prescriptive parameters grounded in sound design principles. Poeppelbuss and Roeglinger (2011) outlined six foundational design principles for maturity model design:

- a. Application domain
- b. Purpose of use
- c. Target group
- d. Class of entities under investigation
- e. Domains, dimensions, maturity levels, and maturation paths
- f. Level of granularity available in maturation

These principles have been adopted and operationalised in several maturity model-related studies, notably by Van Dyk (2013) and Maisiri and Van Dyk (2020), and will form the foundational basis for the design requirements of the model to be developed. However, to date, no maintenance maturity model has been identified that explicitly develops its design requirements based on these principles. The complete set of design requirements for the model to be developed are presented in Table 16.

Table 16: Maintenance maturity model design requirements

Design principles	Design requirements (DR)
Application domain	DR 1: The model must address the operational and strategic requirements of the water infrastructure sector as its primary application domain, while remaining adaptable for broader use across other asset-intensive industries.
Purpose of use	DR 2: The model must function as a diagnostic tool to assess the current maturity level of an organisation's maintenance practices.
	DR 3: It must guide organisations in identifying gaps and areas for improvement, leading to optimised maintenance practices and operations.
	DR 4: The model must offer flexible pathways for various maintenance strategies, allowing organisations to select and progress along the path that best aligns with their specific goals, resources, and operational contexts.
Target group	DR 5: It must be designed for use by maintenance practitioners, and decision-makers at different organisational levels, ensuring accessibility and ease of understanding for users with varying expertise.
Class of entities under investigation	DR 6: The model must provide a comprehensive view of maintenance operations, addressing all key aspects rather than focusing on a single element.
Maturity and dimensions of maturity	DR 7: The maintenance maturity model must encompass all relevant domains and/or dimensions, including a distinct domain dedicated to defining and differentiating maturity levels.
	DR 8: The maintenance maturity model capability statements must be explicitly defined with clear, concise language to ensure they are easily interpretable and actionable by all users, regardless of their level of expertise.
Maturity levels and maturation paths	DR 9: The maintenance maturity model capability statements must distinctly differentiate between each maturity level, ensuring that the characteristics, processes, and performance metrics at each level are clearly defined
	DR 10: The maintenance maturity model must provide clear guidelines for organisations to progress from one maturity level to the next, with a focus on continuous improvement.

7.3.2 Establishing the need for a new model

According to Mettler (2010), identifying the need or opportunity for a new model must begin with a thorough understanding of existing solutions. This approach aligns with Becker et al. (2009), who emphasised the importance of reviewing existing models before initiating new developments. Such a practice not only avoids redundancy but also ensures that new models build upon proven frameworks, enhancing both their design quality and practical relevance.

Following this rationale, the present study conducted a brief comparative analysis of existing maturity models. This step was three-fold in purpose:

1. It aligned with the principles of DSR as articulated by Hevner et al. (2004), by using existing artefacts to inform and guide the design process through the identification of gaps and opportunities for improvement;
2. It established a foundational understanding of the maturity model landscape within asset-intensive and infrastructure-driven environments, ensuring that the proposed model is both practically relevant and positioned to offer a meaningful contribution beyond existing frameworks;
3. It satisfied the second phase of maturity model development outlined by Becker et al. (2009) as implemented by Tortora et al. (2022), Hellweg et al. (2021), Maisiri and Van Dyk (2020) and Thordsen and Bick (2020).

To demonstrate the value and relevance of this study, the proposed design requirements were systematically compared against those addressed by models found in the literature. This comparative analysis was critical in determining whether a new model was justified (Tortora et al., 2022). Had any of the existing models fulfilled all outlined requirements, the development of a new model would have been deemed unnecessary.

7.4 Methodology

A systematic mapping review (SMR) is regarded as a key tool used in numerous studies to highlight knowledge gaps within scope existing body of knowledge making it ideal for fields in the early stages of academic investigation (Grant and Booth, 2009, Peters and Wood, 2017). The SMR employed the research protocol detailed in Table 18 to meet the objectives of the chapter.

The SMR process was defined and executed through a structured approach in three main steps. Firstly, data was gathered using a predefined search procedure, ensuring a comprehensive capture of relevant literature. This was followed by selecting pertinent data based on predefined inclusion and exclusion criteria presented in Table 17. This step is crucial in narrowing down the vast amount of information to what is most relevant for the study. Finally, key insights were distilled from the reviewed literature, consolidating knowledge and highlighting gaps in the research.

This meticulous method allows researchers to map out the landscape of existing studies, providing a clear overview of the current state of research and pinpointing areas that need further exploration.

7.4.1 Research protocol

Table 17 presents the protocol guiding the SMR execution.

Table 17: Research protocol

Purpose	To perform a comprehensive gap analysis on existing maintenance maturity models.
Research questions	i. What maintenance maturity models are documented in the literature? ii. To what extent do current maintenance maturity models align with the established design requirements for an effective maintenance maturity model?
Inclusion criteria	• The paper discusses the development and application of the maintenance maturity model • The paper discusses the domains and dimensions of maintenance maturity models.
Exclusion criteria	• The paper is published more than once. • The complete content of the paper is not in English, with the exception for the title. • The full text of the paper is not accessible. • The research paper imprecisely uses terms and synonyms associated with maintenance and maturity models. • Papers that do not provide specific insights into the domains and dimensions of the models. • Papers that do not focus on maintenance maturity models or frameworks. • Papers that discuss general maintenance practices without a focus on maturity models or frameworks
Search Database	Scopus and Web of Science
Search scope	2000 - 2023
Keywords	Maintenance and "maturity model"

7.4.2 Search strategy

The search strategy for this SMR involved identifying relevant literature on maintenance maturity models through a comprehensive keyword-based search across Scopus and Web of Science. Search terms such as "maintenance maturity models," "maintenance frameworks," "maintenance assessment," and "maturity models" were combined using Boolean operators to form search strings that ensure a broad search. Search terms were meticulously chosen to align with the primary themes outlined in the research questions, considering spelling variations, synonyms,

and variations in usage. This approach was designed to maximise the likelihood of identifying relevant studies (Siddaway et al., 2019). The following search string was used:

*("maintenance maturity model" OR "maintenance maturity framework") AND ("assessment" OR "evaluation") AND ("maintenance maturity**")*

7.4.3 Study selection

During the selection process, a substantial number of papers were found to be irrelevant to the central focus of the study, leading to their exclusion from further consideration. Subsequently, citation searching was implemented as an additional method to identify further articles pertinent to the study's focus. This approach not only broadened the scope of the research but also ensured the inclusion of comprehensive and relevant literature. Figure 13 summarises the selection process followed in this SLR.

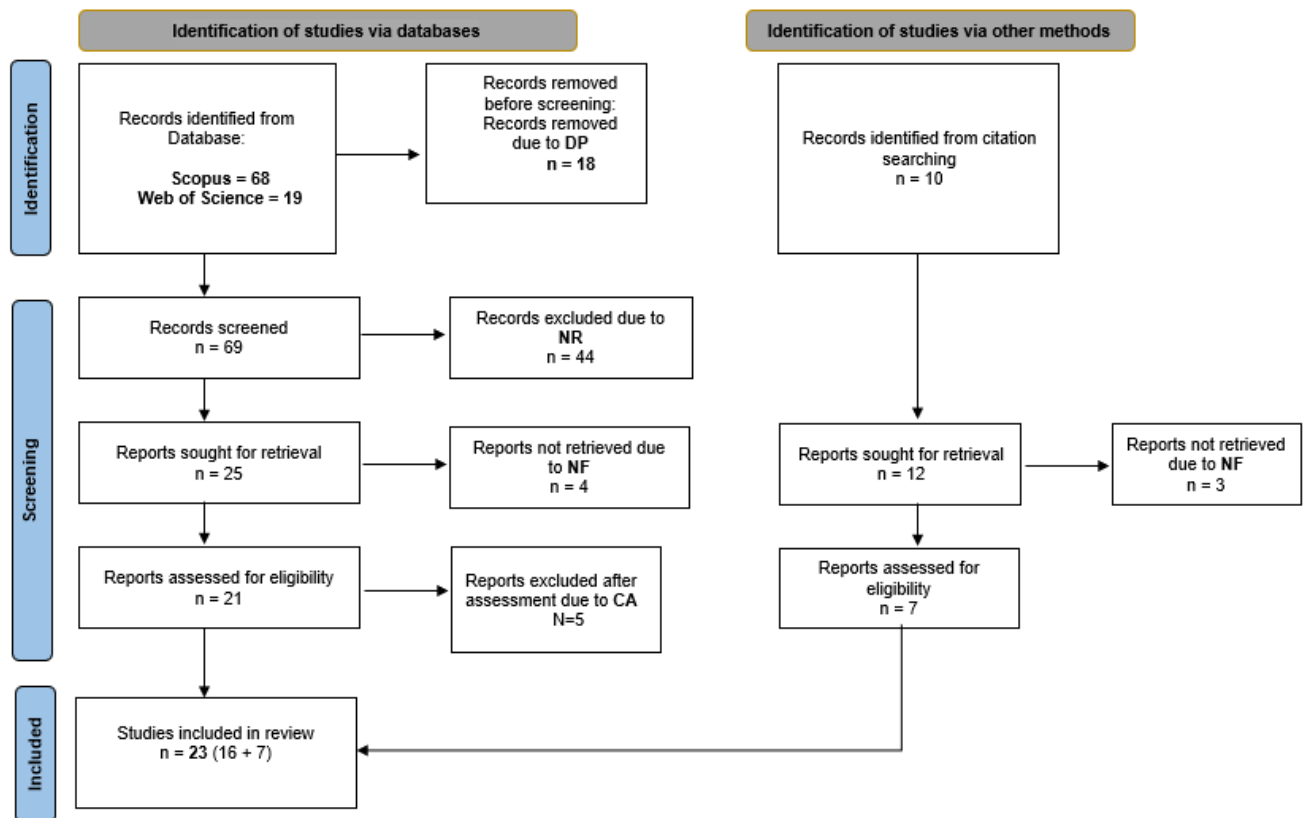


Figure 13: PRISMA flow diagram for the systematic mapping review

7.4.4 Data analysis

The data analysis aimed at addressing research questions (i) and (ii), as outlined in Table 17. The extracted and analysed data included the title, industry, method of assessment, dimensions or knowledge areas, and maturity levels of each study as outlined in Table 18. This analysis provides a comprehensive understanding of the diverse model structure, development approaches and outcomes across various sectors.

Table 18: Characteristics of the extracted data

Characteristic	Description
Title	The articles reviewed have varied titles that encapsulate their core focus and objectives. These titles often indicate the primary concern, or the specific area of maturity being investigated, providing a quick reference to the study's central theme.
Maturity Levels	Maturity levels represent the stages of development or proficiency in the identified dimensions or knowledge areas, ranging from initial or ad hoc stages to optimised or advanced stages. Each level is characterised by specific attributes and capabilities that denote an organisation's progression in terms of maturity.
Industry/domain	Each article concentrated on a specific industry, ranging widely across sectors such as SMEs and manufacturing. The industry focus is significant as it determines the context in which maturity is being evaluated, influencing the relevant dimensions and methodologies used.
Method of assessment	The assessment methods employed in the included studies are diverse, including surveys, interviews, case studies, and quantitative analyses (Mehairjan et al., 2016). The choice of assessment method reflects the article's aims and the nature of the data required to gauge maturity accurately. Some studies used self-assessment tools, while others rely on third-party evaluations or a mixed-methods approach to gather comprehensive insights (Oliveira and Lopes, 2020).
Dimensions or Knowledge Areas	Each article identifies specific dimensions or knowledge areas pertinent to the industry and the maturity model applied. These areas form the basis for evaluating an organisation's maturity, providing a structured framework for assessment (Becker et al., 2009).

A key aspect of this analysis was the identification of gaps in the design of the models. Each study was evaluated against a set of predefined design requirements essential for an effective maintenance maturity model. This evaluation helped to highlight areas where the models may fall short and need further development.

7.5 Findings

In response to research questions (i) and (ii) presented in Table 17, 23 papers were meticulously selected for in-depth analysis and subsequently included in the systematic mapping review as illustrated in Figure 13.

Table 31 (Appendix A) summarises the literature reviewed, offering a concise overview of each article's content. This summary directly supports the analysis related to research question (i).

The review of existing studies indicates a notable scarcity of research on maintenance maturity models. A trend analysis of published works illustrated in Figure 14, suggests that despite the overall low volume, there has been a recent uptick in studies dedicated to the maintenance of infrastructure assets over the past five years. This recent surge signifies a growing recognition of the importance of maintenance maturity in various sectors.

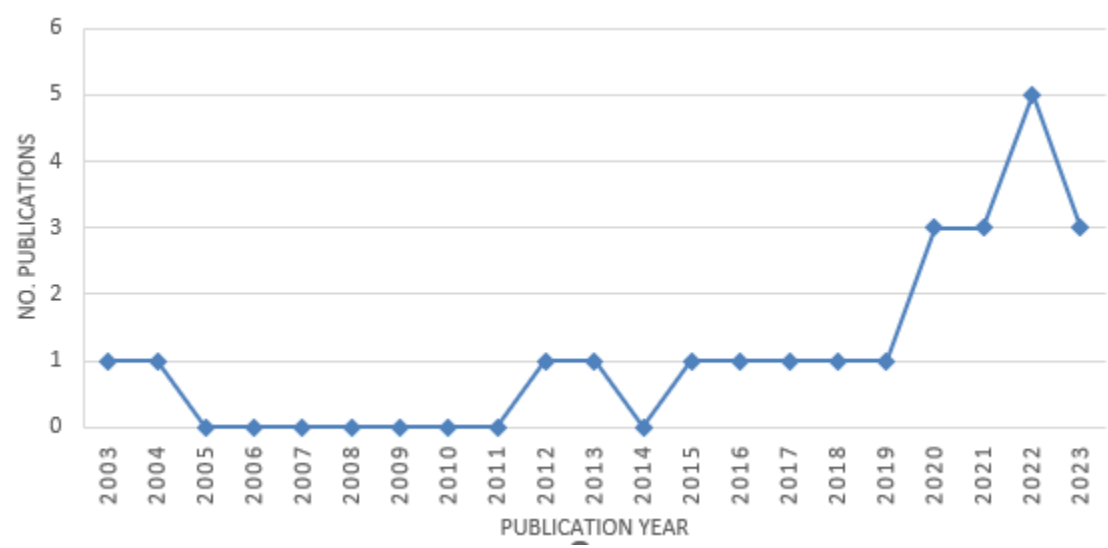


Figure 14: Number of publications per year

7.5.1 Gap analysis

The analysis revealed several areas where existing maintenance maturity models fall short, indicating a need for further development and refinement. Table 19 presents how each model aligns with a set of predefined design requirements. In this table, a “Y” (highlighted in red) indicates that a model satisfies a particular design requirement, while an “N” (shaded in yellow) highlights a clear inadequacy in meeting the respective criterion.

Notably, many of the reviewed studies demonstrate strong compliance with design requirement 2 (DR2), which emphasises the model's role as a diagnostic tool for assessing maintenance maturity. This diagnostic capacity is essential, as it enables organisations to identify operational strengths and weaknesses, facilitating more informed strategic planning. This finding aligns with the observations of Reis et al. (2017) and De Bruin et al. (2005), who underscore the value of diagnostic functionality in guiding structured improvement. In addition, there is broad alignment

with design requirement 3 (DR3), which supports the identification of areas for improvement. This contributes to the optimisation of maintenance practices and promotes a culture of continuous enhancement. Furthermore, substantial compliance with design requirement 7 (DR7) is evident, suggesting that many models adequately cover the necessary domains and maturity levels.

Table 19: Gap analysis results

REFERENCE	DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9	DR10
A Strategic Roadmap to Improve the Maturity Level of Maintenance Information Management Systems (Tortora et al., 2023)	N	Y	N	N	N	N	Y	Y	Y	Y
A Maintenance Maturity and Sustainability Assessment Model for Manufacturing Systems (Franciosi et al., 2023)	N	Y	Y	N	N	Y	Y	N	Y	N
Maturity model for evaluating building maintenance practice: A fuzzy-DEMATEL approach (Desbalo et al., 2023)	N	Y	Y	N	Y	Y	Y	N	N	N
A Maintenance Maturity Model for Assessing Information Management Practices for Small and Medium Enterprises (M3AIN4SME) (Tortora et al., 2022)	N	Y	Y	N	N	N	Y	Y	Y	N
The Evaluation of Maturity Level on Heavy Equipment Maintenance Management According to ISO 55001:2014 (Siswantoro et al., 2022)	N	Y	Y	N	N	N	Y	N	N	Y
Evaluation of maintenance management of a thermoplastic industry using maintenance maturity model (Oliveira et al., 2022)	N	Y	Y	N	Y	Y	Y	N	N	Y
Improving the level of predictive maintenance maturity matrix in industrial enterprise (Mesarosova et al., 2022)	N	Y	Y	N	N	Y	Y	N	N	N
A Maturity Model Proposal for Industrial Maintenance and Its Application to the Railway Sector (Errandonea et al., 2022)	N	Y	Y	Y	N	Y	Y	N	N	Y
Development of a Generic Framework to Assess Asset Management Maturity within Organisations (Maier et al., 2021)	N	Y	Y	N	Y	Y	Y	N	N	N
Identifying Maturity Dimensions for Smart Maintenance Management of Constructed Assets: A Multiple Case Study (Johannes et al., 2021)	N	Y	Y	N	N		N	N	N	N
Evaluation of the Maturity in the Management system of Maintenance of Electricity Distribution Networks – A Case Study (de Oliveira et al., 2021)	N	Y	Y	N	Y	N	Y	Y	Y	N
Evolution of a Lean Smart Maintenance Maturity Model towards the new Age of Industry 4.0 (Schmiedbauer et al., 2020)	N	Y	Y	N	Y	Y	Y	N	N	N
Evaluation and improvement of maintenance management performance	N	Y	Y	N	Y	Y	Y	Y	Y	N

REFERENCE	DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9	DR10
using a maturity model (Oliveira and Lopes, 2020)										
Validation of a Lean Smart Maintenance Maturity Model (Maier et al., 2020)	N	Y	Y	N	Y	Y	Y	N	N	N
A maturity assessment procedure model for realizing knowledge-based maintenance strategies in smart manufacturing enterprises (Nemeth et al., 2019)	N	Y	Y	N	Y	N	N	N	N	N
PriMa-X: A reference model for realizing prescriptive maintenance and assessing its maturity enhanced by machine learning (Nemeth et al., 2018)	N	Y	Y	N	N	N	N	N	N	N
Development of a theoretical framework for evaluating maintenance practices (Muchiri et al., 2017)	N	Y	Y	N	Y	N	Y	Y	Y	N
Development and implementation of a maturity model for professionalising maintenance management (Mehairjan et al., 2016)	N	Y	Y	N	Y	Y	Y	N	N	Y
Asset maintenance maturity model: Structured guide to maintenance process maturity (Chemweno et al., 2015)	N	Y	Y	Y	Y	N	Y	N	N	Y
A maintenance maturity assessment method for the manufacturing industry (Macchi and Fumagalli, 2013)	N	Y	Y	N	N	Y	Y	N	N	N
Maintenance management based on the organization maturity level (Oliveira et al., 2012)	N	Y	Y	N	N	N	Y	N	Y	N
The status of maintenance management in UK manufacturing organisations: results from a pilot survey (Cholasuke et al., 2004)	N	Y	Y	N	Y	Y	Y	N	N	N
Reliability centered maintenance maturity level roadmap (Hauge et al., 2003)	N	Y	Y	N	N	N	Y	Y	Y	N

However, while these strengths are commendable, the analysis also reveals a concerning number of unmet design requirements, particularly where “N” (yellow) indicators are prevalent. Design requirement 1 (DR1)—focus on water infrastructure was unmet, reflecting a critical gap in addressing sector-specific priorities. Similarly, design requirement 4 (DR4), which calls for flexible and progressive improvement pathways, also shows notable non-compliance. These shortcomings constrain the practical utility and robustness of existing models. Addressing them is vital to enhance responsiveness to varying operational needs and to support the development of more comprehensive, adaptable frameworks that drive sustainable maintenance excellence.

Central to the effectiveness of any maturity model is the clarity and rigour of its underlying design criteria. As Oost (2024) notes, these design requirements/criteria form the foundation upon which usability and reliability are built. Of particular concern is the widespread failure to meet design

requirement 8 (DR8) and design requirement 9 (DR9). DR8 pertains to the clarity and comprehensibility of model descriptions, while DR9 relates to their ease of use in practical settings. Several studies present models using vague or overly complex language, which acts as a barrier to interpretation and application.

As highlighted by Röglinger et al. (2012) and Poeppelbuss and Roeglinger (2011), such ambiguity undermines user confidence and limits the practical utility of the models. This ultimately compromises their fundamental purpose: to offer a structured and comprehensible pathway for improvement. As Becker et al. (2009) and Linhart et al. (2017) argue, the success of a maturity model lies not only in its conceptual design but also in its ability to be clearly communicated and easily operationalised.

Importantly, a novel perspective is offered by Errandonea et al. (2022a), who presented a framework that diverges from the conventional capability maturity model (CMM) progression structure. Their model proposes four maturity levels aligned with distinct maintenance strategies namely, preventive, condition-based, predictive, and prescriptive. This strategy-oriented approach introduces an alternative lens through which maintenance maturity can be assessed. It also highlights the potential value of tailoring maturity levels to real-world maintenance practices rather than adhering strictly to traditional maturity modelling conventions. By grounding model design in practical maintenance strategies, such frameworks may offer enhanced relevance and accessibility for practitioners.

7.5.2 Discussion

Despite the proliferation of maintenance maturity models, the field is characterised by significant diversity in terms of the models' structures, assessment criteria, and application contexts. The findings highlight the inherent complexity and rigorous demands associated with developing a generic maintenance maturity model. This challenge is consistent with the perspectives of Oliveira et al. (2022) and Tortora et al. (2023), who argued that the creation of such models involves multifaceted considerations that are difficult to generalise. Consequently, many of the papers reviewed have opted for customisation, tailored to specific contexts, reflecting the nuanced requirements and unique challenges faced by different industries and sectors. The customisation indicates that while there is progress in the field, there is still a need for broader, more adaptable models that can be applied across various sectors.

This trend towards specialised adaptation underscores the necessity for maintenance models that are flexible enough to cater to the distinct needs of varying environments. It also suggests that while the concept of a universal maintenance maturity model is appealing, practical implementation often necessitates context-specific modifications to ensure efficacy and relevance.

Moreover, the rapid pace of technological advancements, particularly the advent of Industry 4.0, has introduced new dimensions to maintenance practices, such as the integration of the internet of things (IoT), big data analytics, and artificial intelligence (Maier et al., 2020b, Schmiedbauer et al., 2020). Furthermore, these developments have necessitated the evolution of maintenance maturity models to incorporate these emerging technologies and reflect the changing landscape of maintenance management.

On that note, although various maintenance maturity models exist in the literature, none are specifically tailored or designed for the unique needs of water infrastructure. Existing models typically offer narrow frameworks applicable across industries, yet they overlook the intricacies involved in water systems. These systems require specialised approaches that account for factors like asset criticality, risk of contamination, and the necessity for uninterrupted service. Furthermore, the reviewed generic maintenance maturity models lack a specific focus on evaluating water infrastructure maintenance. This gap is noteworthy because water infrastructure presents unique challenges, including aging pipelines, variable demand, and environmental regulations.

