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Research Paper

Advancing Maintenance 4.0 through an Asset Management Framework: a South African Petrochemical Industry Case Study

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Abstract. The rapid advancement of digital technologies has raised uncertainty about the adequacy of traditional maintenance models to meet Industry 4.0 requirements. This study develops and validates an asset management framework to support the South African petrochemical industry's transition to Maintenance 4.0. The framework was validated through a quantitative survey conducted within a leading petrochemical company in South Africa, ensuring its practical applicability. Descriptive statistical analysis confirmed 15 of 17 framework characteristics and supported five of seven theoretical propositions. Key enablers of Maintenance 4.0 adoption include the integration of human intelligence, machine learning, and real-time data, as well as the role of organizational culture and asset resilience in shaping outcomes. The study offers both theoretical contributions and practical guidance for maintenance professionals seeking to align maintenance practices with Industry 4.0 principles, with relevance extending beyond the immediate case context.

Keywords: Asset Management, Maintenance, Maintenance 4.0, Industry 4.0, Petrochemical Industry.

Introduction

In the era of Industry 4.0, the South African petrochemical industry faces increasing demands to integrate advanced digital technologies to remain competitive, efficient, and sustainable. The petrochemical industry also depends highly on its asset management system to make guided decisions about asset management activities. Industry 4.0 introduces a paradigm shift in asset management and maintenance by deploying predictive analytics, artificial intelligence, the Internet of Things (IoT), and other digital technologies. Digitalization and sustainability are the challenges faced by multiple industries, and their support is prompted by the changes necessitated by Industry 4.0. The transition to Maintenance 4.0 within the petrochemical industry, particularly in South Africa, presents unique challenges and opportunities. Traditional maintenance approaches, largely reactive and preventive, may no longer be adequate to meet the demands of Industry 4.0.

Recent research underscores that Maintenance 4.0 is the most technologically advanced and proactive form of maintenance. Werbińska-Wojciechowska and Winiarska [1] emphasises that the primary aim of

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these technologies is to maximise equipment uptime by reducing unplanned, reactive interventions through real-time data aggregation and analysis across virtual networks. However, achieving Maintenance 4.0 still remains to be widely achieved. In PWC's "Predictive Maintenance 4.0. Predict the Unpredictable" report from companies in Belgium, Germany, and the Netherlands, only 11% of respondents indicated that their companies had reached Level 4.0 [2].

While predictive maintenance approaches promise to minimise downtime and extend asset life, Achouch, et al. [3] cautions that successful Maintenance 4.0 adoption requires not only technological upgrades but also requires organisations to overcome significant organizational cultural, financial, data governance and resource allocation challenges during implementation. Such challenges highlight the need for integrated asset management frameworks that support organisational learning and strategic alignment during the Maintenance 4.0 transition.

Els and Visser [4] studied shortcomings in the implemented asset management strategy, which may result in unexpected events causing production losses or equipment damage in a South African petrochemical facility. They found that there were some areas where the asset management framework is not diligently implemented or applied. A shortcoming is the concept of asset management maturity. It was found that areas that have a mature asset management implementation achieved better overall asset performance. Each area seems to have their own level of maturity in asset management associated with their own unique problems to solve.

This study aims to address these challenges by developing a tailored asset management framework to guide the petrochemical industry in South Africa toward successful Maintenance 4.0 adoption. Furthermore, the framework developed in this study is intended to serve as a practical tool for asset and maintenance managers, providing them with a structured approach to integrate Maintenance 4.0 principles within their organizations. This research contributes to the theoretical understanding of Maintenance 4.0 in the context of the South African petrochemical industry and practical applications, offering guidance that can be validated and refined through further industry testing.

1. Literature Review

Industry 4.0 refers to "a fourth generation of industrial activity as a result of the fourth industrial revolution, characterized by smart systems and Internet-based solutions" [5]. The combination of industrial petrochemicals with assets, processes, and maintenance management differs from the past, encouragingly, introducing additional strength of advanced industry with internet technologies. The characteristics of Maintenance 4.0 are influenced by Industry 4.0, for example, the use of technology coordination and links of unsettling perception to the business model, maintenance techniques, sharing data through Information and Communication Technologies (ICT), which is the secondary supportive scope to the advancement of the petrochemical industry. Bokrantz, et al. [6] acknowledges that organizational support of technologies is more effective through the association with nanotechnology and robotics as a strategy for Industry 4.0 implementation.

With the Industry 4.0 era, China [7] and Beijing [8] use the term smart factory, considering the use of workshops by petrochemicals to reduce hazards and risk of fieldwork in the highly flammable environment through digitalization, and with energy consumption in New Zealand [9] emphasize the

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use of smart energy integrated into the process of producing petrochemicals. Industry 4.0 focuses on establishing intelligent products and production processes; thus, the key is integration, improving existing processes with the virtual world [10].