7.6 Conclusion

This chapter critically reviewed existing maintenance maturity models (MMMs), highlighting a persistent gap between ideal design principles and the characteristics of current models. Despite their acknowledged potential to improve maintenance performance, many MMMs lack comprehensiveness, adaptability, and clear assessment metrics. The analysis underscores the need for a more integrated and context-specific approach, particularly suited to the operational challenges faced by water utilities in South Africa. In response, Chapter 7 laid the groundwork for the development of a new MMM guided by DSR principles. Chapter 8 introduces the proposed conceptual model and details the development process.

CHAPTER 8: DEVELOPMENT OF A MAINTENANCE MATURITY MODEL

8.1 Introduction

This chapter presents the development of a maintenance maturity model (MMM) to guide the prioritisation of water infrastructure maintenance in South Africa. Anchored in the design requirements outlined in the preceding chapter, the model is constructed through a structured, iterative process informed by established theoretical frameworks. The development unfolds across a series of interrelated phases, each contributing a critical component to the overall framework. These phases collectively culminate in the formulation of the MMM, which is introduced at the conclusion of the chapter.

8.2 Model development plan

The development of maturity models has gained prominence as a systematic approach for diagnosing organisational inefficiencies and facilitating structured pathways for continuous improvement (Richard Caralli et al., 2012). MMs have been widely adopted across diverse sectors, a persistent shortcoming lies in the absence of standardised methodologies guiding their design and implementation (Mettler, 2010). This methodological ambiguity has often led to disparities in model architecture, internal coherence, and practical applicability. In an effort to address these limitations, several scholars have proposed structured frameworks aimed at enhancing the methodological robustness of maturity model development. These frameworks are synthesised and critically compared in Table 20 to highlight their respective contributions and methodological distinctiveness.

Building on this foundation, the chapter adopted a hybrid approach by integrating Becker et al. (2009)'s framework with Maier et al. (2012)'s roadmap. This combined methodological rigour with practical relevance to guide the development of a maintenance maturity model (MMM) that is both theoretically sound and contextually applicable.

Table 20: Comparative summary of maturity model development frameworks

De Bruin framework (De Bruin et al., 2005)	Maier roadmap (Maier et al., 2012)	Becker et al guidelines (Becker et al., 2009)	Mettler design decisions (Mettler, 2010)
i. Scope ii. Design iii. Populate iv. Test v. Deploy vi. Maintain	Phase 1: Planning i. Specify audience ii. Define aim iii. Clarify scope iv. Define success criteria Phase 2: Development i. Select process areas ii. Select maturity levels iii. Formulate cell text iv. Define administrative mechanism Phase 3: Evaluation i. Validate ii. Verify Phase 4: Maintenance i. Check benchmark ii. Maintain results database iii. Document and communicate the development process and results	i. Problem definition ii. Comparison of existing models iii. Development strategy iv. Iterative MM development v. Concept of transfer and evaluation vi. Implementation of transfer media vii. Evaluation Rejection of Maturity Model	i. Identify need or new opportunity ii. Define scope iii. Design model iv. Evaluate design v. Reflect evolution

The framework of Becker et al. (2009) emphasises scientific validity through clearly defined problems, systematic comparisons of existing maturity models, and iterative model refinement. This approach ensures content and construct validity, enabling evidence-based modifications, and supporting contextual adaptability. On the other hand, Maier et al. (2012) introduced a comprehensive development lifecycle comprising four key phases: planning, development, evaluation, and maintenance. Their roadmap provides the operational structure that Becker et al.'s framework lacks.

In this study, taking the strengths of Becker et al. (2009) and Maier et al. (2012) frameworks, the two are integrated to produce a hybrid MMM development plan.

The complete development process is structured into four key phases: planning, development, evaluation, and maintenance, adapted from the guidelines proposed by Maier (2012 as illustrated in Figure 15. This chapter will focus on the first two phases: planning and development. The remaining phases, evaluation and maintenance, will be addressed in Chapter 9.

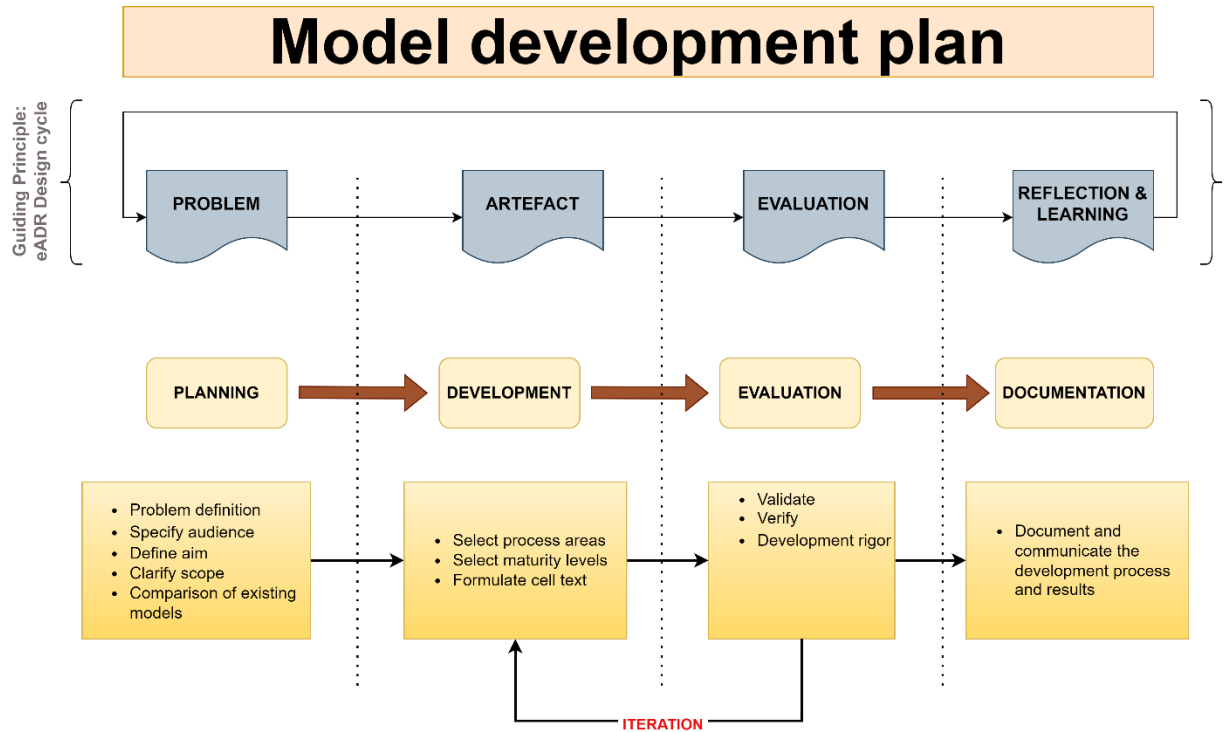


Figure 15: Development plan (Adapted from (Becker et al., 2009, Maier et al., 2012))

8.3 Planning phase

The planning phase establishes the problem space by identifying the core issue underpinning this chapter's rationale. As outlined by Maier et al. (2012), this phase involves defining the intended audience (the user community and the improvement entity), clarifying the purpose of the assessment, and delineating its scope and success criteria. To enhance the robustness of this phase, this chapter also incorporates the steps (i) and (ii) proposed by Becker et al. (2009) as outlined in Table 20.

It is important to recall that the problem diagnosis and validation were comprehensively addressed in preceding chapters (Chapters 4, 5, and 6), particularly through the elaborated action design research (eADR). This work highlighted frequent breakdowns, inadequately structured maintenance strategies, and poor planning practices that undermine asset performance and service delivery. This foundational understanding informs the detailed steps taken in the planning phase, ensuring that the maintenance maturity model (MMM) developed here is relevant and targeted.

Building on this solid foundation, the current chapter outlines a structured approach to planning the MMM's development. Table 21 presents the foundational steps undertaken during this phase, serving as a roadmap to guide the creation of a model that is both comprehensive and practical.

Table 21: Planning phase

Step	Description
i. Problem definition	Frequent water infrastructure breakdowns, caused by inadequately structured and adaptable maintenance plans and strategies, significantly hinder the provision of uninterrupted service delivery. (Section 1.3)
ii. Aim	The study aims to develop a maintenance maturity model (MMM) tailored for prioritising water infrastructure maintenance in South Africa. (Section 1.4)
iii. Audience	Maintenance practitioners, asset managers
iv. Scope	Water infrastructure in South Africa
v. Comparison of existing models	This stage is inspired by Becker et al. (2009) and is presented in Chapter 7 through a systematic mapping review. The study reviewed existing maturity models and compared them against a set of design requirements. This comparison provided a comprehensive overview of the various constructs within the models and highlighted areas of overlap between them.

8.4 Development phase

The model was developed through an iterative process, incorporating progress feedback from academic supervisors and industry experts to ensure theoretical coherence and practical relevance. The structure comprising various domains, maintenance dimensions, and maturity levels evolved over several drafts, with refinements driven by critical evaluation of conceptual clarity, contextual applicability, and alignment with best practices. This iterative refinement ensured the model's robustness before further refinement and formal validation through the Delphi study in Chapter 9.

Central to this development was a structured conceptualisation phase in which four initial design alternatives were formulated and iteratively assessed, as presented in Sections 8.4.1 to 8.4.4. The conceptual objective underpinning each design was twofold: firstly, to provide an accurate diagnosis of prevailing maintenance deficiencies; and secondly, to enable the formulation of targeted, actionable strategies for progressive improvement.

Each conceptual design proposed a distinct configuration of domains intended to capture the multifaceted nature of maintenance evolution. The exploration of these alternatives aimed to ensure that the final model would reflect a comprehensive and multidimensional perspective on maturity progression. The domains considered during this phase included:

- **Strategic maturity:** Based on the maintenance strategy pyramid, reflecting the progression from reactive to prescriptive maintenance approaches.
- **Decision-making levels:** Incorporating operational, tactical, and strategic layers to align with organisational hierarchy and influence.
- **Process maturity:** Informed by the Capability Maturity Model Integration (CMMI), assessing the sophistication and repeatability of maintenance processes.
- **Sustainability indicators:** Integrating Environmental, Social, and Governance (ESG) metrics to evaluate long-term maintenance viability.
- **Triple bottom line (TBL):** Addressing sustainable maintenance practices' economic, social, and environmental dimensions.
- **Maintenance management functional areas:** Encompassing critical areas such as policy and organisational structure, resource management, information systems, and performance monitoring.

The iterative evaluation of these conceptual alternatives played a paramount role in shaping the final configuration of the MMM. This final version synthesised the most effective elements of each design, balancing theoretical depth with practical applicability. To enhance its comprehensiveness, the model was further refined based on emergent insights from the development process, ensuring its capacity to address the dynamic challenges of infrastructure maintenance and continuous improvement.

8.4.1 Design one

This design integrates maintenance maturity within the organisational hierarchy by mapping three dimensions: decision-making levels (strategic, tactical, and operational), maintenance functional areas, and the maintenance strategy progression as illustrated in Figure 16. This structured framework enables a comprehensive assessment of how well maintenance strategies and practices align with organisational decision-making authority and responsibilities.

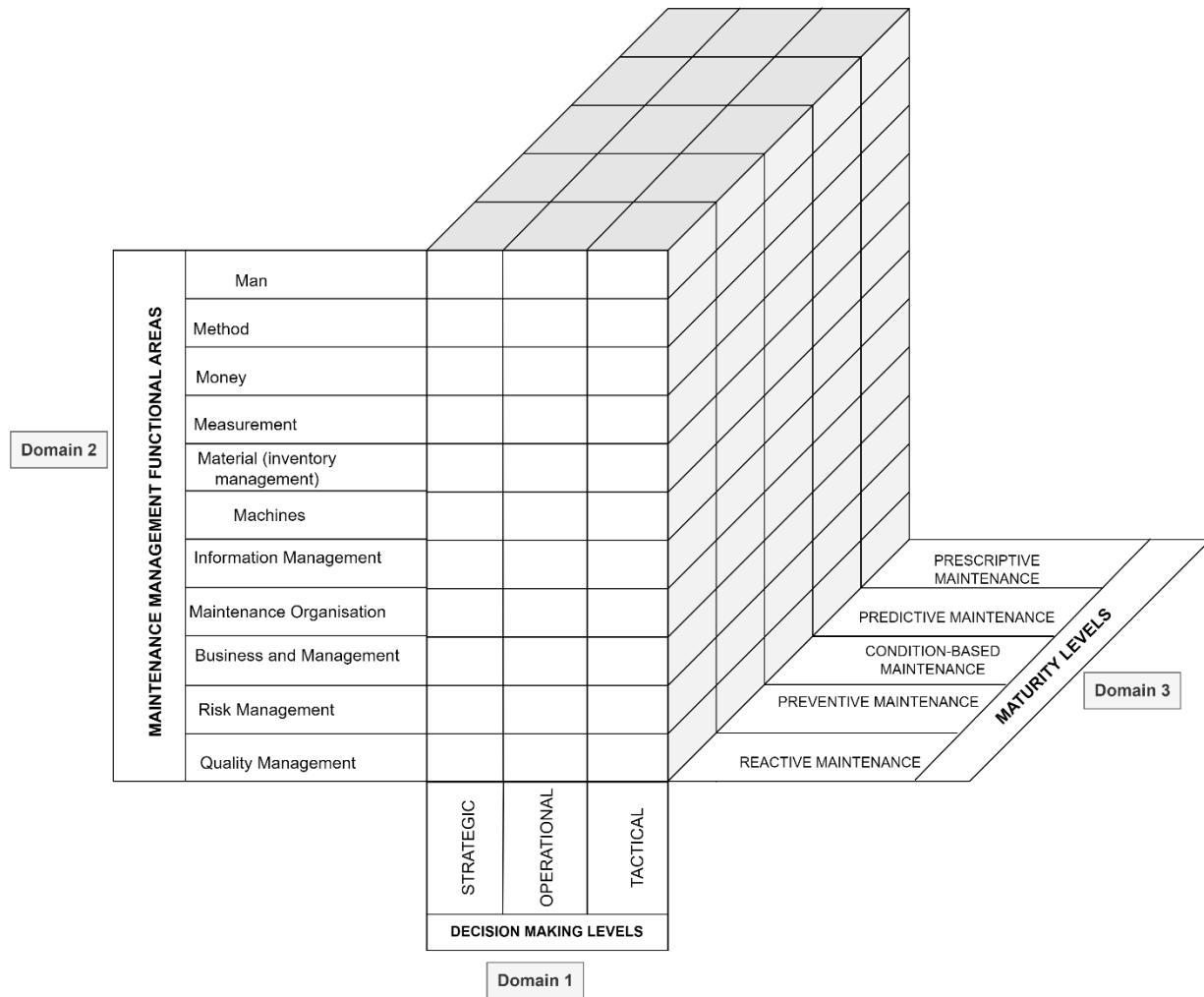


Figure 16: Decision-making-oriented model

8.4.2 Design two

This model integrates triple bottom line (TBL) dimensions—economic, social, and environmental—with maintenance functional areas and strategic maintenance progression levels (reactive to prescriptive) across three domains as presented in Figure 17. It objectively evaluates how maintenance practices support sustainability goals while advancing maturity. The model identifies performance gaps, promotes balance across TBL factors, and guides the shift toward sustainable, value-driven maintenance strategies.

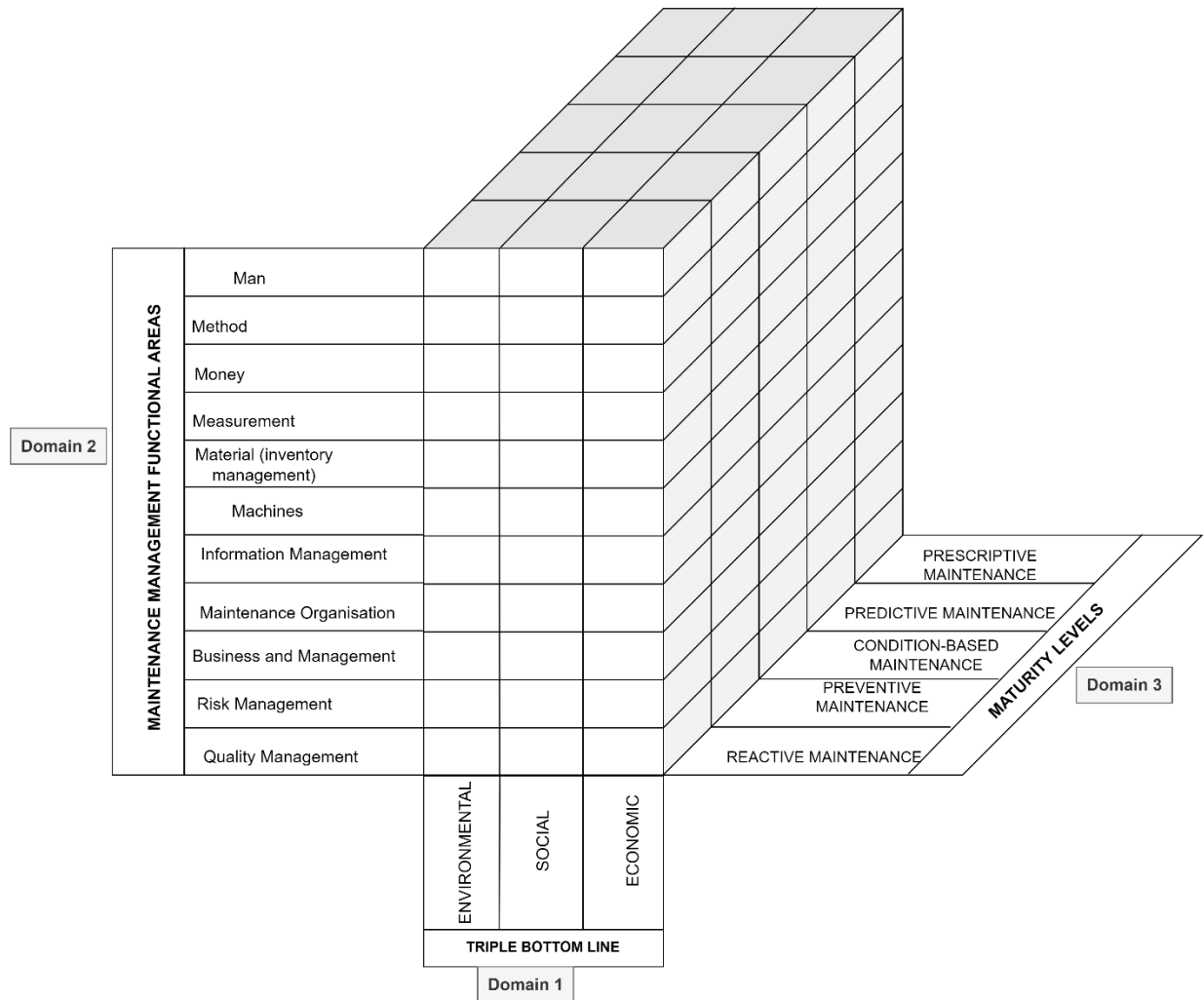


Figure 17: Triple-bottom-line-driven model

8.4.3 Design three

This model integrates environmental, social, and governance (ESG) dimensions into assessing maintenance management functional areas across a strategic maintenance progression continuum. It aligns maintenance management with corporate governance and sustainability frameworks, enabling organisations to evaluate and enhance maintenance practices directly supporting ESG performance objectives. By embedding ESG considerations, the model fosters responsible asset stewardship, operational resilience, and compliance with evolving sustainability standards. Figure 18 illustrates the mapping of the aforementioned domains.

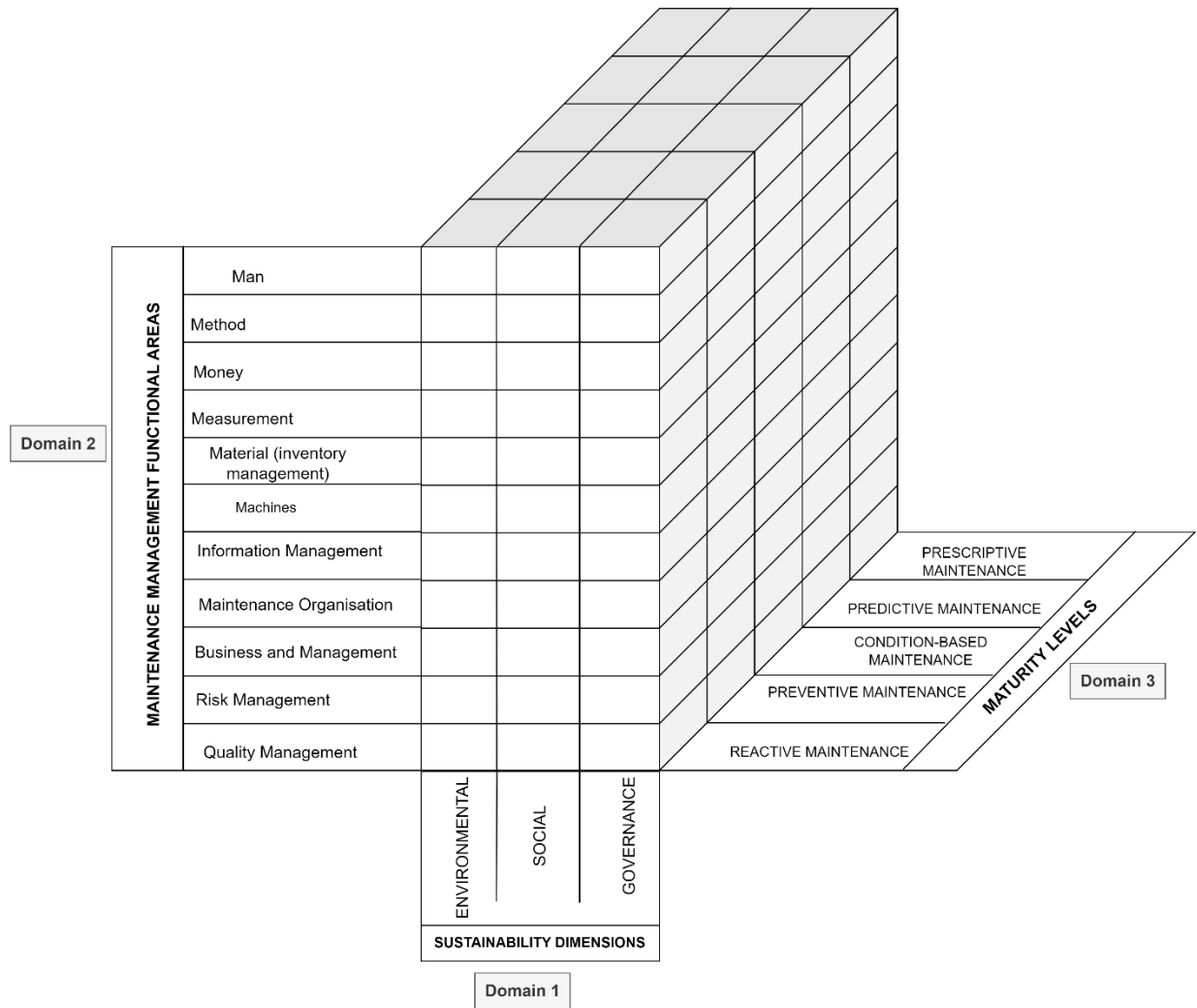


Figure 18: ESG-aligned model

8.4.4 Design four

Figure 19 illustrates a design that provides a multidimensional framework for assessing and guiding organisational maintenance maturity. Integrating the evolution of maintenance strategies, core functional maintenance domains, and process maturity levels delivers a holistic roadmap that supports the transformation from basic, reactive maintenance practices to advanced, prescriptive maintenance excellence.

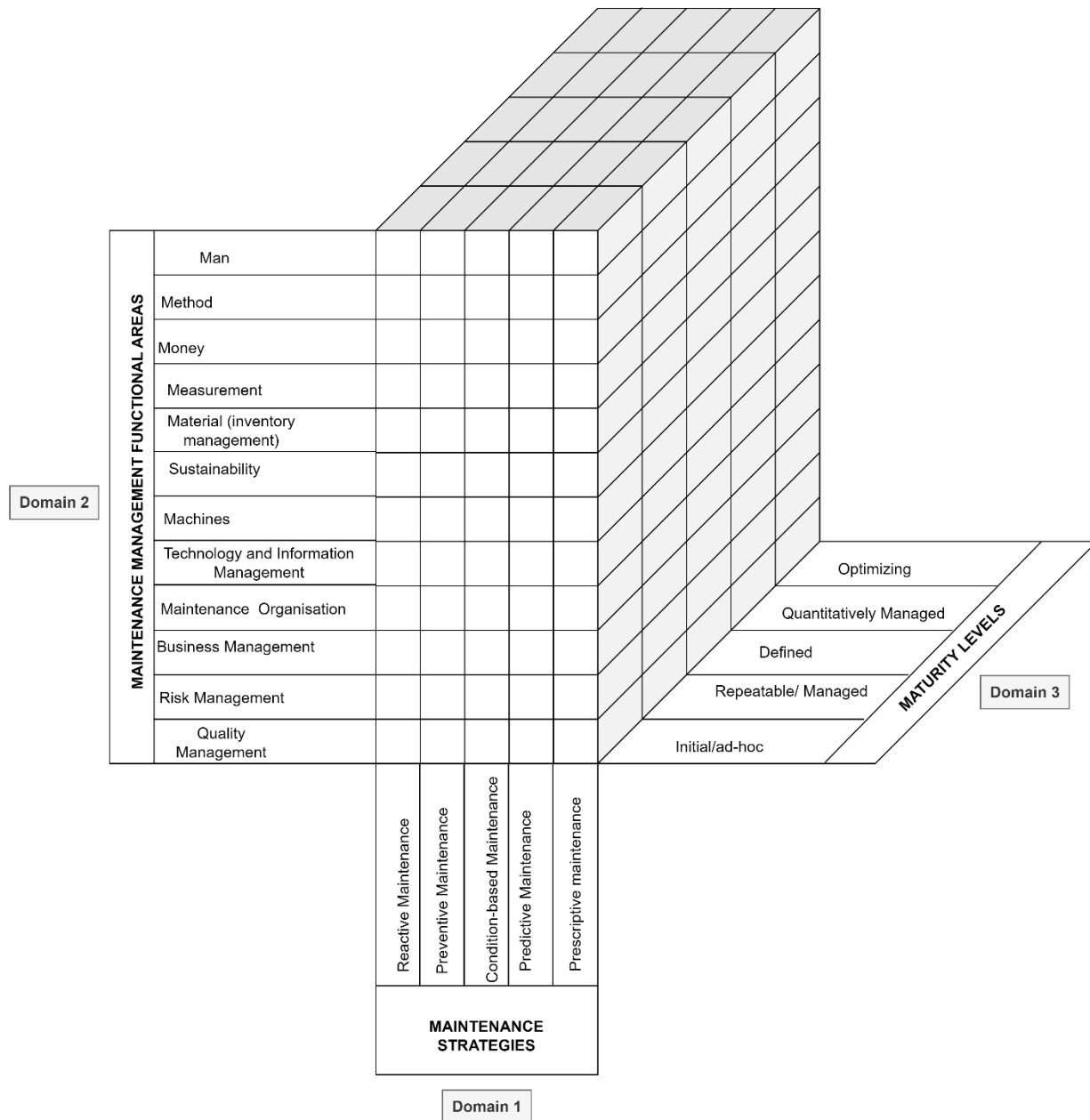


Figure 19: Strategy-process integrated model

8.4.5 Comparative analysis of maintenance maturity model conceptual designs

Each of the proposed designs was subjected to critical evaluation, with attention given to their capacity to: (1) expose systemic maintenance gaps; (2) support structured advancement across organisational maintenance practices; and (3) align with existing organisational structures and functions. Following a comparative assessment of each model's conceptual strengths and

limitations as outlined in Table 22, Design four emerged as the most contextually appropriate and operationally feasible framework for addressing inadequate maintenance practices, particularly in complex, infrastructure-reliant environments like water utilities.

Table 22: Comparative analysis of maintenance maturity model designs

	Domain 1	Domain 2	Domain 3 (maturity levels)	Strengths	Weaknesses
Design one	Decision-making levels (Strategic, Tactical, Operational)	Maintenance functional areas	Strategic maturity (Maintenance pyramid)	- Aligns maintenance functions to organisational decision levels. - Highlights gaps in translating strategy into action.	- May underplay the sustainability and economic dimensions. - Strategic maturity represented on domain_3 may confuse levels with decision-making hierarchy.
Design two	Triple-bottom line (Economic, Social, Environmental)	Maintenance functional areas	Strategic maturity (Maintenance pyramid)	- Integrates sustainability with maintenance, critical for public infrastructure. - Encourages a holistic view (beyond cost-driven maintenance).	- May dilute the technical and operational focus needed to resolve immediate inadequacies. - Overlap and conceptual clash between the economic dimension on domain_1 and the "Money" functional domain on the domain_2 creates redundancy and introduces interpretive ambiguity,
Design three	Sustainability dimensions (Environmental, Social, Governance)	Maintenance functional areas	Strategic maturity (Maintenance pyramid)	- Strong focus on ESG, aligning with modern asset management trends. - Governance aspect is helpful for institutional issues (e.g., lack of accountability).	- May divert attention from the practical maintenance process improvement. - ESG indicators may be too high-level for immediate tactical maturity development.

	Domain 1	Domain 2	Domain 3 (maturity levels)	Strengths	Weaknesses
Design four	Maintenance strategies (Reactive → Prescriptive)	Maintenance functional areas	Process maturity levels (CMMI-style)	• Clear focus on the evolution of strategy. • Domain_3 (CMMI-like levels) reflects process improvement over time. • Strong alignment with maturity model theory and structured evolution.	• Less direct integration of sustainability or organisational hierarchy. • Could require supplementary tools to assess economic or social impact.

Among the four conceptual designs proposed for structuring an MMM, Design four emerged as the most relevant and applicable for addressing the challenge of inadequate maintenance practices, particularly in asset-intensive and infrastructure-dependent sectors.

Design four adopts a three-dimensional framework in which:

- Domain 1 - represents the evolution of maintenance strategies, progressing from reactive to preventive, condition-based, predictive, and ultimately prescriptive maintenance.
- Domain 2 - comprises various maintenance functional areas, such as policy and organisation, resource management, data and information systems, and performance measurement.
- Domain 3 - incorporates CMMI-inspired maturity levels, reflecting the continuum of process maturity from ad hoc and disorganised practices to fully optimised, data-driven, and continuously improving systems.

Design 4 uniquely integrates strategic orientation (maintenance strategies), functional breadth (domain-specific practices), and process depth (organisational capability maturity), offering a holistic yet structured framework for maturity assessment and improvement.

In contrast to the other designs, which emphasise sustainability dimensions (Designs two and three) or decision-making hierarchies (Design one), Design four centres on the operational realities of maintenance transformation. This renders it particularly relevant for organisations like water utilities, where maintenance is reactive, poorly coordinated, and lacks a structured

developmental trajectory. By explicitly linking current strategies to process maturity and functional performance, Design four enables organisations to diagnose their existing state and chart a targeted path towards higher maturity levels. This makes it a highly effective model for guiding strategic interventions to overcome maintenance deficiencies and ensure sustainable asset performance within water utilities.

8.4.6 Select process areas

In the development of any maturity model, the careful selection of process areas or dimensions is essential to building a robust and balanced assessment framework (Maier et al., 2012, Maier et al., 2009). Dimensions serve as the categories against which an organisation's maintenance processes are evaluated. They must collectively capture all critical aspects of maintenance without overwhelming the assessment with unnecessary complexity.

One challenge in defining dimensions is achieving both comprehensiveness and manageability. While existing maintenance maturity models offer a wealth of insights into potential dimensions (Lasrado et al., 2015), not every dimension applies equally across all organisations. Factors such as organisational size, industry sector, and specific maintenance objectives influence which dimensions are most relevant (Oost, 2024). Thus, expert input was invaluable in ensuring that the selected dimensions are pertinent and practical for the intended context.

Balancing depth and efficiency is crucial in developing assessment models; an overly granular approach can become time-consuming and challenging to implement, while an overly streamlined framework risks overlooking critical factors (Oost, 2024). By reviewing a range of established models and consulting with domain experts, this chapter identified a core set of dimensions tailored to the specific requirements of the assessment. This approach aligns with the perspectives of Lasrado et al. (2015) and Maier et al. (2012), who emphasise the importance of contextual relevance and expert validation in model development.

8.4.6.1 Maintenance strategies domain

The maintenance strategies domain encompasses a spectrum of approaches: reactive maintenance, preventive maintenance, condition-based maintenance, predictive maintenance, and prescriptive maintenance. This trajectory aligns with the strategic development articulated in the maintenance pyramid discussed in section 2.4.2. This domain enables organisations to review their existing maintenance practices and align them with industry best practices most appropriate

for their operational context. Each strategy reflects a distinct philosophy of asset management, offering varying levels of proactiveness, resource utilisation, and risk mitigation. By understanding and implementing the right mix of strategies, organisations can enhance asset reliability, optimise performance, and reduce lifecycle costs.

8.4.6.2 Maintenance management functional areas domain

According to Oliveira and Lopes (2020), the development of a maturity model necessitates the identification of key factors that significantly influence performance within the specific domain of interest. This foundational step ensures that the model captures the essential dimensions required for assessing and guiding organisational growth. In maintenance management, these factors are commonly referred to as enablers or critical success factors that are essential for ensuring operational continuity and aligning maintenance practices with organisational objectives.

This chapter refers to these enablers as functional areas, as they represent the core domains spanning the full maintenance management lifecycle. The selection of these functional areas was informed by the need to encompass all aspects critical to effective maintenance performance, as informed by findings from the preceding chapters.

The effectiveness of maintenance strategies in any organisation can be evaluated through a set of these critical functional areas. Given the availability of numerous existing maturity models, there is a solid foundation for selecting appropriate dimensions. Furthermore, drawing on insights from existing maintenance maturity models and literature (Crespo Marquez and Gupta, 2006, European Federation of National Maintenance Societies (EFNMS), 2022, Kumar et al., 2013, GFMAM, 2021, Velmurugan and Dhingra, 2015, Garg and Deshmukh, 2006, Saihi et al., 2022, Maier et al., 2020b, Society for Maintenance & Reliability Professionals (SMRP)), twelve core dimensions were identified as particularly significant. These are presented in Table 23. While not exhaustive, they represent the most salient areas recognised in academic and industrial practice.

Table 23: Functional area dimensions

Functional area	Description	Reason for inclusion
Human Resources	This area encompasses the skills, training, and workforce planning required to perform maintenance activities effectively. It focuses on ensuring that the workforce possesses the necessary knowledge and experience for efficient operations.	A well-trained and skilled workforce is fundamental to achieving maintenance goals and ensuring operational efficiency. Human resource management influences the success of maintenance programs, particularly in asset-intensive industries where specialised skills are crucial.

Functional area	Description	Reason for inclusion
Asset maintenance strategy development	Involves the creation of long-term plans and approaches for maintaining assets, including defining the frequency and type of maintenance activities needed to prolong asset life.	A structured asset maintenance strategy is essential for ensuring that maintenance activities align with the overall business objectives. It ensures that resources are utilised efficiently and helps make informed decisions about maintenance priorities.
Maintenance tactics, methods	This function includes the strategies and techniques employed to execute maintenance activities.	Adopting appropriate maintenance tactics directly impacts the effectiveness and cost-efficiency of asset management. Well-defined methods ensure maintenance is carried out efficiently, reducing downtime and optimising asset performance.
Maintenance work management	Encompasses the planning, scheduling, and execution of maintenance tasks, ensuring they are performed on time, while meeting budget limits, and in compliance with safety standards.	Efficient maintenance work management ensures minimal disruption to operations, improves service delivery, and reduces the risk of unplanned breakdowns. It is central to achieving maintenance goals and optimising workforce productivity.
Material and inventory management	This area manages spare parts, tools, and materials required for maintenance tasks, ensuring the right resources are available at the right time.	Effective material and inventory management ensures that maintenance activities are not delayed due to stock shortages, which can lead to extended downtime and increased costs. It helps streamline procurement and stock control processes.
Asset performance management	Focuses on monitoring and improving the performance of assets through data collection, analysis, and optimisation practices.	Monitoring asset performance is essential for identifying potential failures early, improving reliability, measuring the maintenance value-contribution and maximising asset uptime. Asset performance management drives informed decision-making, resulting in cost reductions, justifying investment and increased asset lifespan.
Sustainability	Sustainability in maintenance involves adopting practices that promote environmental stewardship, reduce energy consumption, and extend asset life through responsible management.	Sustainable practices reduce the environmental impact of maintenance operations and contribute to cost savings and regulatory compliance. As industries move towards greener solutions, sustainability in maintenance is becoming increasingly important.
Technology and information management	Involves integrating technological tools, systems, and data management practices to support maintenance activities, such as CMMS (Computerised Maintenance Management Systems), predictive maintenance tools, and data analytics.	Technology and information systems are pivotal in modern maintenance management, enhancing decision-making, reducing manual tasks, and enabling predictive maintenance strategies. This function supports timely decision-making, which leads to more efficient operations.
Maintenance policy and organisation	This area focuses on developing maintenance policies, procedures, and organisational structures that guide the execution of maintenance activities.	Clear policies and well-defined organisational structures ensure consistency in maintenance practices and accountability. It establishes the framework within which all

Functional area	Description	Reason for inclusion
		maintenance activities are carried out, ensuring alignment with strategic goals.
Business Strategy and Management	This functional area aligns maintenance objectives with the broader organisational strategy, ensuring that maintenance efforts support business goals such as cost reduction, production targets, and service quality.	Integrating maintenance with the business strategy ensures that maintenance priorities align with overall business objectives, optimising resource allocation and enhancing long-term organisational performance.
Leadership and culture	This area focuses on the leadership style, organisational culture, and employee engagement that support effective maintenance practices.	Strong leadership and a positive culture are essential for motivating employees, encouraging adherence to best practices, and driving continuous improvement in maintenance processes. Effective leadership ensures that maintenance strategies are implemented successfully across all levels.
Risk management	This function addresses identifying, assessing, and mitigating risks related to asset failure, safety hazards, and operational disruptions.	Maintenance practices must consider risk factors to minimise safety hazards, environmental impacts, and asset downtime. Risk management is crucial to ensuring the safety and continuity of operations and maintaining legal and regulatory compliance.
Quality Management	Involves ensuring that maintenance activities meet predefined quality standards and continuous improvement practices to enhance performance.	Quality management is integral to achieving high reliability and operational efficiency. It ensures that maintenance tasks meet required standards, reducing rework and improving long-term asset performance and durability.

8.4.7 Select the maturity levels

This study adopted a five-level maturity structure adapted from Paulk et al. (1993) as applied by Macchi and Fumagalli (2013a), CMMI (2019), Van der Merwe (2021) and Chigangacha et al. (2021b). The initial, managed, defined, managed, and optimising levels are organised sequentially, as illustrated in Figure 20. Maier et al. (2012) emphasised that maturity levels must be distinct, well-defined, and logically progressive to facilitate the straightforward interpretation of results, which guided their selection for this study.

Building on this foundation, maturity levels function as developmental milestones, offering a structured pathway for individuals, organisations, or systems to advance their capabilities systematically over time (Fernández and Márquez, 2012). Van Dyk (2013) further highlighted that maturity levels benchmark progress and support continuous growth towards higher levels of sophistication and operational excellence.

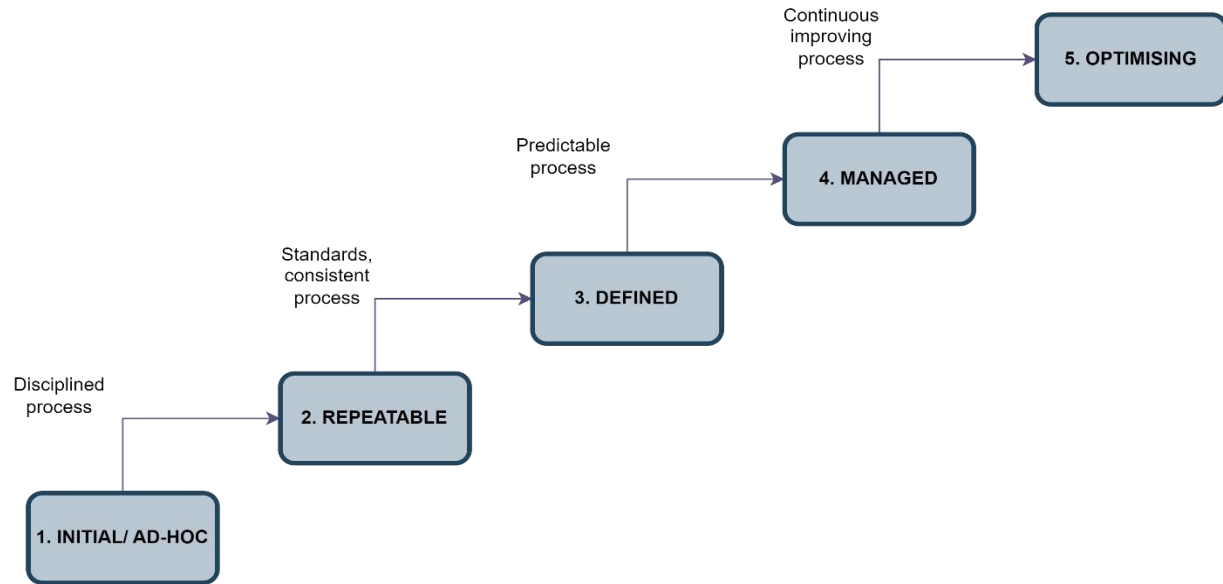


Figure 20: Maturity levels (Adapted from (Paulk et al., 1993))

In this research, the nomenclature and progression of maturity levels remained standardised and intuitive to ensure that decision makers and practitioners can easily interpret and apply them. This aligns with design requirement 5 (DR5), emphasising clarity and ease of understanding in the framework's design. Table 24 serves as the foundation for defining the premises associated with each maturity level.

Table 24: Maturity progression levels (Macchi and Fumagalli, 2013b, Muchiri et al., 2017)

Level	Description
Level 1: Initial	At this stage, awareness is limited, and processes or behaviours are often ad hoc and reactive. this stage represents an unpredictable process, which is unstable and disorganised. The outcome of the process depends on the practitioner's expertise.
Level 2: Repeatable and Reactive	This level introduces the establishment of basic structures and processes. Indicates a repeatable process that is performed consistently. The process is structured around predefined objectives and remains reactive primarily.
Level 3: Defined and Proactive	There is a clear understanding of goals and practices, characterised by a well-implemented program within the organisation. The process relies on established methods and technologies, with suitable measures to guide the process in a controlled manner.

Level	Description
Level 4: Managed	In this level, the emphasis shifts to metrics and data-informed decision-making. Here, the process is controlled with the use of quantitative techniques, including statistical analysis where appropriate. Maintenance objectives are reviewed through an understanding of the quantitative results, allowing for data-informed adjustments, continuous improvement, and better control over outcomes.
Level 5: Optimised	Continuous improvement is prioritised in alignment with strategic business goals. Established policies guide process quality management through the use of quantitative metrics and performance feedback for effective monitoring and control..

8.4.8 Formulating capability statements

Maier et al. (2012) introduced the concept of "cell text" to denote the intersection between process areas and maturity levels. In this study, the term "capability statements" is adopted, consistent with the usage by Van Dyk (2013) and Maisiri and Van Dyk (2020). According to Van Dyk (2013), a capability statement is defined as a generic articulation of a process characteristic corresponding to a specific maturity level. These statements function as benchmarks or descriptors, systematically guiding organisations through progressive stages of maturity (Maier et al., 2012). Thus, the capability statements serve as evaluative tools and actionable blueprints for organisational improvement.

Furthermore, capability statements must clearly describe process characteristics, with distinct differentiation between maturity levels Maier et al. (2012) . In alignment with this principle, this chapter's formulation of capability statements was directed by design requirements 9 and 10. These requirements were critical in maintaining support for the overarching design framework while producing capability statements that are both descriptive and prescriptive.

The initial step of developing the capability statements involved establishing the extremities of the maturity continuum, 'initial/ad hoc' as the lowest and 'optimising' as the highest maturity levels, for each process area or dimension. Defining these boundaries provided a logical framework from which the intermediate maturity levels could be systematically constructed. The capability statements are illustrated in Tables 33 and 34 (in Appendix C & D, respectively).

8.5 Conceptual model

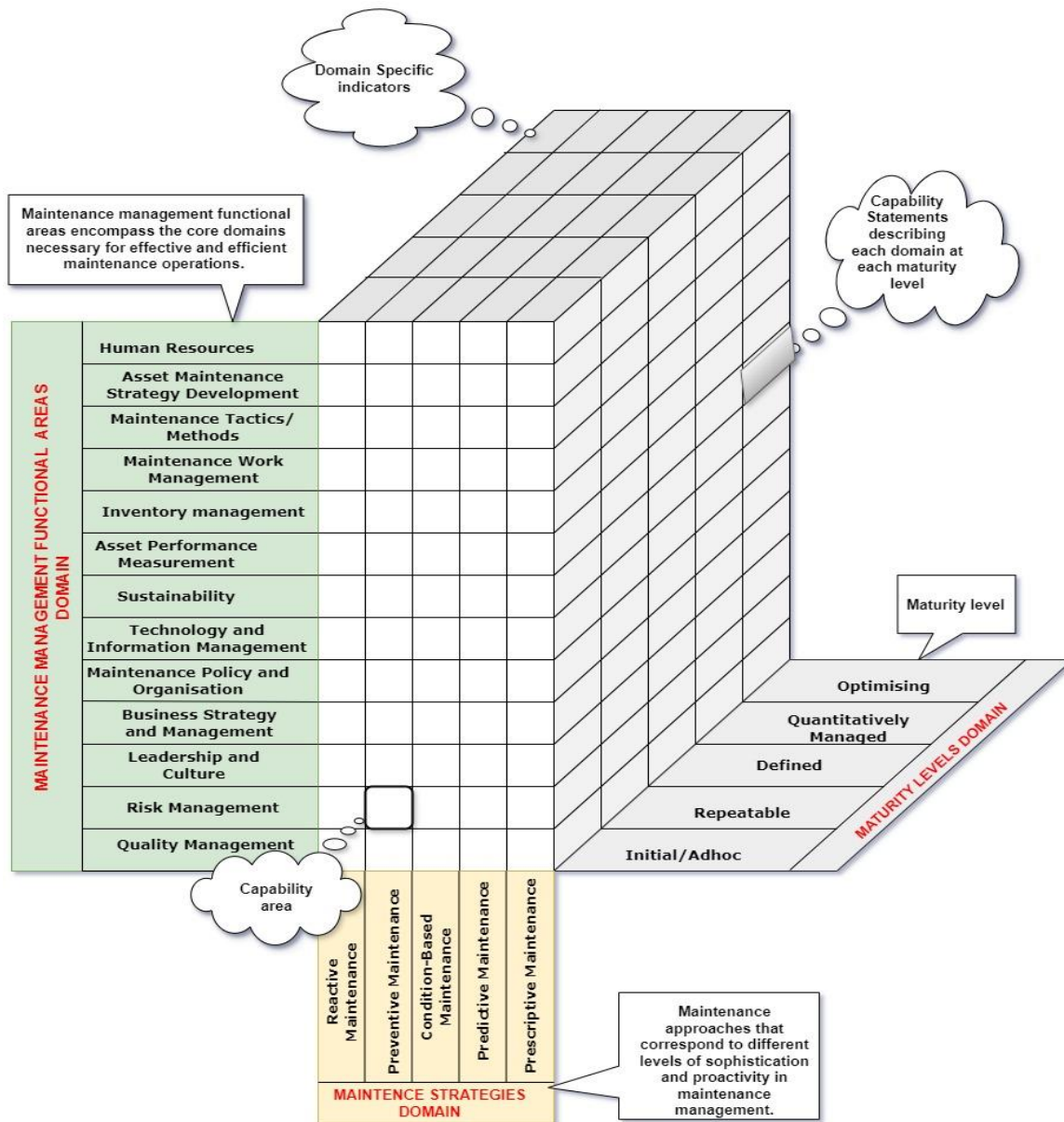


Figure 21: Conceptual MMM.