1.1. Asset Management Overview

Suakanto, et al. [11] states that the latest industry generation requires more than investing in modern technology; it requires transforming approaches for an organization's asset management and sustaining continuous improvements to petrochemicals. In general, the term "asset" is demarcated by real or probable value to an organization, and that valuable thing contributes to the performance that realizes the organization's objectives [11]; this definition agrees with ISO 55000 [12]. For the utmost value of an asset to be recognized by an organization, vigilant scrutiny of the resources framework in value management is essential throughout the asset's lifespan [11]. Asset management is the approach to the organization's complete vigilant analysis of an asset to ensure the realization of value from the assets within the conditions of the organization.

Industry 4.0 has introduced an asset with diverse properties, such as the Internet of Things (IoT), defined as the system of physical substances "things' implanted by high-tech devices (sensors, software, and other technologies) with the drive of linking and interchanging information with additional devices and systems within the virtual world [11]. Therefore, IoT is an advanced asset in economics and capabilities that impose forward-thinking in asset management. The features of data and the process of realizing, understanding, and cooperating with trends in petrochemicals are precisely for asset management, which [13] calls the analytical system architecture process.

1.1.1. Organizational and people

The People, Process, and Technology (PPT) framework, established in the 1960s [14], remains central to organizational transformation, emphasizing that effective asset management relies on a balanced integration of all three elements. Recognizing people within this asset management highlights how stakeholders' influence can both enable and constrain asset management implementation, as they drive process optimization through technology [11].

1.1.2. Asset information and management system

Asset information and management systems are guided by industry standards like ISO55000 and the IIMM, which serve as best practice guides for asset management. The Asset Management Information System (AM-IS) integrates people, processes, and technology to deliver essential outcomes such as risk reduction, cost efficiency, improved asset performance, policy compliance, resource optimization, and infrastructure investment [11].

1.1.3. Asset supporting actions

Asset supporting actions aim to reduce asset risks through condition monitoring, which quantifies risks by tracking asset operability and preventive measures that assess reliability and availability. AI and machine learning technologies support predictive maintenance, while performance evaluation guides feasibility and financial risk assessment [11].

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1.1.4. Organizational risk and objective

Organizational risk and objectives are closely interconnected, underscoring the importance of aligning asset management with an organization's financial and strategic goals. Organizational objectives are defined as the outcomes an organization aims to achieve, which typically include financial targets such as revenue growth, return on investment (ROI), and cost reduction. In asset management, achieving these objectives requires a comprehensive understanding of risk factors associated with asset ownership and operations. These risks encompass various dimensions, including financial risks (e.g., unexpected costs of repair or replacement), regulatory compliance risks, and risks associated with asset functionality and longevity [11].

Asset management integrates risk assessments into decision-making by evaluating cost, value, and risk together, enabling a balanced asset investment and maintenance approach. Organizations can better anticipate potential financial or operational challenges by incorporating risk assessment, ensuring that asset-related decisions align with broader strategic objectives. This alignment not only minimizes losses and optimizes resource allocation but also promotes sustainable, long-term asset management practices that support organizational resilience and goal achievement [11].

1.2. Industry 4.0 data

Big data analysis perception, the term architecture exists to offer an all-inclusive interpretation of the characteristics of assets and necessities, with resolutions of asset management [13]. The importance of structure is that with big data, the amount of data categorizing and storing presents the potential of data not being used. subsequently, data not fulfilling its intended purpose impacts the efficiency of the asset management process [13]. Therefore, established and distinct architectures in petrochemicals, inclusive of uniform asset valuation, reduce faults by conquering the uncertainties associated with ill-informed decisions through an unstructured technique.

One of the technologies that offers flexibility, reliability, and user customization, as outlined as a requirement for petrochemical industry systems, is the Digital Twin (DT) technique [15]. The DT approach combines the physical and the virtual environment through the digital revolution, resulting in a close presentation of the physical online. The presentation affects the entire petrochemical industry system lifespan, including design, material, engineering details, and components [15].

For the petrochemical industry, where the highest risk is associated with employees, complex facilities and training are used as an organizational barrier appropriate to manage within the facilities and enable the use of engineered assets. DT adds to the training and learning aspects with the benefits of a virtual platform, thus controlling the undesirable events versus the chances of those undesirable events possible in the physical world while learning [16]. From observation of the asset DT model and framework of the assembly shop-floor data, not only is the system complex due to links to many organizational parts and systems that are interconnected to accomplish analytic and predictive resolutions [15], but it is also a potential threat that can result in more glitches being carried over to the petrochemical systems. To counterweigh the threats and overcome complexity, manufacturers can begin by determining the possibilities to familiarize themselves and be ready for high-tech variations

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such as the DT model. Loaiza and Cloutier [15] states it is an exposed system that advances uninterruptedly and familiarizes itself with diverse conditions.