Figure 21 illustrates the structural design of the maintenance maturity model, represented as a three-dimensional prism. This configuration highlights the interconnectivity of the three identified process areas, emphasising their integrated and relational nature within the model's framework.

The subsequent stage in the development continuum involves the validation of the model, constituting the evaluation phase. This is undertaken to ensure that the model satisfactorily meets

the defined design requirements. Hevner et al. (2004) emphasise that evaluating all intermediary artefacts must employ rigorous scientific methods. Furthermore, Maier et al. (2012) highlighted that, ideally, such evaluation should be conducted by individuals independent of the model's development to ensure objectivity.

Tables 33 and 34 (in Appendix C & D, respectively) offer an applied perspective on assessing performance measurement and human resources capability functions, presenting capability statements aligned to each maturity level. While these tables serve to illustrate the operational dynamics of the maintenance maturity model, they are selected to represent, not to cover the entirety of, the broader developmental landscape necessary for a fully realised model.

8.6 Conclusion

This chapter outlined the design process of the proposed model for prioritising water infrastructure maintenance. It addressed objective (d), as defined in section 1.5, by detailing the development of the model. Chapter 9 will focus on the evaluation stage, as described in section 8.2, where the model's validity will be assessed.

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CHAPTER 9: REFINING AND VALIDATING THE MAINTENANCE MATURITY MODEL: DELPHI PROCESS

9.1 Introduction

The maintenance maturity model (MMM) development followed a systematic process involving the diagnosis and validation of the research problem, the establishment of design requirements, and the subsequent development and validation of the model. This process was guided by the elaborated action design research (eADR) methodology, which facilitates continuous learning and iterative evaluation throughout the development and refinement of the design solution (Mullarkey and Hevner, 2019). A key strength of the eADR approach lies in its capacity to integrate verification and validation within the design process, thereby strengthening the model's theoretical and practical underpinnings.

To validate the MMM, this study adopted the Delphi technique. The Delphi method has been widely employed to support the development and validation of various artefacts, including models that rely on informed judgment and domain-specific expertise (Fink-Hafner et al., 2019, Ogbeifun et al., 2016). Numerous researchers, such as Kagias et al. (2023), McLean et al. (2023), Ziam et al. (2023), Martinek-Jaguszewska and Rogowski (2023), Almaiah et al. (2022), Liyanage and Chinedu (2023), Głuszek (2021), and Smarandache et al. (2020), have successfully utilised this technique to validate artefacts, further demonstrating its relevance and robustness. Accordingly, the Delphi technique was deemed appropriate for the development and validation of the MMM.

Validation, in this context, refers to assessing whether a tool is fit for its intended purpose (Petty, 2009). The Delphi method is a structured and iterative approach aimed at reaching expert consensus through successive rounds of questionnaires and feedback (Fink-Hafner et al., 2019). Through the systematic elicitation and refinement of expert opinions, the method enhances the credibility and dependability of the findings, ensuring the final model adequately addresses the core research problem.

The Delphi technique offers several advantages that make it particularly suitable for validating complex frameworks. It facilitates independent and anonymous expert participation, thereby minimising the risk of groupthink and encouraging candid input (Fink-Hafner et al., 2019). Furthermore, the iterative structure allows for the refinement of viewpoints, fostering the gradual development of consensus. Its adaptability across various disciplines, including healthcare

(Cocchieri et al., 2021) and technology development (Yogarajah et al., 2020), further underscores its methodological utility.

Despite its strengths, the technique is not without challenges. Potential issues such as expert attrition, prolonged timeframes, and the necessity for well-constructed and engaging questionnaires must be carefully managed to ensure the integrity of the process (Fink-Hafner et al., 2019). Nevertheless, the method remains a valuable and credible tool in research, particularly when validating models that require expert judgement.

The decision to adopt the Delphi technique in this study was underpinned by several key considerations outline below (Fink-Hafner et al., 2019, Skulmoski et al., 2007a):

- Facilitate the development of consensus across multiple rounds;
- Enable remote participation from geographically dispersed experts;
- Explore novel frameworks for which empirical evidence is limited;
- Ensure anonymity, thereby promoting open and honest expression of opinions;
- Allow participants to revise and refine their views as the process unfolds.

The chapter is structured as follows:

- Section 9.2 presents the research methodology, detailing the Delphi study process, participant selection criteria, and consensus measurement techniques used to validate the framework.
- Section 9.3 presents the results and findings of the Delphi rounds, emphasising key areas of expert consensus and outlining the final maintenance maturity model, which was iteratively refined to incorporate expert feedback throughout the process.
- Section 9.4 outlines the implications of the Delphi study outcomes used to refine and validate the maintenance maturity model (MMM), highlighting their alignment with existing literature and practical relevance to maintenance prioritisation in infrastructure.
- Section 9.5 concludes the Delphi study with recommendations for future research and practical implementation strategies.

9.2 Methodology

The study was structured as an iterative Delphi process, purposefully designed to continue through successive rounds until consensus was reached among the expert panel. This section outlines the methodological approach adopted for the Delphi study, detailing the rationale for selecting the Delphi method, the expert panel selection process, the design of each round, the data collection procedures, and the techniques used to analyse responses and determine consensus. The methodological rigor was maintained to ensure that the resulting model reflects collective expert judgement, particularly in the context of maintenance maturity and prioritisation within asset-intensive industries. The approach emphasises anonymity, structured feedback, and the statistical synthesis of participants' responses (Smarandache et al., 2020) to reduce the influence of dominant individuals and encourage unbiased input across multiple rounds.

9.2.1 Selection of panel of experts

A purposive sampling strategy was employed to identify and select panel experts, in alignment with the Delphi principles. Purposive sampling was used in this study to ensure the involvement of participants whose expertise is relevant to the subject of the study, thereby enriching the depth and relevance of the findings (Bhardwaj, 2019). To further expand the participant pool, a snowball sampling technique was utilised as guided by Taherdoost (2016), wherein existing participants were encouraged to recommend other potential experts meeting the inclusion criteria. This approach was guided by recommendations from Baltes and Ralph (2022) and Bhardwaj (2019), who provide comprehensive guidelines on sampling techniques. The combined use of purposive sampling and snowball sampling ensured that the study benefited from the expertise of a highly qualified panel while overcoming recruitment challenges.

The Delphi method, renowned for its structured approach to eliciting and refining expert opinion, does not prescribe a fixed panel size (Skulmoski et al., 2007a). Nevertheless, in cases involving a relatively uniform panel of participants, a panel size of ten to fifteen members is normally deemed effective (Kagias et al., 2023, Skulmoski et al., 2007a). Importantly, the strength of the Delphi technique lies not in the number of participants, but in the relevance and expertise they bring to the study. Norani et al. (2012) emphasised that the credibility of the method is rooted in the quality of the expert panel rather than its size.

In line with this, 30 invitations were extended to experts in the field of infrastructure asset maintenance. Of these, 14 agreed to participate, resulting in a response rate of 46.7%. The first-

round questionnaire was subsequently distributed to these participants, with 10 completing the round—yielding a 71.4% response rate. This level of engagement is consistent with earlier Delphi studies conducted by Norani et al. (2012), Cocchieri et al. (2021), and Esmaeili (2023), all of which successfully employed smaller yet carefully selected panels to generate meaningful and robust findings.

To further strengthen the study, the panel was intentionally composed of a diverse cohort of maintenance professionals drawn from various industry sectors and academic institutions, as illustrated in Figure 22. The deliberate inclusion of such diversity aimed to ensure the representation of a wide range of perspectives, thereby enriching the overall validity and comprehensiveness of the research.

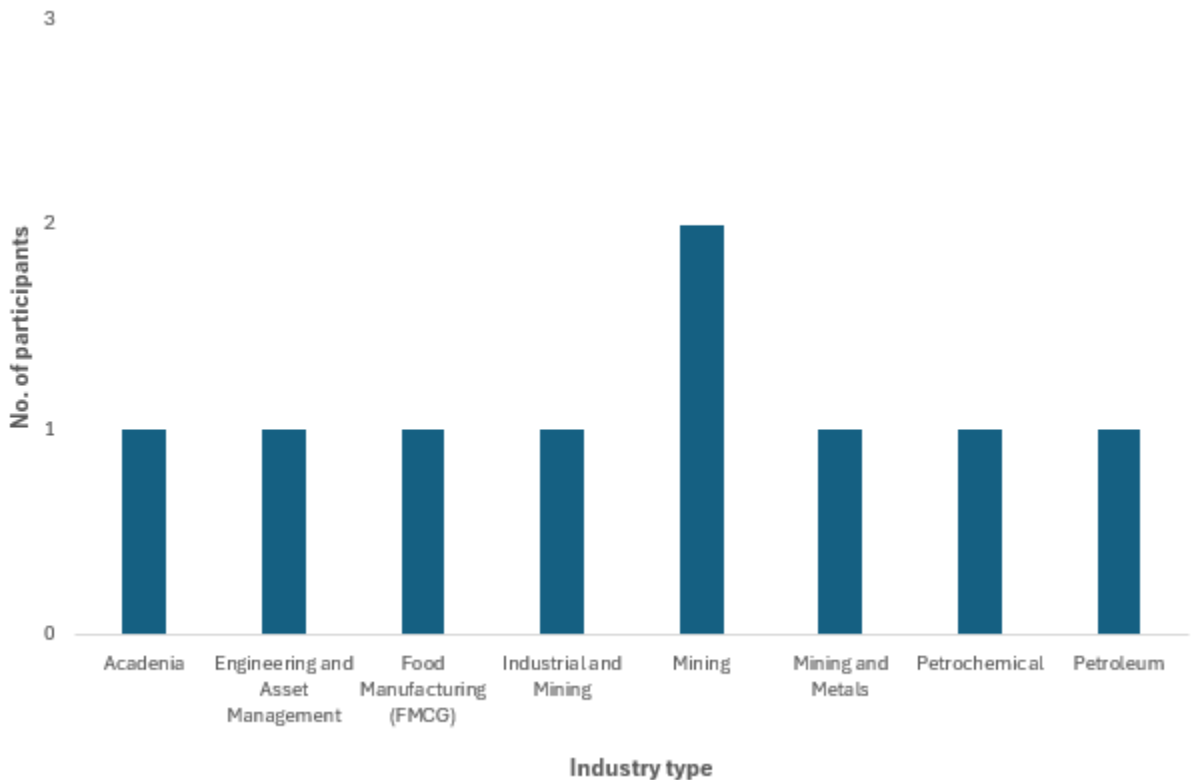


Figure 22: Distribution of “What type of industry does your organisation belong to?”

According to Reeb (2023), the selection of experts for a Delphi study should prioritise domain-specific knowledge, professional experience, and meaningful contributions to the relevant field. In alignment with this, the selection of participants in the present study was guided by the criteria proposed by (Skulmoski et al., 2007a), who emphasise the following key considerations:

- i. At least five years of proven experience and domain expertise in infrastructure asset maintenance;
- ii. A demonstrated willingness and commitment to partake in the study actively;
- iii. Sufficient availability to meaningfully contribute throughout the research process
- iv. Strong communication competency to effectively engage in discussions and provide clear insights..

The incorporation of such a diverse and qualified expert panel was instrumental in capturing a holistic view of the subject under study. This approach, consistent with the recommendations of (Skulmoski et al., 2007a), contributes to the academic rigour of the study by ensuring that findings are informed by a breadth of practical and theoretical insights.

The experience levels of the participants varied, with Figure 23 showing that 78% of them possessed at least 11 years of experience in the field.

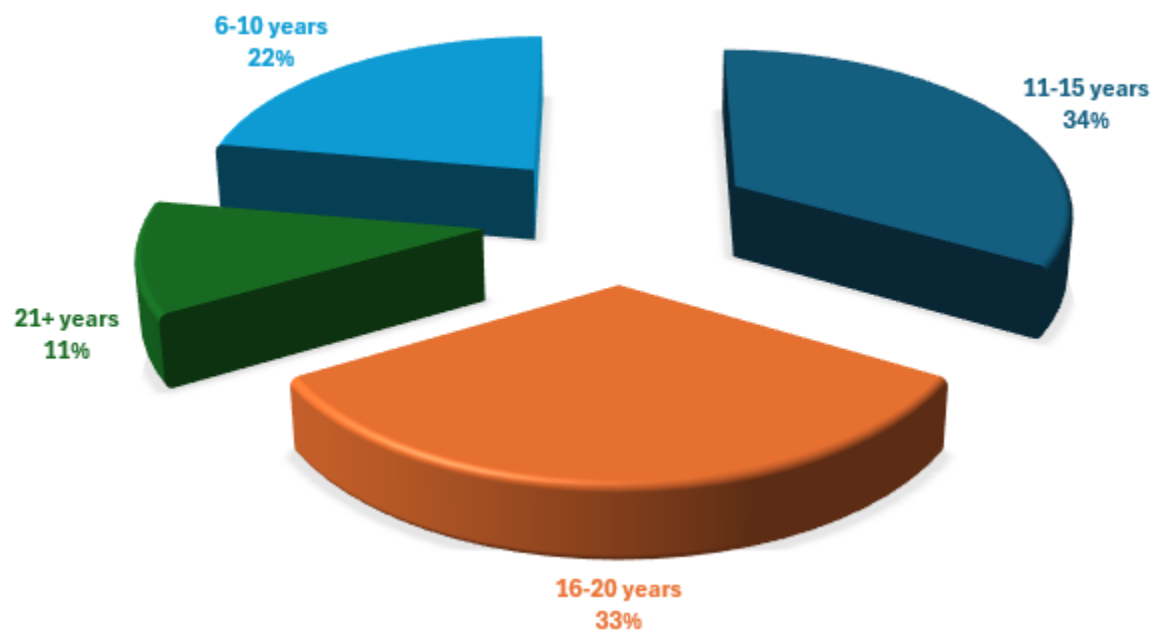


Figure 23: Years of experience in Maintenance/Asset Management:

To ensure transparency and enable traceability of insights, especially when using direct quotations from participants, each expert was assigned a unique identifier (e.g., P1, P2, P3...) for use throughout the study. These identifiers are used to anonymise responses while still allowing

readers to track consistency and divergence of opinions across different Delphi rounds. Table 25 summarises the profile of the selected panel members.

Table 25: Summary of expert panel composition and assigned participant identifiers

Unique ID	Years of Experience	What type of industry does your organization belong to	Role?
P1	11-15 years	Engineering and Asset Management	Senior Reliability Engineer
P2	11-15 years	Mining	Asset manager
P3	16-20 years	Mining	Maintenance Engineer
P4	16-20 years	Food Manufacturing (FMCG)	Engineering Manager
P5	11-15 years	Academia	Snr Lecturer
P6	6-10 years	Industrial and Mining	Senior Reliability Engineer
P7	16-20 years	Petroleum	Regional maintenance manager
P8	21+ years	Petrochemical	Senior Manager
P9	6-10 years	Mining and Metals	Reliability Engineer
P10	6-10 years	Manufacturing	

9.2.2 Construction of the questionnaire

The design of the Delphi study questionnaire was carefully developed to elicit both quantitative and qualitative feedback from participants, ensuring a comprehensive evaluation of the maintenance maturity model (MMM). Drawing from the established methodological guidance of Hsu and Sandford (2007), Skulmoski et al. (2007a) and Norani et al. (2012), the questionnaire incorporated two distinct types of questions:

- **Quantitative questions** were included to measure the degree of agreement with specific statements relating to the model's attributes, such as clarity, relevance, and practicality. These items employed a Likert scale (e.g., 1 to 5, where 1 = strongly disagree and 5 = strongly agree), allowing for the systematic aggregation and comparison of expert opinion.
- **Qualitative questions** were designed at the end of each section to capture open-ended responses, encouraging participants to provide detailed reflections, suggestions, and critiques. This qualitative input was critical in identifying ambiguities, gaps, and areas in need of refinement, thereby complementing the quantitative findings with nuanced insights.

The questionnaire (Appendix E) was structured around the core components of the MMM: the research problem, design requirements, and conceptual structure. In round 1 of the Delphi study,

participants evaluated key statements (see Table 32, Appendix B) addressing these elements. Their feedback offered critical insights into clarity, relevance, and alignment with the objectives of the study, guiding refinements and strengthening the model's validity for subsequent rounds.

9.2.3 Administration of the questionnaire

The questionnaire was administered through a structured google form. Each participant received an email containing a direct link to the questionnaire, explaining the instructions and the estimated completion time of 25-30 minutes.

A strategic follow-up was implemented to maximise response rates and ensure comprehensive data collection. After two weeks, those who had not completed the survey were gently reminded through a second email. This approach aimed to boost participation by reminding individuals of their initial interest and the importance of their input. Balancing informative outreach with respectful reminders, the survey sought to gather robust data while maintaining an ethical and participant-focused approach.

After completing the 1st round of the survey, the results and feedback were systematically tabulated and analysed. A follow-up email was sent to participants whose comments lacked clarity or specificity in highlighting concerns or suggestions. For example, one participant noted, *"Some aspects can be amalgamated and grouped into subsections,"* without specifying which aspects or subsections they were referring to. The email politely requested further elaboration to ensure that all feedback can be accurately considered and integrated into the study.

In subsequent rounds, the results from the previous round were summarised and shared with the participants, along with any new questions or modifications to the survey based on initial feedback. This iterative process allowed for the refinement of the model based on the consensus of the expert group (Skulmoski et al., 2007b, Fink-Hafner et al., 2019).

9.2.4 Defining consensus

The Delphi method is primarily employed to facilitate the development of expert consensus. This study defined consensus as achieving a minimum of 75% agreement on a given item, as measured using a 5-point Likert scale. This threshold was interpreted as an average rating of 3.75 and above (Norani et al., 2012, Chetouani, 2022). When this level of agreement was not reached, qualitative analysis of participants' comments was conducted to figure out the reasons underlying

the divergence in expert opinion. These insights were used to clarify ambiguous items and refine the wording of statements to promote clearer interpretation and mutual understanding.

While participant feedback played a vital role in enhancing the clarity and relevance of the items, the overarching aim remained the convergence of expert judgment. Revisions to the questionnaire in subsequent rounds were therefore guided by the need to improve item clarity and alignment with the collective perspective, thereby increasing the likelihood of consensus in later iterations.

9.2.5 Ensuring credibility of the Delphi study

To enhance the credibility of the Delphi study findings, several methodological safeguards were implemented, drawing inspiration from Reeb (2023):

- **Expert validation:** Selecting a well-qualified expert panel ensured that the study findings were grounded in industry best practices and theoretical rigor.
- **Anonymity:** Maintaining anonymity among participants mitigated potential groupthink and response biases, ensuring that opinions were expressed independently.
- **Iterative refinement:** The structured feedback loop between rounds allowed for progressive improvement in the clarity and accuracy of the model.
- **Controlled feedback:** Participants were provided with anonymised summaries of collective feedback from previous rounds, preventing dominant voices from unduly influencing the process.

9.2.6 Ethical considerations

The study was carried out following the guidelines of, and with approval from, the North-West University Engineering Research Ethics Committee (NWU-ENGREC), under ethics clearance number: NWU-00232-23.A3. The ethical clearance certificate is in the appendix (Appendix I) for reference.

9.3. Results and Findings

This section presents the results and findings from the Delphi study, structured into two rounds. The study aimed to reach expert consensus on the maintenance maturity model by refining and validating its attributes. A total of 10 participants responded in the first round, while 8 participants

contributed to the second round. Consensus was achieved in the second round, indicating a convergence of expert opinions. This section details the feedback progression, the evolution of consensus, and the critical insights derived from the study.

9.3.1 Round one results

The first round sought to capture initial expert perspectives on the proposed maintenance maturity model, assessing its sufficiency, accuracy, and relevance. Participants provided both quantitative ratings and qualitative feedback, which were analysed to identify key themes and areas requiring further refinement. This section presents the results of the quantitative feedback from the participants.

9.3.1.1 Research problem validity

To assess the validity of the research problem, participants were asked to indicate their level of agreement with a series of statements and questions presented in Table 26, using a 5-point Likert scale ranging from 'Strongly Disagree' to 'Strongly Agree.' This process aimed to evaluate the perceived clarity, relevance, and significance of the research problem from the perspective of domain experts.

Table 26: Research problem validity questions

	SURVEY STATEMENTS	
RESEARCH PROBLEM VALIDITY	Q1	There is an urgent need for the development of comprehensive maintenance frameworks that are flexible and responsive to the dynamic challenges faced by asset-intensive sectors like water utilities, to mitigate breakdown occurrences.
	Q2	Ineffective maintenance strategies contribute to resource misallocation, further exacerbating infrastructure failures and undermining operational efficiency.
	Q3	The persistence of ad-hoc maintenance practices within many organisations indicates a cultural resistance to change, which is detrimental to long-term operational sustainability and needs to be addressed through effective change management strategies.
	Q4	Maintenance personnel in South Africa's asset-intensive industries- public sector; lack the adequate training and competency to implement effective infrastructure maintenance strategies.
	Q5	There are insufficient mechanisms for regularly monitoring and evaluating maintenance plans for physical infrastructure assets.
	Q6	The recurring nature of infrastructure failures highlights systemic deficiencies in maintenance practices, necessitating a comprehensive re-evaluation of existing frameworks to foster resilience and reliability.

There was no consensus among experts regarding the validity of some of the research problem statements, as illustrated by the mean ratings in Figure 24. Hence, the study took a collaborative

approach by incorporating expert suggestions within its scope and re-evaluating the validity in the 2nd round of the survey.

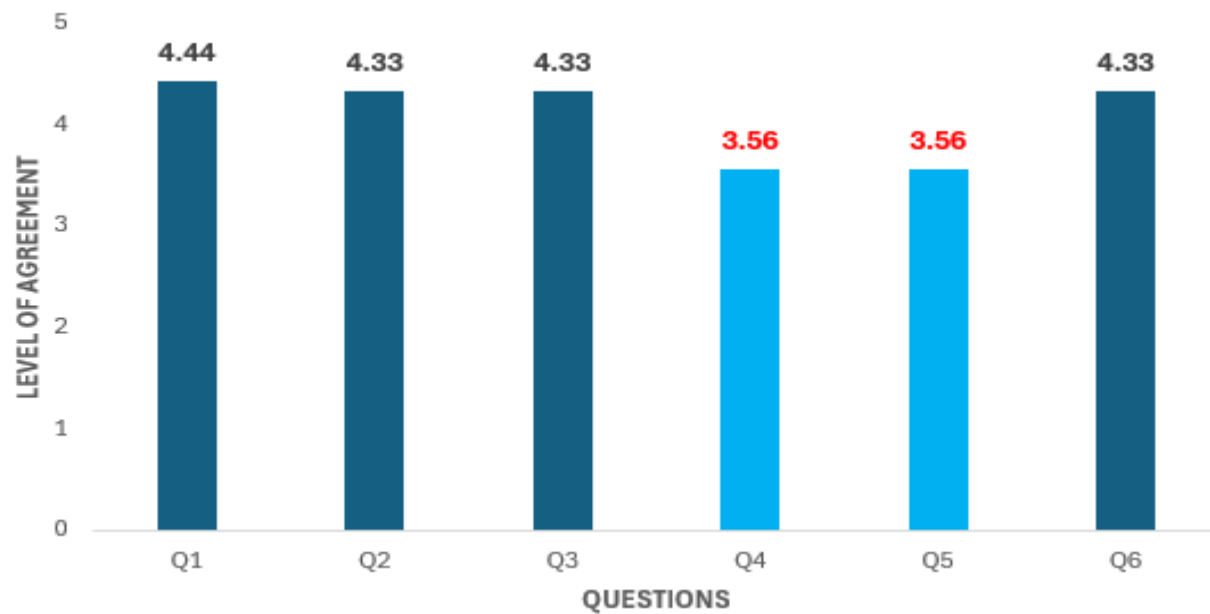


Figure 24: Research problem validation mean ratings

9.3.1.2 Design requirements validity

In the first round of the questionnaire, participants were requested to rate their level of agreement on the adequacy of the design requirements (outlined in Table 27) in directing the development of the model.

Table 27: Design requirements validity questions

SURVEY STATEMENTS		
DESIGN REQUIREMENTS VALIDATION	Q7	The design requirements for the model are articulated clearly, ensuring they are specific and easily interpretable by all stakeholders involved in the Delphi study.
	Q8	The design requirements emphasise the importance of continuous improvement in maintenance practices, guiding the development of a Maintenance Maturity Model that encourages organisations to assess their current capabilities and implement strategies for ongoing enhancement.
	Q9	The design requirements comprehensively address the essential elements necessary to guide the development of the Maintenance Maturity Model, making it relevant and beneficial for both industry practitioners and academic researchers in the field of maintenance management.
	Q10	The design requirements adequately outline the foundational criteria needed to create a Maintenance Maturity Model that can effectively evaluate and direct the identification and development of maintenance competencies and practices within asset-intensive industries.

There was a strong consensus among experts regarding the validity of the design requirement statements, as evidenced by the mean ratings, which were significantly above 3.75, as shown in Figure 25. Hence, the design requirements statements were excluded in the second round of the study.

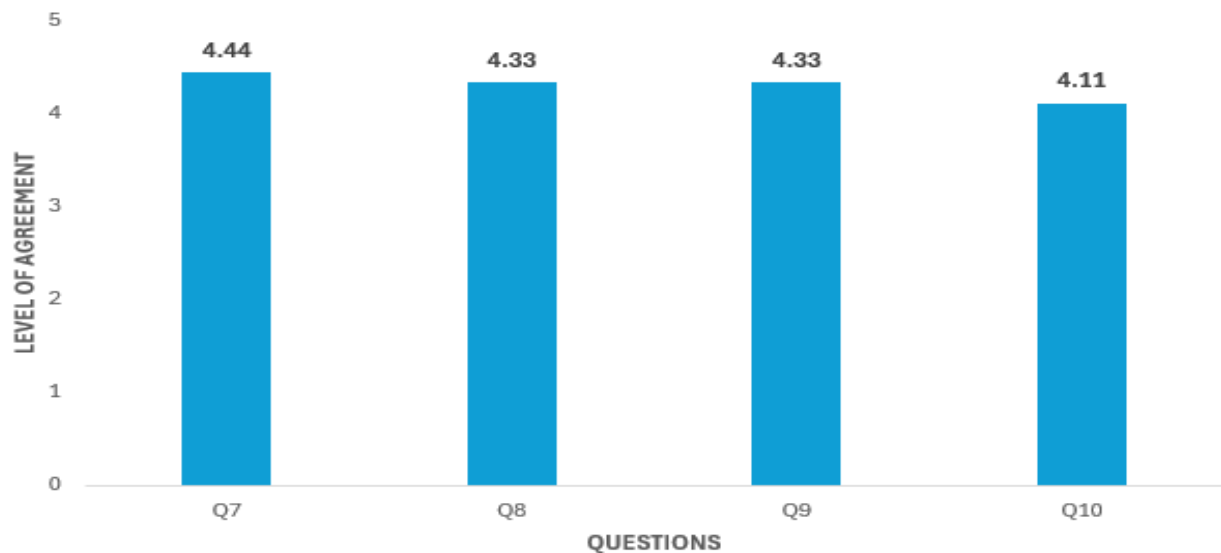


Figure 25: Design requirements validation mean ratings

9.3.1.3 Conceptual model validity

To assess the conceptual model's validity, participants were asked to indicate their level of agreement with a series of statements designed to evaluate various aspects of the model. As outlined in Table 28, these statements aimed to measure dimensions such as the model's clarity, comprehensiveness, sufficiency, accuracy, relevance, and practical usefulness.

Table 28: Conceptual model validity questions

CONCEPTUAL MODEL VALIDATION	SURVEY STATEMENTS	
	Q11	The conceptual model is clearly articulated and easily understood by participants?
	Q12	The maintenance strategies dimensions are appropriate and relevant?
	Q13	The functional areas domain accurately and sufficiently reflects maintenance operations and management practices?
	Q14	The maturity levels dimension is sufficient to provide a holistic evaluation of an organisation's maturity stages within each domain?
	Q15	The dimensions within the model are distinct and do not overlap, ensuring clear differentiation between maturity levels?
	Q16	The conceptual model accurately reflects the reality of maintenance practices in the field and is based on sound theoretical foundations.

	SURVEY STATEMENTS	
	Q17	The conceptual model is user-friendly and can be easily implemented by organisations to assess and enhance their maintenance strategies?
	Q18	The insights that can be gained from applying the model are actionable and provide valuable guidance for organisations seeking to improve their maintenance maturity.
	Q19	The conceptual model is practical for conducting assessments and flexible enough to accommodate the diverse needs and contexts of different organisations within asset-intensive industries?
	Q20	The Maintenance Maturity Model offers a practical framework to enhance infrastructure maintenance practices in the water utilities industry

In the initial round of evaluating the maintenance maturity model, no consensus was reached among experts regarding the adequacy of its conceptual structure, with Q11, Q17 and Q19 falling below the threshold consensus margin as outlined in Figure 26.

This disparity in opinions might have stemmed from differing perspectives, experiences, or expectations regarding the model's components and their applicability. This lack of agreement highlighted the need for further refinement and revision of the model. The experts' feedback was carefully considered and incorporated into developing a round 2 questionnaire to address the concerns and suggestions raised.

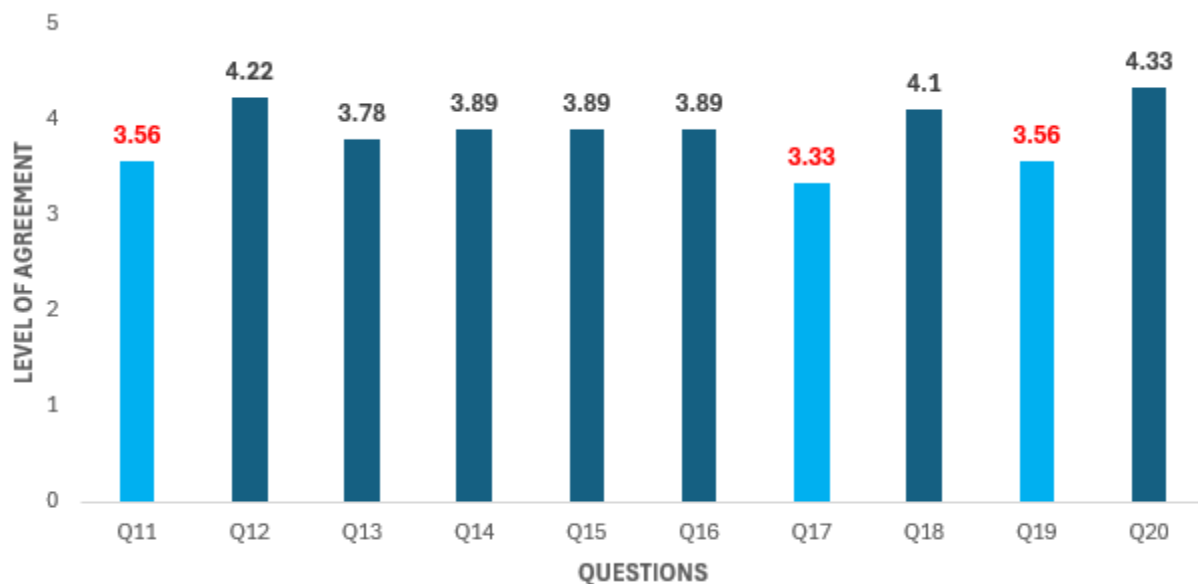


Figure 26: Conceptual model validation mean ratings

9.3.2 Round one findings

The experts qualitative feedback in round one was systematically analysed qualitatively as guided by Braun and Clarke (2006)'s thematic approach as presented in this section. This approach

enabled a nuanced understanding of expert perspectives and guided targeted revisions to the questionnaire content. This process ensured a rigorous and methodologically sound interpretation of the data, informing the development of the round 2 questionnaire.

9.3.2.1 Scope Definition

The analysis revealed strong consensus among participants (87%) regarding the relevance of statement Q20: *“The maintenance maturity model offers a practical framework to enhance infrastructure maintenance practices in the water utilities industry.”* This high agreement affirmed the perceived utility of the MMM in addressing infrastructure maintenance within the sector. However, participants indicated that the framework’s generalised design could be problematic when applied across multiple industries, each governed by distinct standards, compliance requirements, and operational contexts. The following illustrative excerpts capture this concern:

“I think the design requirements are well defined and complete for a holistic overview of the development of the maintenance maturity model. I do think however the topic is very broad in that it looks at the various industries maintenance topics. You will find that each sector has governing standards, rules and requirements from an asset management point of view that might make a generalized model a bit tricky to complete,” P6

“The broad scope of the model to include for the various types of industries with different standards and requirements” P6

These insights were categorised under the theme of sector-specific relevance. Consequently, the research problem was revised to focus specifically on water infrastructure:

Frequent breakdowns in water infrastructure, caused by inadequately structured and adaptable maintenance plans and strategies, significantly hinder the provision of uninterrupted service delivery.

This revised framing provided a more accurate reflection of the challenges targeted by the MMM and enhances the contextual relevance of the study. Furthermore, statements Q4 and Q5 were reworded to improve alignment with the specific challenges experienced in the water utilities sector:

Revised Q4: *Maintenance personnel in South Africa's water utilities lack specialised training and competency, hindering the implementation of effective maintenance strategies for water infrastructure.*

Revised Q5: *There are inadequate mechanisms in place for the regular monitoring and evaluation of maintenance plans specifically tailored for water infrastructure assets*

These changes ensured clarity and contextual fit, eliminating the ambiguity present in earlier versions of the statements.

9.3.2.2 Ease of understanding

Thematic analysis also highlighted significant concerns regarding the comprehensibility of the model. In particular, low ratings for Q1 signalled difficulties in understanding the MMM's three-dimensional structure, an aspect that distinguishes it from more conventional two-dimensional models. This finding aligns with the views of De Bruin et al. (2005), who stress that conceptual models must maintain a balance between theoretical complexity and user simplicity.

To address this, a comprehensive explanatory overview of the model's domains and dimensional structure was developed and sent to participants along with the round 2 questionnaire. This addition aimed to improve participants' cognitive engagement with the model and enhance the ease of understanding, particularly for non-academic stakeholders.

9.3.2.3 Further areas for improvement

Responses to the question: *"What challenges do you foresee in implementing this model in an organisation?"* revealed three dominant themes: the need for training and capacity building, the necessity for top management buy-in, and difficulties in understanding asset management principles. The following illustrative excerpts capture this concern:

"Organisational culture - resistance to change" P3;

"Most organisations do not have maintenance strategists, they understaff and managers or supervisors then prefer to use or default to Breakdown maintenance. they will not devote time to analysis tools" P4;

"Lack of top management buy in or lack of understanding, so benefits should be shared in a top bottom manner" P7;

"Difficult to grasp and understand if asset management is a new concept" P9

Based on this, Q17 was revised to explicitly acknowledge the importance of training and support as prerequisites for effective model implementation:

Revised Q17: *With appropriate training and support, the conceptual model is user-friendly and can be effectively implemented to assess and enhance maintenance strategies.*

9.3.2.4 Elimination of redundancy

Lastly, a critical review of questionnaire content using principles of parsimony and non-redundancy revealed that statement Q19 lacked specificity and overlapped with both Q17 and Q20. In line with best practices in survey design, Q19 was omitted from round 2. The rationale for this decision was twofold:

1. **Generality:** Q19 attempted to cover multiple aspects of the model in one statement, making it difficult to evaluate precisely.
2. **Thematic redundancy:** The key themes addressed in Q19 were already covered more effectively in the revised Q17 and Q20.

The outcomes of thematic analysis and the modifications made are summarised in Table 29.

Table 29: Summary of thematic analysis and revisions to round 2 questionnaire

Theme	Participant feedback	Action taken / revision made
Sector-specific relevance	"The topic is very broad in that it looks at the various industries' maintenance topics..." "Different industries have different standards and requirements."	Narrowed scope from general industry coverage to focus specifically on water infrastructure maintenance.
Alignment of problem statements	General research problem statements were too broad and lacked specificity regarding water utilities.	Revised research problem statements to focus on frequent breakdowns in water infrastructure due to poor maintenance strategies.
Clarity of problem statements	Original Q4 and Q5 were not clearly aligned with the context of water infrastructure.	Reworded Q4 and Q5 to reflect challenges specific to water utilities maintenance.
Ease of understanding	Q1 received low ratings due to complexity; the three-dimensional model was difficult to grasp.	Developed a detailed explanatory appendix (Appendix 2) outlining domains and structure of the model.
Training and implementation support	Concern over implementation challenges: need for training, limited asset management understanding.	Revised Q17 to acknowledge that model usability depends on appropriate training and support.
Redundancy and generalisation	Q19 is considered too broad and overlaps with Q17 and Q20.	Q19 was omitted from the round 2 questionnaire to improve clarity and reduce redundancy.

9.3.3 Round two results and findings

Based on the results obtained from the first round, participants were subsequently presented with the second-round questionnaire, as outlined in Appendix G. The second round incorporated the collective feedback from the initial phase, presenting participants with a refined set of statements and definitions based on their prior inputs. This phase aimed to test the level of agreement on key aspects of the maturity model and resolve any remaining ambiguities. Additionally, qualitative comments were solicited to capture any suggestions or concerns. The results from round two demonstrated improved alignment among experts.

9.3.3.1 Research problem validity

Figure 27 presents the mean ratings collected in the second round concerning the validity of the research problem. This data provides an insight into how participants perceive the relevance and coherence of the research issue addressed.

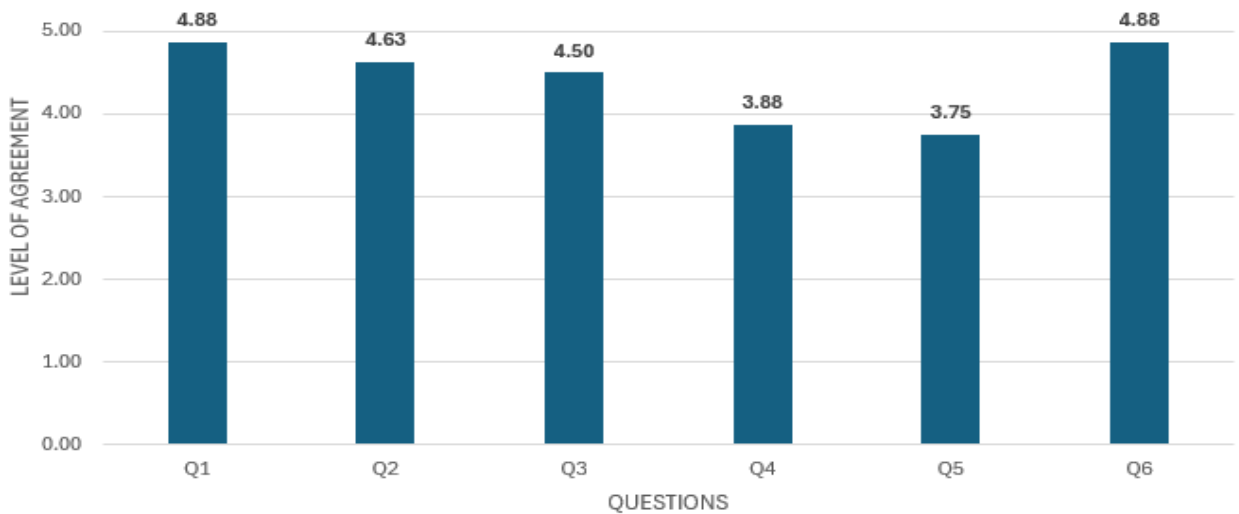


Figure 27: Research problem validity: Round 2 mean ratings

Figure 28 compares ratings from round 1 and round 2 on the validity of the research problem, highlighting a noticeable increase. This upward trend suggests that the modifications or refinements made between the two rounds were well-received by participants. The overall improvement in scores across all attributes indicates a strengthened consensus, particularly in areas where notable discrepancies were observed in round 1.

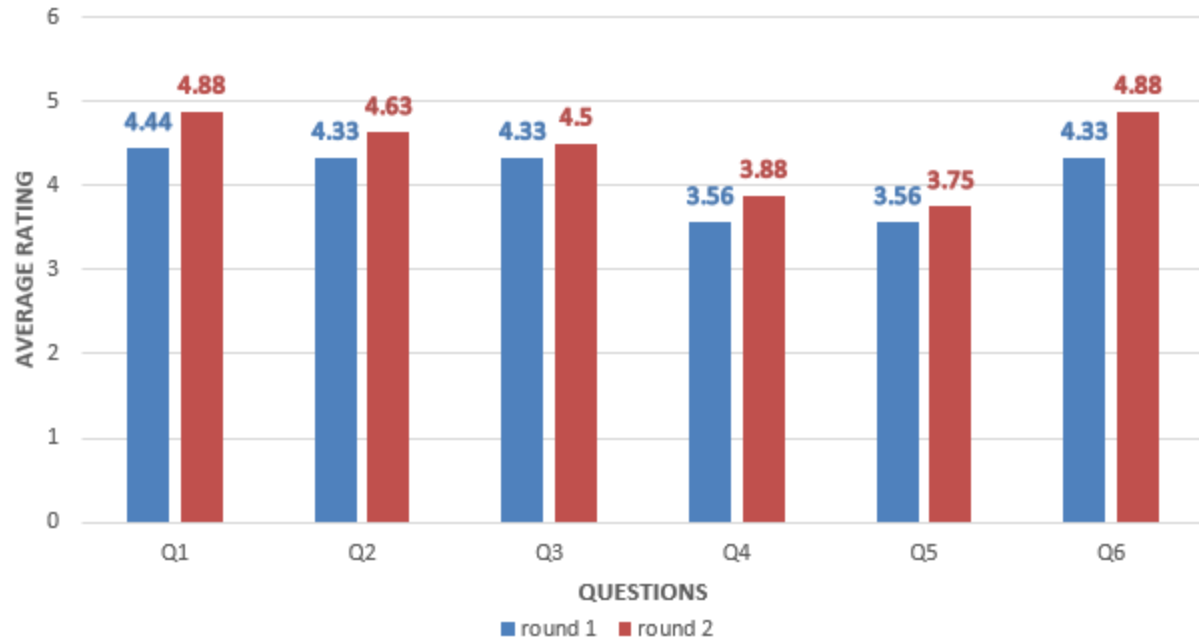


Figure 28: Research problem validity: round 1 vs round 2

9.3.3.2 Conceptual model validation

Similarly, Figure 29 illustrates a comparison of ratings between round 1 and round 2 regarding the validity of the conceptual model structure.

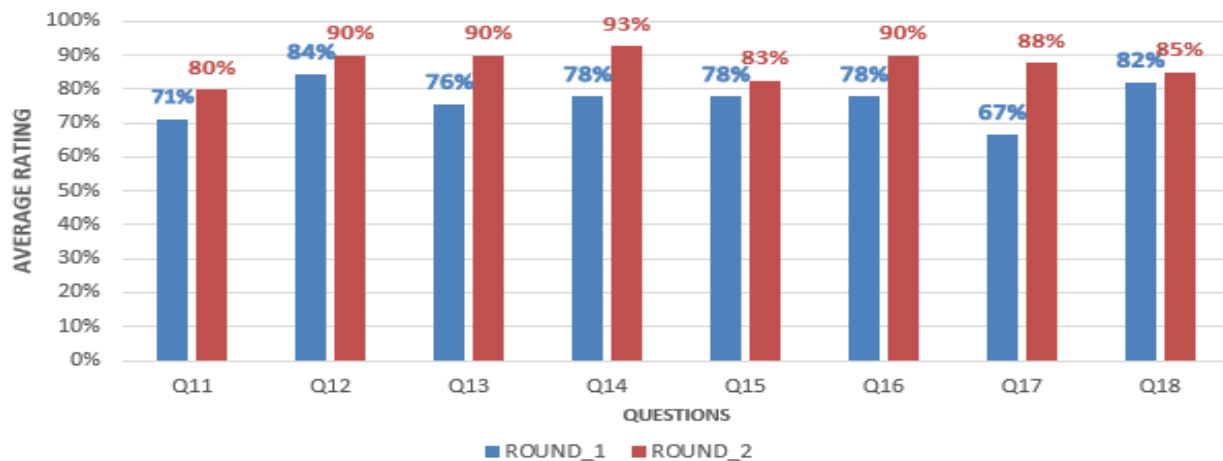


Figure 29: Conceptual model validation: round 1 vs round 2

The results show a notable improvement in round 2, where all the statements achieved consensus among the participants. This indicates a strengthened agreement on the conceptual framework's validity, suggesting that any initial ambiguities or disagreements were effectively addressed

between rounds. The progression demonstrates a refinement and solidification of understanding, likely due to the iterative feedback process. This led to a more robust and universally accepted model structure by the end of round 2.

Following the completion of round 1 of the Delphi study, expert feedback was carefully analysed. The responses indicated no substantive concerns regarding the conceptual model's design components or structural composition.

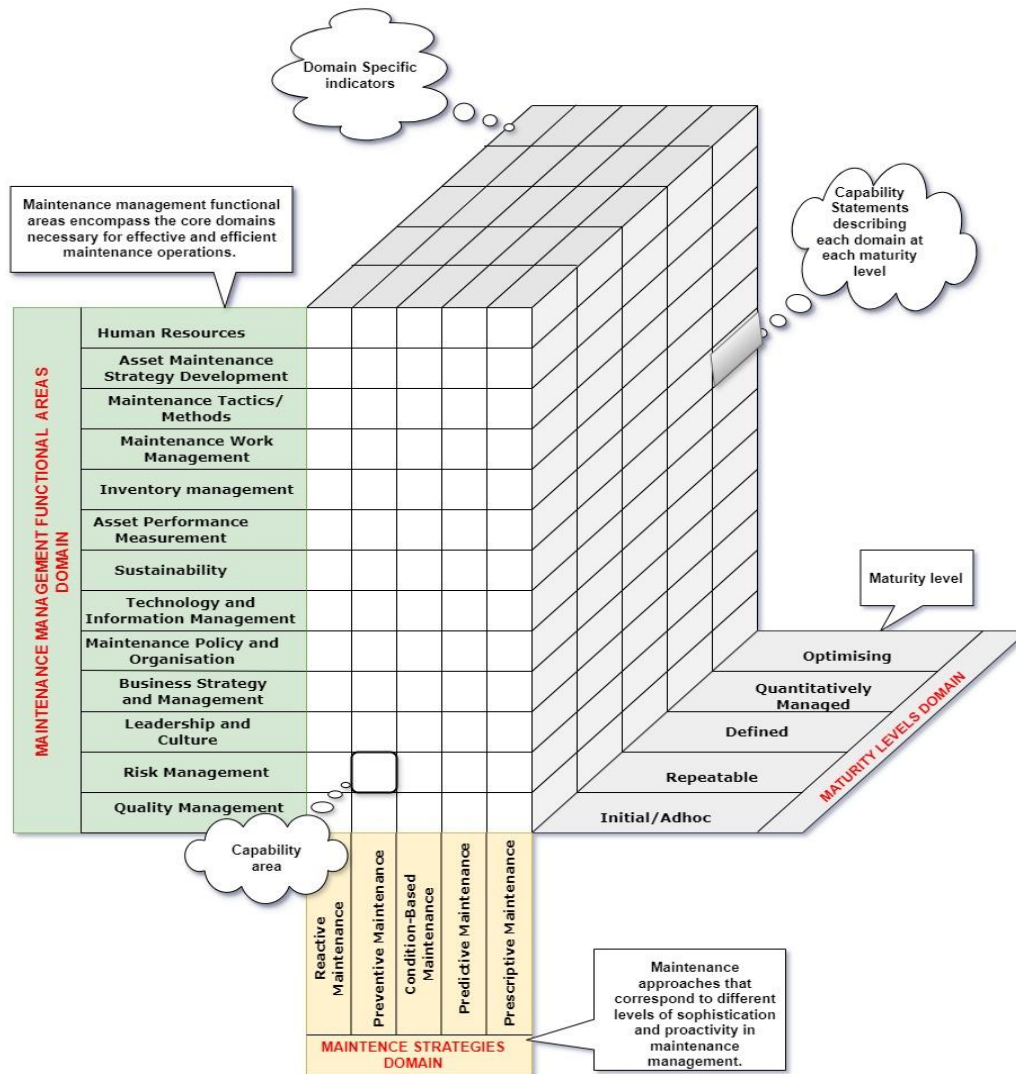


Figure 30: Final MMM structure

Consequently, no significant modifications were required, and the model remained consistent with its original formulation. As such, the final structure of the model, which was subsequently verified against the predefined design requirements through expert consensus, is presented in Figure 30.

9.3.4 Consensus achievement and study completion

Consensus was achieved in the second round, with all eight participants agreeing across all attributes. The increase in mean ratings between rounds indicated heightened alignment among experts. As the predefined consensus threshold of 75% was met, further Delphi rounds were deemed unnecessary, and the study was concluded.

9.4 Discussion

The results of this Delphi study provide critical insights into the development and validation of a maturity-based maintenance prioritisation model. This section interprets the study findings, evaluates their practical implications, discusses the strengths and limitations of the Delphi methodology and suggests directions for future investigation.

9.4.1 Interpretation of consensus outcomes

The attainment of complete consensus among participants in the second round signifies strong agreement on the model's key attributes, reinforcing its robustness and applicability in water industries. The iterative Delphi process allowed for the refinement of the model, ensuring that ambiguities were resolved. This suggests that the model can serve as a reliable framework for water utilities to systematically assess and enhance their maintenance maturity.

Moreover, the chapter highlights the increasing recognition of the benefits associated with structured maintenance management. Consensus among the expert panel affirms that maintenance maturity models are practical tools for assessing current practices and offering prescriptive pathways for improvement. These models facilitate the alignment of maintenance strategies with organisational objectives and established asset management best practices. This view is consistent with Oliveira et al. (2012), who stated, "based on the maturity level of the organisation, suitable recommendations for maintenance management can be defined."

The findings align with existing studies by Maier et al. (2020a), Chemweno et al. (2015) and Oliveira and Lopes (2020) that emphasise the role of maturity models in maintenance and asset management. Similar frameworks, such as the ISO 55000 series, PAS 55 and one proposed by GFMAM (2021), have underscored the importance of structured progression in maintenance practices. However, this study contributes to the field by specifically integrating maintenance prioritisation within the maturity assessment.

For policymakers and industry leaders, the model serves as a strategic tool for standardising maintenance practices across sectors.

9.4.2 Strengths and limitations of the Delphi study

The chapter presented a rigorous Delphi methodology, which facilitated structured expert input and iterative refinement of the model. The diversity of the expert panel, representing various domains within maintenance and asset management, enhanced the credibility and applicability of the findings. Additionally, reaching a consensus in two rounds indicates a high level of agreement, suggesting that the model is well-defined and easily interpretable by industry professionals.

While the Delphi study achieved its objectives, some limitations were acknowledged:

- **Sample size constraints:** The sample size of 10 participants, though adequate for a Delphi study, may limit the extent to which the findings can be generalised across all industries. Although a larger panel might have introduced greater diversity, the purposive selection of experts ensured a depth of insight that aligned with the study's objectives.
- **Potential dropout effects:** Two participants did not respond to the second round; however, their absence did not compromise the validity of the findings, as the remaining participants provided sufficient consensus.
- **Time constraints:** The study was designed to conclude within a set timeframe, which may have limited extended deliberations. Nonetheless, the Delphi process successfully facilitated convergence within the allotted period.

9.5 Maintenance maturity model

Frequent breakdowns of water infrastructure, primarily caused by inadequately structured and non-adaptive maintenance plans and strategies, disturb the consistent delivery of water services. The proposed maintenance maturity model (MMM) for prioritising water infrastructure maintenance provides a structured, systematic, and adaptive framework that directly addresses this challenge.

The MMM facilitates the structured assessment of an organisation's current maintenance practices by precisely evaluating against defined maturity levels. This structured evaluation enables organisations to identify weaknesses and gaps in their maintenance approaches that

may contribute to asset failures. By understanding their current maturity state, organisations are empowered to make informed, targeted decisions for maintenance improvement.

Importantly, the model offers a prioritised and phased improvement roadmap tailored to an organisation's existing capabilities. Rather than imposing a generic solution, the MMM enables organisations to focus first on critical deficiencies and progressively evolve towards advanced maintenance practices. This stepwise approach allows entities to strengthen their maintenance capability sustainably and practically, thereby reducing the frequency and severity of infrastructure breakdowns over time.

A central feature of the MMM is the promotion of structured yet adaptable maintenance strategies. As organisations mature within the model, they are guided to transition from static, time-based maintenance approaches to dynamic, data-driven strategies that respond to real-time asset conditions and operational demands. This adaptability ensures that maintenance plans remain effective and relevant, helping to prevent unforeseen failures that result from outdated maintenance schedules.

The integration of risk-based prioritisation within the MMM further enhances maintenance effectiveness. Maintenance activities are prioritised based on asset criticality, the likelihood of failure, and the potential impact on service delivery. This ensures that maintenance resources are concentrated on assets that present the highest risk to service continuity, thereby mitigating the likelihood of catastrophic breakdowns and service interruptions.

Moreover, the MMM emphasises the alignment of maintenance activities with broader organisational objectives, particularly the goal of ensuring uninterrupted service delivery. Maintenance key performance indicators are explicitly linked to customer satisfaction, regulatory compliance, operational resilience, and other strategic outcomes. This alignment ensures that maintenance is recognised as a vital contributor to the organisation's mission rather than a purely technical or support function.

Recognising that effective maintenance is not solely a technical issue, the MMM also promotes the development of human resource capabilities and a maintenance-supportive organisational culture. By encouraging leadership engagement, workforce training, and cross-functional collaboration, the model supports the establishment of institutional capacity necessary to design, implement, and sustain structured and adaptive maintenance strategies.

Furthermore, the MMM advocates for the systematic use of asset data to drive maintenance decisions. By embedding practices such as condition monitoring, performance analysis, and predictive diagnostics, organisations are better equipped to identify emerging issues early, predict potential failures, and dynamically adjust maintenance interventions. This data-driven approach significantly improves the timeliness, precision, and effectiveness of maintenance activities.

Finally, the MMM fosters a culture of continuous improvement. Through mechanisms such as root cause analysis (RCA), post-maintenance reviews, and performance benchmarking, organisations are encouraged to learn from failures and successes alike, thereby progressively refining their maintenance practices and enhancing infrastructure resilience over time.

In summary, the maintenance maturity model mitigates the problem of frequent water infrastructure breakdowns by providing a clear, progressive pathway for improving maintenance practices. It empowers organisations to evolve from fragmented and reactive maintenance approaches towards proactive, risk-based, and strategic maintenance management, thereby supporting sustainable and uninterrupted water service delivery

9.6 Conclusion

This chapter has presented the findings of the Delphi study undertaken to validate the proposed maintenance maturity model (MMM), developed to enhance maintenance prioritisation in asset-intensive sectors. Through successive rounds of expert consultation, a strong consensus emerged regarding the model's relevance, comprehensiveness, and practical utility. The expert panel affirmed the clarity and appropriateness of the research problem, the design requirements, and the structure of the model. Furthermore, the associated capability statements were deemed to be clearly defined, mutually exclusive, and representative of real-world maintenance challenges and industry best practices. The panel also emphasised the value of the MMM in providing a structured framework for evaluating current maintenance practices and supporting systematic improvement. These findings highlight the model's potential to assist organisations in evolving from reactive maintenance practices toward more proactive, data-driven strategies. Overall, the Delphi study has significantly strengthened the rigour and credibility of the proposed MMM, affirming its relevance in both academic and real-world contexts.

CHAPTER 10: CONCLUSION

10.1 Introduction

This study aimed to develop a maintenance maturity model specifically tailored to prioritise water infrastructure maintenance within the South African context. The conclusion chapter provides a comprehensive summary of the key findings and insights generated throughout the research process. It reflects on the study's objectives, evaluates how these objectives were achieved, and discusses the practical implications of the proposed model. Furthermore, this chapter outlines the limitations encountered during the research and offers strategic recommendations for both practitioners and future researchers, thereby charting a path for continued exploration and application in the field of maintenance management.

10.2 Research overview

In light of persistent challenges such as infrastructure deterioration, frequent service delivery disruptions, and inefficient maintenance practices, the study recognised the urgent need for a structured, context-sensitive framework that enables organisations to assess and progressively enhance their maintenance maturity.

Table 30 presents how each research objective aligns with the corresponding dissertation chapters and the methods used to achieve it.

Table 30: Mapping of research objectives to study chapters and methods

Objective	Chapter	Method
a. To perform a systematic literature review on asset maintenance prioritisation approaches relevant to water infrastructure.	Chapter 4	A systematic literature review was conducted using databases such as Scopus. Themes on maintenance prioritisation methods, frameworks, and best practices were synthesised.
b. To analyse current maintenance practices and the state of water infrastructure management in South African municipalities	Chapter 5	A qualitative analysis on the subject was conducted using information from government reports (e.g., SAICE Infrastructure Report Card, Drop Reports) and literature on municipal maintenance performance.

Objective	Chapter	Method
c. To identify and analyse the key factors influencing maintenance prioritisation decisions in water utilities	Chapter 6	A thematic analysis was conducted based on the literature review
d. To develop a maintenance maturity model	Chapter 8: Development of the Maintenance Maturity Model	A conceptual framework was developed based on insights from literature, empirical findings, and best practices. The model consists of three domains.
e. To validate the proposed maintenance maturity model through expert consultations	Chapter 9: Model Validation and Refinement	A Delphi study was conducted with subject matter experts in water infrastructure maintenance. The model was refined based on expert feedback, consensus analysis, and validation metrics such as relevance, sufficiency, and clarity.

The study employed the eADR methodology, focusing on the problem diagnosis and concept design stages. Sections 3.3 and 3.4 outlined the iterative cycles followed for each stage. The *problem diagnosis* stage was conducted over three iterative cycles, each designed to progressively deepen understanding of the problem context and lay a robust foundation for developing a maintenance maturity model for water infrastructure maintenance.

The first iteration addressed objective (a) by conducting a comprehensive literature review of prevailing maintenance practices and the broader state of water infrastructure management within South African municipalities. The findings revealed systemic deficiencies rooted in inadequate governance, chronic financial constraints, and pervasive operational inefficiencies. Despite numerous interventions to improve water supply systems' reliability and sustainability, many municipalities continue to adopt fragmented, predominantly reactive maintenance strategies. Such reactive approaches not only contribute to frequent service disruptions but also accelerate the degradation of infrastructure assets, ultimately compromising the long-term sustainability of essential water services.

In the second iteration, a systematic literature review was undertaken to examine existing asset maintenance prioritisation approaches, particularly those relevant to water infrastructure. This stage addressed objective (b) and underscored the need for data-driven, rounded, and adaptable maintenance prioritisation methods. The review exposed significant limitations in existing frameworks, especially concerning their responsiveness to localised constraints and the dynamic service demands of municipal water utilities.

The third iteration addressed objective (c) by exploring and synthesising key factors influencing maintenance prioritisation decisions in water utilities. Drawing from both academic literature and industry reports, this phase provided a nuanced understanding of the complex, multi-dimensional decision-making environment. The study identified a constellation of interrelated factors—technical, financial, environmental, social, and operational—that collectively shape maintenance priorities. The inherent interdependence of these factors revealed a system wherein decisions in one domain often trigger cascading effects in others. These findings reinforced the need for a structured, multi-criteria decision-making framework capable of facilitating balanced, sustainable, and contextually appropriate maintenance choices under resource-constrained conditions.

The *concept design* stage of the research also proceeded through three iterative cycles. The first design iteration aimed to establish the foundational requirements of the MMM. A systematic mapping review of existing maintenance maturity models was conducted to identify prevailing gaps and limitations. The analysis revealed notable deficiencies in existing models, particularly in terms of adaptability, domain comprehensiveness, and their ability to support prioritisation. Consequently, ten critical design requirements were formulated, thereby justifying the development of a new, more robust and context-specific model.

Building on the insights from the first phase, the second design iteration focused on constructing a conceptual framework for the proposed MMM, in alignment with objective (d). This iteration followed the model development guidelines proposed by Becker and Maier to ensure a methodologically sound and theoretically grounded framework. The resultant model incorporated key success domains and maturity attributes synthesised from the literature, thereby ensuring that the framework was both comprehensive and tailored to the unique maintenance challenges of South Africa's water infrastructure.

The third design iteration, aligned with objective (e), entailed the validation and refinement of the proposed MMM. A Delphi study involving academic scholars and industry practitioners was conducted to evaluate the model in terms of sufficiency, accuracy, relevance, and usability. Consensus was successfully reached during the second round on all evaluation criteria. As a result, the model was verified and validated through expert agreement, confirming its potential as a valuable tool for guiding maintenance maturity assessment and prioritisation within water infrastructure systems.

10.3 Contribution

From a Design Science Research (DSR) perspective, this study contributes by developing an artefact i.e. a maintenance maturity model specifically designed to address the limitations of existing models within the context of water infrastructure. The comparative gap analysis established that while various maintenance maturity models are available, none sufficiently satisfied the predefined design requirements necessary to guide developing an MMM. Consistent with DSR principles and the view of (Sein and Rossi, 2019), who emphasise that meaningful contributions involve reducing or closing an identified gap, this study delivers both a purposeful artefact and prescriptive design knowledge. The proposed model enhances practical utility by informing structured decision-making in prioritising maintenance, while also contributing to the theoretical development of maturity modelling in infrastructure asset management. In doing so, it supports the advancement of reliable and sustainable maintenance practices in the water sector, delivering value to both academic and practitioner communities within this critical public service domain.

Furthermore, this research contributes to the academic body of knowledge through the dissemination of its findings in a peer-reviewed conference paper presented at the South African Institute of Industrial Engineers (SAIIE) conference. The paper reviewed existing maintenance prioritisation approaches relevant to water infrastructure, highlighting current practices and scholarly efforts. By doing so, it aims to bridge the gap between theory and practice, fostering a more integrated approach to ensuring infrastructure reliability and resilience.

10.4 Limitations and recommendations

The development of the MMM in this study followed the elaborated Action Design Research (eADR) method, characterised by iterative cycles of diagnosis and design. Through three iterations in both the diagnosis and design stages, the model evolved in response to feedback and theoretical insights. While this iterative process allowed for rigorous model development and expert validation, several limitations remain, particularly concerning the model's practical implementation and wider generalisability.

10.4.1 Methodological limitations

While the framework was conceptually designed with municipal infrastructure systems in mind, it was not grounded in direct municipal data collection. Instead, its development relied on expert validation through a structured Delphi study.

A significant limitation of this research lies in the absence of real-world implementation and testing of the MMM. Although theoretical validation and expert consensus were achieved, the model was not applied within operational maintenance environments. Consequently, its effectiveness, usability, and adaptability under actual working conditions remain untested. This constraint limits the extent to which definitive conclusions can be drawn regarding the model's practical value in enhancing maintenance decision-making or asset performance outcomes.

Furthermore, while the Delphi study participants brought valuable insights, it may not fully capture the diversity of maintenance contexts across different industries and geographical regions. This may affect the model's applicability in sectors or regions that operate under different regulatory frameworks, organisational structures, or cultural norms.

10.4.2 Opportunities for future research

Despite these limitations, the study establishes a solid foundation for future inquiry and presents several avenues for further research:

- a. **Empirical validation:** Future studies should prioritise the application of the MMM in real-world industrial settings to evaluate its utility in guiding maintenance prioritisation. Empirical testing through case studies or pilot projects would provide evidence of the model's impact on decision-making, resource allocation, and maintenance outcomes.
- b. **Longitudinal impact studies:** Long-term studies that assess the sustained impact of the MMM on asset reliability, downtime reduction, cost optimisation, and service delivery are essential. Such research would validate the strategic value of the model by demonstrating its influence on performance over time.
- c. **Integration with digital technologies:** The increasing digitisation of asset management offers an opportunity to integrate the MMM with smart technologies and data-driven tools such as AI, ML, predictive analytics, and IoT. Investigating how these technologies can support or enhance the implementation of the model could lead to more dynamic and responsive maintenance strategies.

- d. **Development of a scoring matrix:** A structured and transparent scoring matrix is required to support consistent and objective assessment across the maturity levels. Future research should focus on designing a robust, scalable, and user-friendly scoring mechanism to enhance the model's practicality and adoption.
- e. **Broader contextual validation:** Although consensus was achieved among the expert panel, the study did not explore variations in implementation across different organisational types, sizes, and maturity levels. Future research should broaden the participant base to include practitioners from a more diverse range of geographical locations. This would help identify context-specific challenges and ensure the model's robustness across various operational environments.

These future research directions will be critical to realising the full potential of the MMM in supporting sustainable and strategic asset maintenance practices.

10.5 Conclusion

In summary, South Africa continues to face persistent infrastructure failures, primarily due to the inadequate maintenance of water infrastructure. This enduring challenge poses a significant threat to socio-economic development, impedes the realisation of fundamental human rights, and obstructs progress towards Sustainable Development Goal 6, as well as other interdependent goals that rely on the consistent delivery of clean water and sanitation services. The developed maintenance maturity model (MMM) underscores the strategic importance of maintenance by offering a structured and systematic framework for enhancing maintenance management practices. The MMM can serve as a practical and adaptable tool to support decision-makers, practitioners, and policymakers in strengthening maintenance performance across the water sector. By promoting a culture of continuous improvement, the MMM enables organisations to progressively advance their maintenance capabilities, thereby reinforcing infrastructure resilience and ensuring the lasting reliability of water services.

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APPENDIX A: Overview of the SMR studies

Table 31: Summary of the studies included in the review

Reference	Title	Industry	Method of assessment		Dimensions or Knowledge areas	Maturity levels
(Tortora et al., 2023)	A Strategic Roadmap to Improve the Maturity Level of Maintenance Information Management Systems	SMEs		5	Equipment database; Maintenance personnel database; Maintenance work order; Report database	L1-Chaos; L2-Orientation; L3-Definition; L4-Maintain; L5-Best in class
(Franciosi et al., 2023)	A Maintenance Maturity and Sustainability Assessment Model for Manufacturing Systems	Manufacturing industry	Questionnaire and interviews	9	Asset life cycle management; risk management; maintenance planning and budgeting; product quality management; certifications; human resource organisation and empowerment; relationships with other business functions and with suppliers; monitoring diagnostic and prognostic systems; maintenance information management systems.	Basic, qualitatively managed, defined, quantitatively managed, optimising Strong sustainability; Weak sustainability; Not sustainable
(Desbalo et al., 2023)	Maturity model for evaluating building maintenance practice: A fuzzy-DEMATEL approach	Construction		12	Maintenance Policy and Strategy, Human Resource Management, Technical and Functional, Appropriateness, Maintenance Organisation, Maintenance Information Management, Building Design Life, Maintenance Budget/Finance, Culture and Leadership, Maintenance Materials and Spare part Management, Risk Management, Performance Management, Environmental and Social Impact of the Built asset	Initial, Developing, Defined, Quantitatively managed, Optimised
(Tortora et al., 2022)	A Maintenance Maturity Model for Assessing Information Management Practices for Small and Medium Enterprises (M3AIN4SME)	SMEs	Questionnaire + semi-structure interviews	4	Equipment, maintenance personnel, maintenance work order, maintenance reports	L1-Chaos; L2-Orientation; L3-Definition; L4-Maintain; L5-Best in class

(Siswanto et al., 2022)	The Evaluation of Maturity Level on Heavy Equipment Maintenance Management According to ISO 55001:2014	Transportation - shipping	Questionnaire	7	Organisation Context, Leadership, Planning, Support, Operation, Work Evaluation, Improvement	Innocent, Aware, Developing, Competent, Beyond, Beyond
(Oliveira et al., 2022)	Evaluation of maintenance management of a thermoplastic industry using maintenance maturity model	Manufacturing industry - thermoplastics		10	Organisational culture; maintenance policy; performance management; failure analysis; planning and programming of preventive maintenance activities; CMMS; spare parts inventory management; standardisation and document control; human resource management and results management (maintenance costs and quality).	
(Mesarosova et al., 2022)	Improving the level of predictive maintenance maturity matrix in industrial enterprise	Manufacturing industry	Not mentioned	6	People, Applications, Infrastructure, Process, Data, and Organisation	Level 1 – Visual inspections; Level 2 – Instrument inspections; Level 3 – Real-time condition monitoring; Level 4 – Predictive maintenance 4.0
(Errandonea et al., 2022a)	A Maturity Model Proposal for Industrial Maintenance and Its Application to the Railway Sector	Transportation - Railway	Not mentioned – case study	3	18 domains are further divided into three areas: Asset, Status and Maintenance	preventive, condition-based, predictive and prescriptive
(Maier et al., 2021)	Development of a Generic Framework to Assess Asset Management Maturity within Organisations	Generic – not specified	Questionnaire + interviews	9	philosophy & target system; corporate culture; business model & service strategy; asset strategy; maintenance budget & controlling; organisational structure; process organisation; knowledge management and data & technology,	Incomplete, Initial, Managed, Defined, Quantitatively managed, Optimised
(Johannes et al., 2021)	Identifying Maturity Dimensions for Smart Maintenance Management of Constructed Assets: A Multiple Case Study	Building and construction	Expert consultations	8	Governance structure, Alignment, Tracking and tracing, Data-driven decision-making, Sustainability monitoring, Knowledge management, Culture, Leadership	Not mentioned

(de Oliveira et al., 2021)	Evaluation of the Maturity in the Management system of Maintenance of Electricity Distribution Networks – A Case Study	Utility – electricity distribution	Interviews + case study	3	Base allocation assessment; Work team sizing and allocation; Operational team day to day allocation	L1 - Understanding; L2 - Implementation; L3 - Updating; L4 - Optimisation; L5 - Continuous Improvement.
(Schmiedbauer et al., 2020)	Evolution of a Lean Smart Maintenance Maturity Model towards the new Age of Industry 4.0	Manufacturing	Not mentioned	9	philosophy & target system; corporate culture; business model & service strategy; asset strategy; maintenance budget & controlling; organisational structure; process organisation; knowledge management and data & technology,	Initial, Managed, Defined, Quantitatively managed, Optimised
(Oliveira and Lopes, 2020)	Evaluation and improvement of maintenance management performance using a maturity model	Manufacturing	Maintenance manager's self-assessment based on the reading of the tables' content.	10	organisational culture; maintenance policy; performance management; failure analysis; planning and programming of preventive maintenance activities; CMMS; spare parts inventory management; standardisation and document control; human resource management and results management (maintenance costs and quality).	1-5
(Maier et al., 2020b)	Validation of a Lean Smart Maintenance Maturity Model	Manufacturing	Not mentioned	9	Philosophy & Target System, Corporate Culture, Business Model & Service Strategy, Asset Strategy, Controlling & Budget, Organisational Structure, Process Organisation, Knowledge Management, Data & Technology	Incomplete, Initial, Managed, Defined, Quantitatively managed, Optimising
(Nemeth et al., 2019)	A maturity assessment procedure model for realising knowledge-based maintenance strategies in smart manufacturing enterprises	Manufacturing industry	Indicators	4	(1) Data; (2) information; and (3) knowledge (4) operations	L0-L3 0-100%
(Nemeth et al., 2018)	PriMa-X: A reference model for realising prescriptive maintenance and assessing its maturity enhanced by machine learning			2	(1) maintenance dimension: maintainability, reliability, availability, repair- & downtime, cost & human resource effectiveness; and (2) data analytics dimension: data quality metrics (structure, information & veracity),	

					accuracy of failure patterns, and certainty & reliability of predictions	
(Muchiri et al., 2017)	Development of a theoretical framework for evaluating maintenance practices	Generic	Not mentioned	3	technical, managerial, human–strategic; tactical and organisational.	Basic, Repeatable, Proactive, Managed, Optimum
(Mehairjan et al., 2016)	Development and implementation of a maturity model for professionalising maintenance management	Gas/ electricity	Questionnaire + Interview	5	Organisation and Processes, Policy and Criteria, Information and Systems, Data quality, Performance and Portfolio	Not much in place, Practically Managed, House in Order, Best in Class
(Chemweno et al., 2015)	Asset maintenance maturity model: Structured guide to maintenance process maturity	Generic	Analytic Network Process + Indicators	5	People and environment; Functional and technical aspects; Plant Design Life; Support; Maintenance Budget	1-5 0% -100%
(Macchi and Fumagalli, 2013b)	A maintenance maturity assessment method for the manufacturing industry	Manufacturing industry	Questionnaire + Indicators	3	organisational; (2) managerial; and (3) technological	Initial, Managed, Defined, Quantitatively managed, Optimising
(Oliveira et al., 2012)	Maintenance management based on the organisation maturity level	Manufacturing industry	Interview	5	Maintenance strategy; KPIs; maintenance data systems (Computerised maintenance management system – CMMS); technical competencies (culture); and management models	Low, medium, high
(Cholasuke et al., 2004)	The status of maintenance management in UK manufacturing organisations	Manufacturing industry	Survey	10	Maintenance effectiveness (output); Policy deployment and organisation; Maintenance approach; Task planning and scheduling; Information management and CMMS; Contracting out maintenance; Continuous improvement; Financial aspects; Human resource management; Spare part management	Innocence Understanding Excellence
(Hauge et al., 2003)	Reliability-centered maintenance maturity level roadmap		Not mentioned	6	(1) analysis; (2) analysis documentation; (3) metrics; (4) mentoring & facilitation; (5) training; and (6) living process	Initial, Repeatable , Defined, Self-Sustaining, Continuous Improvement

APPENDIX B: Delphi questionnaire statements

Table 32: Delphi questionnaire statements

	SURVEY STATEMENTS	
RESEARCH PROBLEM VALIDITY	Q1	There is an urgent need for the development of comprehensive maintenance frameworks that are flexible and responsive to the dynamic challenges faced by asset-intensive sectors like water utilities, to mitigate breakdown occurrences.
	Q2	Ineffective maintenance strategies contribute to resource misallocation, further exacerbating infrastructure failures and undermining operational efficiency.
	Q3	The persistence of ad-hoc maintenance practices within many organisations indicates a cultural resistance to change, which is detrimental to long-term operational sustainability and needs to be addressed through effective change management strategies.
	Q4	Maintenance personnel in South Africa's asset-intensive industries- public sector; lack the adequate training and competency to implement effective infrastructure maintenance strategies.
	Q5	There are insufficient mechanisms for regularly monitoring and evaluating maintenance plans for physical infrastructure assets.
	Q6	The recurring nature of infrastructure failures highlights systemic deficiencies in maintenance practices, necessitating a comprehensive re-evaluation of existing frameworks to foster resilience and reliability.
DESIGN REQUIREMENTS VALIDATION	Q7	The design requirements for the model are articulated clearly, ensuring they are specific and easily interpretable by all stakeholders involved in the Delphi study.
	Q8	The design requirements emphasize the importance of continuous improvement in maintenance practices, guiding the development of a Maintenance Maturity Model that encourages organisations to assess their current capabilities and implement strategies for ongoing enhancement.
	Q9	The design requirements comprehensively address the essential elements necessary to guide the development of the Maintenance Maturity Model, making it relevant and beneficial for both industry practitioners and academic researchers in the field of maintenance management.
	Q10	The design requirements adequately outline the foundational criteria needed to create a Maintenance Maturity Model that can effectively assess and guide the identification and development of maintenance competencies and practices within asset-intensive industries.
CONCEPTUAL MODEL VALIDATION	Q11	The conceptual model is clearly articulated and easily understood by participants?
	Q12	The maintenance strategies dimensions are appropriate and relevant?
	Q13	The functional areas domain accurately and sufficiently reflects maintenance operations and management practices?
	Q14	The maturity levels dimension is sufficient to provide a holistic evaluation of an organisation's maturity stages within each domain?
	Q15	The dimensions within the model are distinct and do not overlap, ensuring clear differentiation between maturity levels?
	Q16	The conceptual model accurately reflects the reality of maintenance practices in the field and is based on sound theoretical foundations?
	Q17	The conceptual model is user-friendly and can be easily implemented by organisations to assess and enhance their maintenance strategies?
	Q18	The insights that can be gained from applying the model are actionable and provide valuable guidance for organisations seeking to improve their maintenance maturity?
	Q19	The conceptual model is practical for conducting assessments and flexible enough to accommodate the diverse needs and contexts of different organisations within asset-intensive industries?
	Q20	The Maintenance Maturity Model offers a practical framework to enhance infrastructure maintenance practices in the water utilities industry

APPENDIX C: Capability statements - Performance Measurement

Table 33: Capability statements - Performance Measurement

CAPABILITY FUNCTION	Performance Measurement				
MATURITY LEVELS	MAINTENANCE TYPE				
	Reactive Maintenance	Preventive Maintenance	Condition-based Maintenance (CBM)	Predictive Maintenance (PdM)	Prescriptive Maintenance
INITIAL	There is a lack of structured metrics or performance indicators to assess maintenance effectiveness. Success is measured based on immediate problem resolution rather than long-term outcomes or efficiency.	Basic metrics, such as maintenance schedules and completion rates, may be tracked, but there are no standardized metrics or performance indicators for preventive maintenance. Data is often incomplete or inconsistently recorded.	Measurement systems for CBM are rudimentary or non-existent. Data collection is ad-hoc, with no systematic approach to monitoring equipment condition. Key performance indicators (KPIs) for CBM are not defined, and decision-making is often based on incomplete or inaccurate data.	There is little to no tracking of predictive maintenance performance measurements. Metrics related to prediction accuracy, failure prevention, or cost savings are not established, and data is often underutilized.	Measurement of maintenance activities is sporadic, focusing on immediate issues without considering long-term data trends or predictive analytics. Data collection is inconsistent, with no structured metrics for prescriptive maintenance.

REPEATABLE / MANAGED	Basic performance metrics are established to track maintenance activities. Measurement focuses on immediate issues and response times rather than long-term performance or efficiency. Key performance indicators (KPIs) such as mean time to repair (MTTR) and Number of Reactive Work Orders are tracked.	Basic metrics for preventive maintenance are established and monitored. Performance indicators such as preventive maintenance compliance, downtime reduction, mean time between failures (MTBF) and maintenance costs are tracked, but data analysis may be limited. Preventive maintenance completion rates and effectiveness are reported.	Measurement practices are more systematic, with defined metrics and performance indicators for equipment condition. Data collection is regular but may not be fully integrated into decision-making processes.	Basic performance metrics for predictive maintenance are established, allowing for some tracking and analysis of predictive maintenance effectiveness. Performance indicators such as prediction accuracy and maintenance outcomes are consistently tracked using established procedures.	Basic measurement systems are implemented to track key performance indicators related to prescriptive maintenance. Data collection is more consistent, and initial metrics are established to gauge the effectiveness of prescriptive actions. Performance indicators such as the effectiveness of recommendations, cost savings, and maintenance optimization are consistently measured.
DEFINED	Performance metrics are well-defined and regularly reviewed. There is a structured approach to measuring maintenance effectiveness, focusing on key indicators such as response times, downtime, and cost efficiency.	Comprehensive metrics and performance indicators are used to monitor and evaluate preventive maintenance activities. Data is systematically collected and analysed to assess effectiveness and identify areas for improvement.	Measurement practices are robust, with standardized metrics and performance indicators for equipment condition. Data collection is integrated with maintenance decision-making, providing actionable insights for optimizing CBM.	Data is systematically collected and analysed. Comprehensive metrics and performance indicators are in place to evaluate the effectiveness of predictive maintenance. Predictive maintenance metrics are defined and tracked, including equipment condition indicators and remaining useful life.	A comprehensive measurement framework is developed, with standardized metrics for prescriptive maintenance. Data is consistently collected, analysed, and used to inform maintenance strategies and decisions.

QUANTITATIVELY MANAGED	Maintenance performance is rigorously measured using advanced metrics and analytics. Quantitative data drives decision-making, with a focus on optimizing response times, cost-efficiency, and downtime reduction.	Advanced metrics and performance indicators are used to assess and report the impact of preventive maintenance quantitatively. Data analysis is used to drive decision-making and continuous improvement efforts. e.g., measurement of maintenance schedule compliance, downtime metrics, MTBF (Mean Time Between Failures), MTTR (Mean Time to Repair).	Measurement practices are advanced, with sophisticated metrics and real-time data integration. Performance indicators are continuously monitored and analysed, providing actionable insights for optimizing CBM activities.	Predictive maintenance performance is measured quantitatively, with advanced analytics providing insights into effectiveness and areas for improvement.	Measurement processes are refined and linked to prescriptive models. The organization uses advanced analytics to interpret data, enabling precise tracking and optimization of maintenance activities.
OPTIMISING	Advanced metrics and analytics are used to drive continuous improvement in maintenance performance. Data is leveraged to identify trends, optimize processes, and drive strategic improvements. Performance metrics are tracked and analyzed to assess response times, repair quality, and cost efficiency, with continuous improvements based on measurement outcomes	Key performance indicators (KPIs) for preventive maintenance are well-defined and monitored, including compliance with schedules and effectiveness of preventive actions. Standardized performance metrics are implemented and benchmarked against industry standards.KPIs are regularly reviewed and adjusted based on performance data.	Measurement practices are highly advanced, with real-time analytics and continuous improvement cycles. Performance metrics are refined based on emerging trends and technologies, ensuring optimal maintenance outcomes.	Measurement systems for predictive maintenance are highly sophisticated, incorporating real-time data from sensors and analytics tools to accurately predict equipment failures and maintenance needs. Performance metrics for predictive maintenance are advanced and continuously improved. Data-driven insights drive ongoing enhancements to practices.	Measurement systems are fully integrated into the prescriptive maintenance process, with real-time data analytics driving continuous improvement. Predictive and prescriptive analytics are used to refine metrics and optimize maintenance performance.

APPENDIX D: Capability statements - Humans Resources

Table 34: Capability statements - Human Resources

CAPABILITY FUNCTION	Human resources				
	MAINTENANCE TYPE				
MATURITY LEVELS	Reactive Maintenance	Preventive Maintenance	Condition-based Maintenance (CBM)	Predictive Maintenance (PdM)	Prescriptive Maintenance
INITIAL	Maintenance personnel are typically reactive, addressing issues as they arise. There is minimal training or development related to maintenance practices. Roles and responsibilities are often unclear, leading to inconsistent performance and lack of accountability.	Maintenance activities are performed reactively, with no formal planning or scheduled interventions. Personnel receive some basic training on preventive maintenance tasks. Roles are somewhat defined, but there is still a lack of formal development programs.	The workforce has limited understanding and skills related to condition-based maintenance (CBM). There is minimal training, and reliance on individual knowledge and experience is high. Workforce engagement in CBM practices is inconsistent, and there is no formal competency development program.	The workforce has minimal exposure to predictive maintenance technologies and techniques. Data interpretation skills are underdeveloped, and the workforce may struggle with using even basic predictive tools or software.	Workforce relies on reactive approaches with minimal training in prescriptive maintenance techniques. Skills are mostly centered around immediate problem-solving without predictive or prescriptive analysis. There is no structured plan to develop prescriptive maintenance capabilities.
REPEATABLE / MANAGED	Maintenance personnel have defined roles and responsibilities, and there is some level of training and development. However, training is still often reactive, based on immediate needs rather than a structured program.	Personnel receive basic training for preventive maintenance, and there is some level of structured planning for maintenance activities. Roles and responsibilities are defined. However, training may still be inconsistent, and the focus is primarily on routine tasks.	Personnel involved in CBM have received some training, and roles and responsibilities are defined. There is a more structured approach to knowledge sharing and skill development, leading to more consistent maintenance practices.	Personnel receive basic training in predictive maintenance techniques. There are standardized procedures for using predictive data to guide maintenance decisions.	Basic training is provided to key personnel in prescriptive analytics tools and techniques. Roles are defined, but workforce engagement is limited. Training programs begin to include elements of data interpretation and decision-making based on prescriptive models.

DEFINED	Maintenance personnel receive ongoing, structured training and development. Roles and responsibilities are clearly defined, and there is a focus on building skills that support reactive maintenance efforts.	Personnel are formally trained in preventive maintenance techniques and follow standardized procedures. Training programs are well-structured and regularly updated to ensure skill development and adherence to best practices.	Personnel involved in CBM are well-trained and possess specialized skills. There are structured training programs and clear career development paths for maintenance staff, leading to high competency and expertise in CBM practices.	Personnel are well-trained in predictive maintenance methodologies, with roles and responsibilities clearly defined for implementing predictive strategies.	Workforce is skilled in prescriptive maintenance strategies, with established training programs focused on data-driven decision-making and optimization techniques. Teams actively collaborate with data scientists and engineers to implement prescriptive solutions.
QUANTITATIVELY MANAGED	Maintenance personnel are highly trained, with a focus on data-driven approaches. Performance is quantitatively assessed, and there are metrics in place to evaluate skills and effectiveness to identify and address skill gaps.	Personnel training and performance in preventive maintenance are quantitatively measured and managed. Training effectiveness is assessed using metrics, and ongoing skill development is supported through targeted programs.	Personnel are highly skilled and trained in advanced CBM techniques. Performance metrics and data-driven insights guide ongoing training and development, leading to a high level of expertise and effectiveness in CBM.	Personnel are highly skilled in predictive maintenance, with ongoing training and certification programs. Performance is tracked and managed using quantitative metrics.	Workforce proficiency in prescriptive maintenance tools and techniques is significant. Workforce proficiency in prescriptive maintenance is monitored through metrics and continuous training improvements. Employees are empowered to use advanced tools, and their performance is quantitatively assessed. Collaborative cross-functional teams are established to drive prescriptive maintenance initiatives.

OPTIMISING	Maintenance personnel are continuously trained and developed with a focus on advanced, data-driven techniques. Employees possess high-level skills in troubleshooting and emergency repairs, employing advanced diagnostic methods to swiftly minimize downtime and restore operations. Comprehensive skill assessments and continuous professional development are supported by performance management systems that track and enhance both individual and team capabilities.	The workforce is well-trained in executing systematic preventive measures, utilizing detailed schedules and checklists to proactively address potential issues and maintain equipment in optimal condition. Career development is structured around competency-based training and supported by knowledge-sharing platforms, ensuring the integration of best practices into daily maintenance activities	Personnel are experts in CBM, with ongoing development supported by advanced training programs and career growth opportunities. There is a focus on leveraging cutting-edge skills and knowledge to drive continuous improvement and innovation.	Personnel are skilled in analyzing predictive maintenance data, utilizing advanced signal processing and machine learning models to anticipate and prevent failures. They receive specialized training in predictive analytics, advanced diagnostics, and condition monitoring, supported by continuous learning programs to stay current with emerging technologies.	The workforce is highly proficient and fully integrated into the prescriptive maintenance process, with continuous learning and adaptation as part of the organizational culture. Employees contribute to and refine prescriptive models, utilizing real-time data to anticipate and optimize maintenance actions. Career development is focused on advancing skills in prescriptive analytics, optimization algorithms, and decision-support systems.
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APPENDIX E: Round one Delphi study questionnaire

Development of a maintenance maturity model - Delphi study_round 1

Dear Participant,

Thank you for taking the time to participate in this survey. We appreciate your willingness to participate in this survey. Your expertise and insights are invaluable to the evaluation and refinement of our Maintenance Maturity Model. It is expected to take around 25-30 minutes of your time for its completion. This questionnaire survey aims to collect feedback on the model's design, relevance, applicability, and comprehensiveness. Please provide your honest and thoughtful responses.

After collecting responses from all participants during the first round, we will evaluate and condense the outcomes to create a succinct follow-up survey for round 2.

* Indicates required question

Informed Consent

The researcher guarantees that any data collected during this study will remain confidential and participation is entirely optional. The information obtained will be used exclusively for academic purposes and may be included in the thesis, conference presentation, or published papers adhering to NWU's strict ethical guidelines provided by their research ethics certificate (Ethics clearance no: NWU-00232-23.A3).

For any additional inquiries about the survey, please do not hesitate to get in touch with Prince G Sibanda at 0645119400 or via email: 49471538@nwu.ac.za. If there are lingering concerns about the research that were left unaddressed or if you wish to file a complaint, feel free to reach out to North-West University Engineering Research Ethics Committee through ENG-REC@nwu.ac.za as well.

Please note: Feel free to ask the researcher any questions about this study if there is anything you do not fully understand. It's crucial that you're completely clear on the purpose of this research and your potential involvement in it. Remember, participating is entirely voluntary; choosing not to participate will not have any negative consequences for you. You also have the freedom to withdraw from the study at any time without penalty.

Completing this survey indicates your informed consent to take part in the study.

1. GENERAL PARTICIPANT QUESTIONS

Please provide your information below. All details will remain confidential and used solely to identify participants for future survey rounds.

1. Name and Surname *

2. Email

3. Years of Experience in Maintenance/Asset Management: *

Mark only one oval.

- ☐ 0-5 years
- ☐ 6-10 years
- ☐ 11-15 years
- ☐ 16-20 years
- ☐ 21+ years

4. What type of industry does your organization belong to *

5. Level of management *

Mark only one oval.

- ☐ Strategic
- ☐ Tactical
- ☐ Operational

6. Role?

7. Area of Expertise: (Checkboxes - Allow multiple selections) *

Check all that apply.

- ☐ Maintenance Management
- ☐ Reliability Engineering
- ☐ Asset Management
- ☐ Risk Management
- ☐ Information Systems/CMMS
- ☐ Maintenance planning
- ☐ Others (Please Specify)

2. VALIDATION OF THE RESEARCH PROBLEM

Research problem:

Frequent infrastructure breakdowns, caused by a lack of well-structured and adaptable maintenance plans and strategies, impede uninterrupted service delivery.

Please rate your level of agreement with the following statements aimed at validating the research problem.

8. There is an urgent need for the development of comprehensive maintenance frameworks that are flexible and responsive to the dynamic challenges faced by asset-intensive sectors like water utilities, to mitigate breakdown occurrences. *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

9. Ineffective maintenance strategies contribute to resource misallocation, further exacerbating infrastructure failures and undermining operational efficiency. *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

10. The persistence of ad-hoc maintenance practices within many organizations indicates a cultural resistance to change, which is detrimental to long-term operational sustainability and needs to be addressed through effective change management strategies. *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

11. Maintenance personnel in South Africa's asset-intensive industries- public sector; lack the adequate training and competency to implement effective infrastructure maintenance strategies. *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

12. There are insufficient mechanisms for regularly monitoring and evaluating maintenance plans for physical infrastructure assets. *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

13. The recurring nature of infrastructure failures highlights systemic deficiencies in maintenance practices, necessitating a comprehensive re-evaluation of existing frameworks to foster resilience and reliability. *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

3. VALIDATION OF THE DESIGN REQUIREMENTS

Please take a moment to review the design requirements for developing a maintenance maturity model and respond to the following questions (*if the table is not clear, please refer to the provided template - Conceptual model and Design requirements*):

Design requirements

Design principles	Design requirements (DR)
Application domain	DR 1: The model must address the operational and strategic requirements of the water infrastructure sector as its primary application domain, while remaining adaptable for broader use across other asset-intensive industries.
Purpose of use	DR 2: The model must function as a diagnostic tool to assess the current maturity level of an organisation's maintenance practices.
	DR 3: It must guide organisations in identifying gaps and areas for improvement, leading to optimised maintenance practices and operations.
	DR 4: The model must offer flexible pathways for various maintenance strategies, allowing organisations to select and progress along the path that best aligns with their specific goals, resources, and operational contexts.
Target group	DR 5: It must be designed for use by maintenance practitioners, and decision-makers at different organisational levels, ensuring accessibility and ease of understanding for users with varying expertise.
Class of entities under investigation	DR 6: The model must provide a comprehensive view of maintenance operations, addressing all key aspects rather than focusing on a single element.
Maturity and dimensions of maturity	DR 7: The maintenance maturity model must encompass all relevant domains and/or dimensions, including a distinct domain dedicated to defining and differentiating maturity levels.
	DR 8: The maintenance maturity model capability statements must be explicitly defined with clear, concise language to ensure they are easily interpretable and actionable by all users, regardless of their level of expertise.
Maturity levels and maturation paths	DR 9: The maintenance maturity model capability statements must distinctly differentiate between each maturity level, ensuring that the characteristics, processes, and performance metrics at each level are clearly defined.
	DR 10: The maintenance maturity model must provide clear guidelines for organisations to progress from one maturity level to the next, with a focus on continuous improvement.

Please rate your level of agreement with the following statements aimed at validating the design requirements for the development of the maintenance maturity model.

14. The design requirements for the model are articulated clearly, ensuring they are specific and easily interpretable by all stakeholders involved in the Delphi study. *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

15. The design requirements emphasize the importance of continuous improvement in maintenance practices, guiding the development of a Maintenance Maturity Model that encourages organizations to assess their current capabilities and implement strategies for ongoing enhancement. *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

16. The design requirements comprehensively address the essential elements necessary to guide the development of the Maintenance Maturity Model, making it relevant and beneficial for both industry practitioners and academic researchers in the field of maintenance management. *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

17. The design requirements adequately outline the foundational criteria needed to create a Maintenance Maturity Model that can effectively assess and guide the identification and development of maintenance competencies and practices within asset-intensive industries. *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

18. From the provided list, identify any design requirements that may be potentially irrelevant to the model's development. *

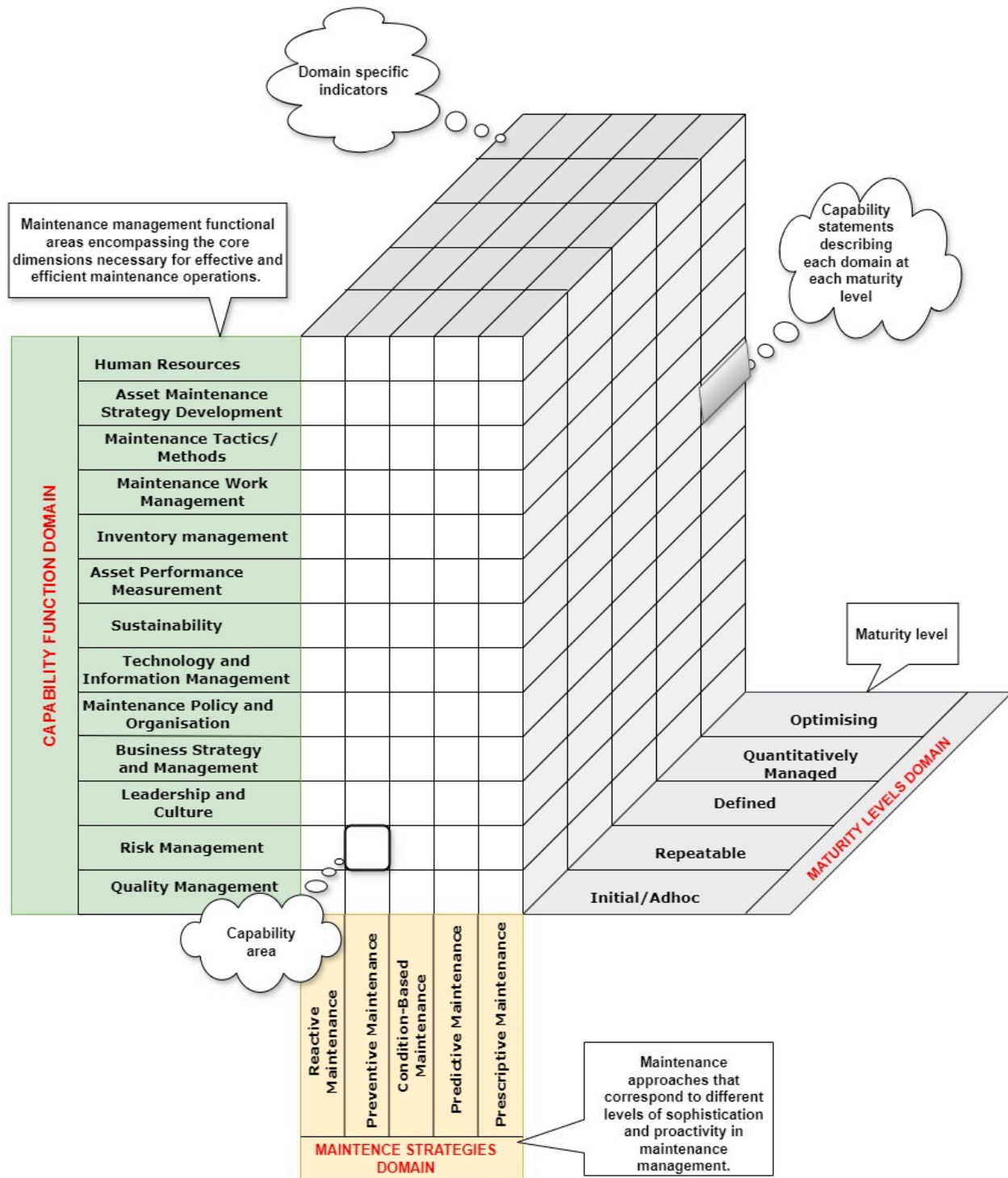
19. Please suggest any additional design requirements that could enhance the development of the model *

20. Comments on the model design requirements (optional)

4. VALIDATION OF THE CONCEPTUAL MAINTENANCE MATURITY MODEL

Please take a moment to review the conceptual model and respond to the questions below (*if the figure is not clear, please refer to the provided template - Conceptual model and Design requirements*). Additionally, consider reviewing the Snapshot of the capability statements for an illustration of human resources and asset performance measurement assessments.

Conceptual maintenance maturity model



This section contains questions designed to assess whether the conceptual model's structure and domains and dimensions align with the design requirements. Please rate your level of agreement with each of the following statements:

21. The conceptual model is clearly articulated and easily understood by participants? *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

22. The maintenance strategies dimensions are appropriate and relevant? *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

23. The functional areas domain accurately and sufficiently reflects maintenance operations and management practices? *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

24. The maturity levels dimension is sufficient to provide a holistic evaluation of an organization's maturity stages within each domain? *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

25. The dimensions within the model are distinct and do not overlap, ensuring clear differentiation between maturity levels? *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

26. The conceptual model accurately reflects the reality of maintenance practices in the field and is based on sound theoretical foundations? *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

27. The conceptual model is user-friendly and can be easily implemented by organizations to assess and enhance their maintenance strategies? *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

28. The insights that can be gained from applying the model are actionable and provide valuable guidance for organizations seeking to improve their maintenance maturity? *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

29. The conceptual model is practical for conducting assessments and flexible enough to accommodate the diverse needs and contexts of different organizations within asset-intensive industries? *

Mark only one oval.

1 2 3 4 5

Strongly Disagree ☐ ☐ ☐ ☐ ☐ Strongly Agree

30. What areas of the model need improvement or refinement? *

31. Are there any domains or dimensions that should be included or removed in the model? *

Mark only one oval.

☐ Yes
☐ No
☐ Maybe

32. If the response to the question above is **"YES"**, please outline your suggestion(s)

33. What do you consider the main strengths of the Maintenance Maturity Model? *

34. What challenges do you foresee in implementing this model in an organization? *

35. Please provide any additional comments or feedback on the conceptual maintenance maturity model. (optional)

Please rate your level of agreement with the following statement

36. The Maintenance Maturity Model offers a practical framework to enhance infrastructure maintenance practices in the water utilities industry *

Mark only one oval.

1 2 3 4 5

Strongly Disagree ☐ ☐ ☐ ☐ ☐ Strongly Agree

37. Please **elaborate** on your response. Specifically, consider how the model could address key challenges such as resource allocation, downtime reduction, service delivery interruptions, overall infrastructure reliability or any other relevant issues. *

6. End of Round 1 of the Delphi Study

Thank you for your valuable feedback! Your insights will help us refine and improve the Maintenance Maturity Model. We appreciate your time and contribution to this research.

APPENDIX F: Delphi round 1 results to the participants

Summary of round 1 results

The round 1 results summary provides an overview of a survey conducted among nine experts using a five-point Likert scale. The scale ranges from 1 (strongly disagree) to 5 (strongly agree), helping to capture the experts' level of agreement with various statements. A key aspect of the summary is the achievement of consensus. For consensus to be deemed reached on a statement, the average score needs to be **3.75 or higher**, indicating that at least 75% of the experts agreed with the statement in some capacity.

This summary sets the groundwork for understanding expert opinions and identifying areas of alignment or disagreement, paving the way for further analysis or rounds of investigation.

Validation of the research problem

Table 35: Mean score of statements validating the research problem

SURVEY STATEMENTS		AVERAGE SCORE
Q1	There is an urgent need for the development of comprehensive maintenance frameworks that are flexible and responsive to the dynamic challenges faced by asset-intensive sectors like water utilities, to mitigate breakdown occurrences.	4.44
Q2	Ineffective maintenance strategies contribute to resource misallocation, further exacerbating infrastructure failures and undermining operational efficiency.	4.33
Q3	The persistence of ad-hoc maintenance practices within many organizations indicates a cultural resistance to change, which is detrimental to long-term operational sustainability and needs to be addressed through effective change management strategies.	4.33
Q4	Maintenance personnel in South Africa's asset-intensive industries- public sector; lack the adequate training and competency to implement effective infrastructure maintenance strategies.	3.56
Q5	There are insufficient mechanisms for regularly monitoring and evaluating maintenance plans for physical infrastructure assets.	3.56
Q6	The recurring nature of infrastructure failures highlights systemic deficiencies in maintenance practices, necessitating a comprehensive re-evaluation of existing frameworks to foster resilience and reliability.	4.33

There was no consensus reached on certain statements (average scores highlighted in red) regarding the validation of the research problem in the initial round. As a result, these statements will be revisited in Round 2 for further deliberation.

Validation of the design requirements

Table 36: Mean score of statements validating the model design requirements

SURVEY STATEMENTS		AVERAGE SCORE
Q7	The design requirements for the model are articulated clearly, ensuring they are specific and easily interpretable by all stakeholders involved in the Delphi study.	4.44
Q8	The design requirements emphasize the importance of continuous improvement in maintenance practices, guiding the development of a Maintenance Maturity Model that encourages organizations to assess their current capabilities and implement strategies for ongoing enhancement.	4.33
Q9	The design requirements comprehensively address the essential elements necessary to guide the development of the Maintenance Maturity Model, making it relevant and beneficial for both industry practitioners and academic researchers in the field of maintenance management.	4.33
Q10	The design requirements adequately outline the foundational criteria needed to create a Maintenance Maturity Model that can effectively assess and guide the identification and development of maintenance competencies and practices within asset-intensive industries.	4.11

In the first round of the study, there appeared to be strong consensus among experts regarding the validity of the design requirement statements.

Validation of the conceptual maintenance maturity model structure

During the initial round of evaluating the maintenance maturity model, **no consensus was reached on certain statements** (average scores highlighted in red) regarding the adequacy of the model's conceptual structure. This lack of agreement has underscored the need for further refinement and validation. Please consider round 2.

Table 37: Mean score of validation statements for conceptual maintenance maturity model

SURVEY STATEMENTS		AVERAGE SCORE
Q11	The conceptual model is clearly articulated and easily understood by participants?	3.56
Q12	The maintenance strategies dimensions are appropriate and relevant?	4.22
Q13	The functional areas domain accurately and sufficiently reflects maintenance operations and management practices?	3.78

Q14	The maturity levels dimension is sufficient to provide a holistic evaluation of an organization's maturity stages within each domain?	3.89
Q15	The dimensions within the model are distinct and do not overlap, ensuring clear differentiation between maturity levels?	3.89
Q16	The conceptual model accurately reflects the reality of maintenance practices in the field and is based on sound theoretical foundations?	3.89
Q17	The conceptual model is user-friendly and can be easily implemented by organizations to assess and enhance their maintenance strategies?	3.33
Q18	The insights that can be gained from applying the model are actionable and provide valuable guidance for organizations seeking to improve their maintenance maturity?	4.1
Q19	The conceptual model is practical for conducting assessments and flexible enough to accommodate the diverse needs and contexts of different organisations within asset-intensive industries?	3.56
Q20	The Maintenance Maturity Model offers a practical framework to enhance infrastructure maintenance practices in the water utilities industry	4.33

APPENDIX G: Round two Delphi study questionnaire

Development of a maintenance maturity model - Delphi study_Round 2

Dear Participant,

Thank you for participating.

We appreciate you taking the time to complete this questionnaire, which will take approximately 10 - 15 minutes.

The purpose of this survey is to achieve consensus on experts' views regarding the validity of the research problem and the sufficiency of the proposed Maintenance Maturity Model structure.

An analysis of participants' feedback from round 1 has been sent to your email.

We kindly encourage you to provide detailed comments, especially in areas of concern or suggestions for improvement. Clear and explicit feedback will greatly assist in refining the model and reduce the need for follow-up emails.

Thank you for your valuable contributions to this research!

* Indicates required question

Informed consent statement

The researcher guarantees that any data collected during this study will remain confidential and participation is entirely optional. The information obtained will be used exclusively for academic purposes and may be included in the thesis, conference presentation, or published papers adhering to NWU's strict ethical guidelines provided by their research ethics certificate (Ethics clearance no: NWU-00232-23.A3).

For any additional inquiries about the survey, please do not hesitate to get in touch with Prince G Sibanda at 0645119400 or via email: 49471538@nwu.ac.za. If there are lingering concerns about the research that were left unaddressed or if you wish to file a complaint, feel free to reach out to North-West University Engineering Research Ethics Committee through ENG-REC@nwu.ac.za as well.

Please note: Feel free to ask the researcher any questions about this study if there is anything you do not fully understand. It's crucial that you're completely clear on the purpose of this research and your potential involvement in it. Remember, participating is entirely voluntary; choosing not to participate will not have any negative consequences for you. You also have the freedom to withdraw from the study at any time without penalty.

Completing this survey indicates your informed consent to take part in the study.

1. GENERAL PARTICIPANT QUESTIONS

Please provide your information below. All details will remain confidential and used solely to identify participants for future survey rounds.

1. Name and Surname *

2. Email

2. VALIDATION OF THE RESEARCH PROBLEM

Research problem: Frequent water infrastructure breakdowns, caused by inadequately structured and adaptable maintenance plans and strategies, significantly hinder the provision of uninterrupted service delivery.

Please rate your level of agreement with the following statements aimed at validating the research problem.

3. There is an urgent need for the development of comprehensive maintenance frameworks that are flexible and responsive to the dynamic challenges faced by asset-intensive sectors like water utilities, to mitigate breakdown occurrences. *

Mark only one oval.

	1	2	3	4	5	
Stro	☐	☐	☐	☐	☐	Strongly Agree

4. Ineffective maintenance strategies contribute to resource misallocation, further exacerbating infrastructure failures and undermining operational efficiency. *

Mark only one oval.

	1	2	3	4	5	
Stro	☐	☐	☐	☐	☐	Strongly Agree

5. The persistence of ad-hoc maintenance practices within many institutions indicates a cultural resistance to change, which is detrimental to long-term operational sustainability and needs to be addressed through effective change management strategies. *

Mark only one oval.

	1	2	3	4	5	
Stro	☐	☐	☐	☐	☐	Strongly Agree

6. Maintenance personnel in South Africa's water utilities lack adequate specialised training and competency, hindering the implementation of effective maintenance strategies for water infrastructure. *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

7. There are inadequate mechanisms in place for the regular monitoring and evaluation of maintenance plans specifically tailored for water infrastructure assets. *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

8. The recurring nature of infrastructure failures highlights systemic deficiencies in maintenance practices, necessitating a comprehensive re-evaluation of existing frameworks to foster resilience and reliability. *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

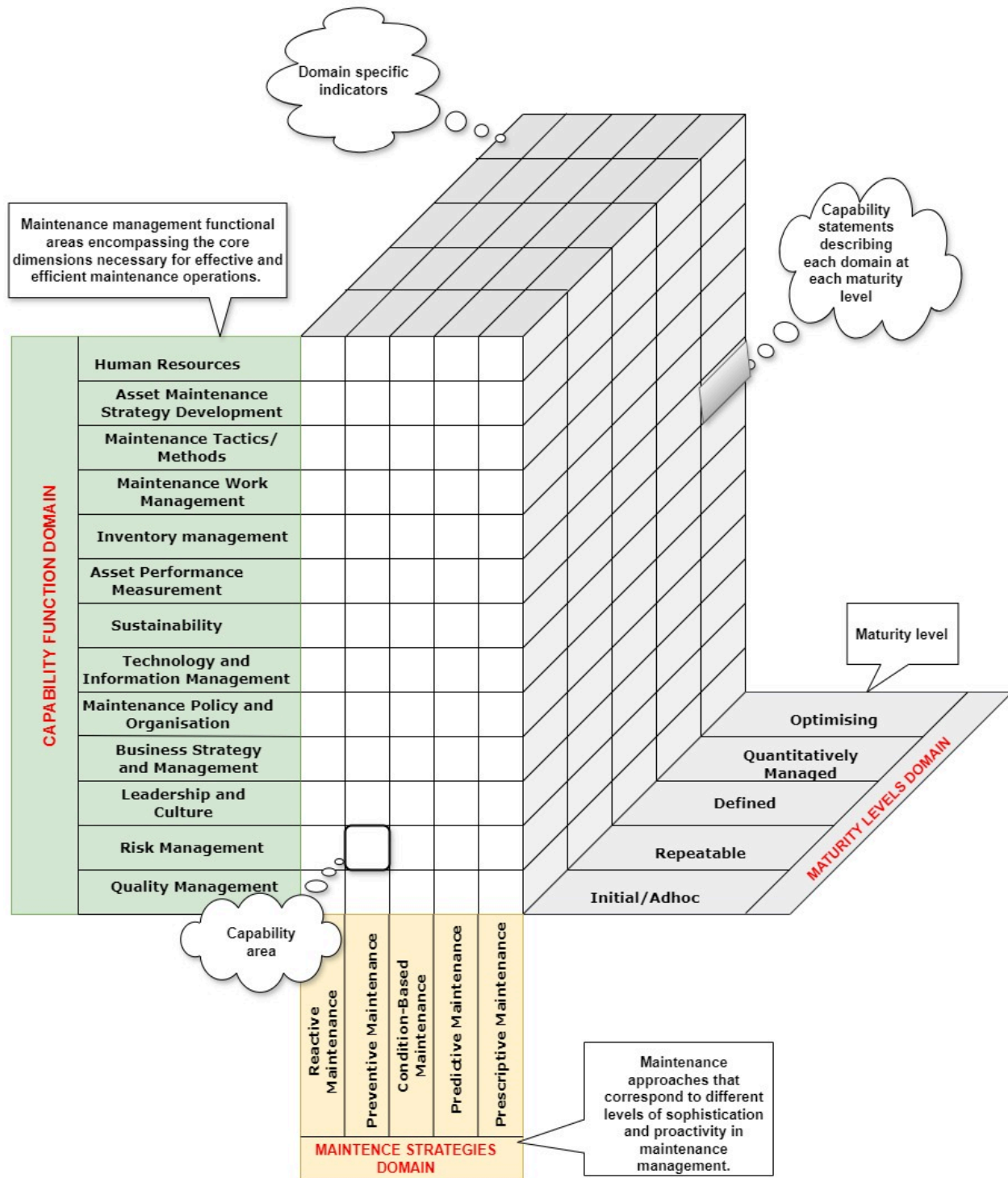
9. Comments on research problem (Optional)

4. VALIDATION OF THE CONCEPTUAL MAINTENANCE MATURITY MODEL

Please take a moment to review the conceptual model and respond to the questions below. To gain a comprehensive understanding, we encourage you to:

1. Review the **Maturity Model Overview** (attached).
2. Examine the **Snapshot of the Capability Statements**, which includes examples of assessments for **Human Resources** and **Asset Performance Measurement** domains.

Conceptual maintenance maturity model



This section contains questions designed to assess whether the conceptual model's structure and domains and dimensions align with the design requirements. Please rate your level of agreement with each of the following statements:

10. The conceptual model is clearly articulated and easily understood by participants? *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

11. The maintenance strategies dimensions are appropriate and relevant? *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

12. The functional areas domain accurately and sufficiently reflects maintenance operations and management practices? *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

13. The maturity levels dimension is sufficient to provide a holistic evaluation of an organization's maturity stages within each domain? *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

14. The dimensions within the model are distinct and do not overlap, ensuring clear differentiation between maturity levels? *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

15. The conceptual model accurately reflects the reality of maintenance practices in the field and is based on sound theoretical foundations? *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

16. With appropriate training and support, the conceptual model is user-friendly and can be effectively implemented to assess and enhance maintenance strategies. *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

17. The insights that can be gained from applying the model are actionable and provide valuable guidance for organizations seeking to improve their maintenance maturity? *

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

18. Please provide any additional comments or feedback on the conceptual maintenance maturity model. (optional)

6. End of Round 2 of the Delphi Study

Thank you for your valuable feedback! Your insights will help us refine and improve the Maintenance Maturity Model. We appreciate your time and contribution to this research.



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APPENDIX H: SAIE conference paper



SAIE34 Proceedings, 14th - 16th October 2024, Vanderbijlpark, South Africa © 2024 SAIE

A SYSTEMATIC LITERATURE REVIEW ON ASSET MAINTENANCE PRIORITISATION APPROACHES RELEVANT TO WATER INFRASTRUCTURE

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ABSTRACT

While various maintenance prioritisation approaches exist, there is a need for a comprehensive understanding of their effectiveness, applicability, and implications for resource allocation and risk mitigation in water infrastructure maintenance. The study aims to identify, examine gaps and best practices in existing knowledge regarding maintenance prioritisation as applied to water infrastructure assets. A systematic literature review methodology was utilised, adhering to the PRISMA reporting protocol, to explore the Scopus database for literature addressing maintenance prioritisation approaches. The findings reveal that organisations commonly use risk-based approaches to prioritise maintenance tasks. The literature emphasises the importance of considering the frequency and consequences of failure when setting priorities for maintenance tasks. Additionally, popular methods for priority-setting include risk assessment and failure mode effect analysis. The study findings could enhance industrial engineers' contributions to maintenance optimisation and inform the development of a prioritisation framework for water infrastructure maintenance for a small South African municipality.

Keywords: maintenance prioritisation, water infrastructure, systematic literature review

APPENDIX I: Ethical clearance certificate

ETHICS APPROVAL LETTER OF STUDY

Based on approval by the North-West University Engineering Research Ethics Committee (NWU-ENG-REC) on 20 November 2023, the NWU-ENG-REC hereby approves your study as indicated below. This implies that the NWU-ENG-REC grants its permission that, provided the general and specific conditions specified below are met and pending any other authorisation that may be necessary, the study may be initiated, using the ethics number below.

Study title: Developing a prioritization framework for water infrastructure maintenance for a small South African municipality

Dr W Maisiri and Prof Liezl Van Dyk Prince Sibanda

Ethics number:

Institution Study Number Year Status

Status: S = Submission; R = Re-Submission; P = Provisional Authorisation; A = Authorisation

Application Type: Single

Approval date: 20-Nov-23

Risk:

Expiry date: 19 – November - 2024

Approval of the study is provided for a year, after which continuation of the study is dependent on receipt and review of annual monitoring report and the concomitant issuing of a letter of continuation.

NWU-00232-23-A3

Low Risk

General conditions:

While this ethics approval is subject to all declarations, undertakings and agreements incorporated and signed in the application form, the following general terms and conditions will apply:

- *The principal investigator/study supervisor/researcher must report in the prescribed format to the NWU-ENG-REC:*
 - *Annually on the monitoring of the study, whereby a letter of continuation will be provided annually, and upon completion of the study; and*
 - *without any delay in case of any adverse event or incident (or any matter that interrupts sound ethical principles) during the course of the study.*
- *The approval applies strictly to the proposal as stipulated in the application form. Should any amendments to the proposal be deemed necessary during the course of the study, the principal investigator/study supervisor/researcher must apply for approval of these amendments at the NWU-ENG-REC, prior to implementation. Should there be any deviations from the study proposal without the necessary approval of such amendments, the ethics approval is immediately and automatically forfeited.*
- *Annually a number of studies may be randomly selected for active monitoring.*

The date of approval indicates the first date that the study may be started

-
- request access to any information or data at any time during the course or after completion of the study;
 - to ask further questions, seek additional information, require further modification or monitor the conduct of your research or the informed consent process;
 - withdraw or postpone approval if:
 - any unethical principles or practices of the study are revealed or suspected;
 - it becomes apparent that any relevant information was withheld from the NWU-ENG-REC or that information has been false or misrepresented;
 - submission of the annual monitoring report, the required amendments, or reporting of adverse events or incidents was not done in a timely manner and accurately; and/or
 - new institutional rules, national legislation or international conventions deem it necessary.
 - NWU-ENG-REC can be contacted for further information via ENG-REC@nwu.ac.za or 018 299 2645
-

Special conditions of the research approval (if applicable): NA

Special in process conditions of the research for approval (if applicable): NA

The NWU-ENG-REC would like to remain at your service and wishes you well with your study. Please do not contact the NWU-ENG-REC for any further enquiries or requests for assistance.

Yours sincerely,



Prof. P. Van Vuuren Chair NWU-ENG-REC

Current details:(25767984) \NWUNextCloud\ENG-REC\Letters sent\[Date]9.1.5.4.3_NWU-ENG-REC_REC_EAL_[student surname_name] File Reference: 9.1.5.4.2