1.3. Maintenance 4.0

The classification of maintenance tasks, namely repairs, inspection, improvement, and services, has the primary objective of ensuring that assets realize their organizational value and that it is sufficient [17]. Maintenance is a critical activity well-thought-out across the organization, with prioritization higher in the industrial sector [13, 18], and technological progress is changing how assets are usually sustained. According to the sound self-explanatory business model, the input-process-output model view of maintenance in an enterprise is systematically supported by where the spares, material, tools, and information are the input of a maintenance system as a process, resulting in the safety according to [18]. From the system view, it is clear that maintenance activities are rooted in an industry system; therefore, progressive maintenance services are also rooted in Industry 4.0 [19].

Recent literature reinforces the idea that Maintenance 4.0 is fundamentally different from earlier maintenance generations. Werbińska-Wojciechowska and Winiarska [1] describe Maintenance 4.0 as a proactive maintenance paradigm in which predictive and smart maintenance strategies are implemented using IoT, cloud computing and immersive technologies. In a systematic literature review consisting of 214 articles, they determined that the current trends in Maintenance 4.0 approaches can be categorized into five groups: Data-driven decision-making in Maintenance 4.0, Operator 4.0, Virtual and Augmented reality in maintenance, Maintenance system architecture, and Cybersecurity in maintenance. Zeghmar, et al. [20] demonstrates that Maintenance 4.0 systems rely on machine-learning algorithms, cyber-physical systems and IoT to anticipate anomalies, foresee failures and reduce asset downtime, organised into four core processes: data collection, data analysis, dynamic monitoring and decision-making.

Complementary Mashaba and Mathaba [21] evaluates how 4IR technologies, such as Smart Sensors, IoT, artificial intelligence (AI), autonomous robotics, cloud computing and augmented reality, impact inspection, repair and service activities in the South African Petrochemical Industry. Smart Sensors and IoT rank highest for real-time diagnostics and interconnected systems, while AI and robotics show weaker performance in the “people” dimension, revealing socio-technical imbalances.

Hien, et al. [19] add that equipment useful life, elevation and improvement in general assets usefulness for participants in the direction of industry sustainability. The connection between asset management and Industry 4.0 is associated with employing the technologies in Industry 4.0, a characteristic feature of Maintenance 4.0 that differentiates it from other maintenance before the Industrial Revolution. Organizations comfortable with conventional maintenance M1.0, 2.0, and 3.0 find it difficult to remain competitive, consequently affecting their performance because of the chosen maintenance strategies in a technologically driven industry 4.0. Navas, et al. [22] states that Maintenance 4.0, must be the first option, Maintenance 3.0 (preventative) is the second option, and the last option is corrective (reactive) maintenance when selecting a maintenance strategy. Manickam [18] identified the following key factors that contributed to the success of maintenance: training and skills, performance measurements, costs and benefits, safety and reliability engineering, maintenance manuals, scheduling and planning, and operational research.

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1.3.1. Predictive and prescriptive maintenance (Maintenance 4.0)

Maintenance is a continuously refining action that boosts service excellence and saves on working capital [23]. Industry 4.0 necessitates organizational improvement, which predictive maintenance (PdM) techniques can achieve. Arnaiz, et al. [23] add that PdM assists with recognizing variances early in the petrochemical maturation and advances Original Equipment Manufacturers (OEM) by solving difficulties differently due to the real-time data obtained through the PdM system. The constraint of PdM technologies is what Spendla, et al. [24] also identified with intelligent predictive maintenance (IPdM) and detailed business scenarios; not all the organizational problems can be solved by adopting Industry 4.0, but certain aspects of the industry can move towards better business margins by applying Industry 4.0. Arnaiz, et al. [23] cautions that lack consideration of some of the PdM technologies, costs, and restraints of change are known weaknesses that articulate evidence that must be offered for precision.

PdM is a progression from the condition-based strategy [24] distinct by its approximations to project possible equipment failure and permit the hindrance cause towards elimination or maintenance before considerably reducing the equipment's best performance condition. PdM is incomparable to preventive maintenance as it can notice maintenance requirements and project equipment status (trends) and examine findings. Spendla, et al. [24] and Jasiulewicz-Kaczmarek, et al. [25] agree that advanced predictive maintenance is founded on a statistical (real-time data) model for predicting failures and maintenance policy, while condition-based predictive maintenance is preceded by changes in the machine's behavior [24] to achieve a complete maintenance workflow [25]. The solid features of Industry 4.0 are derived from its maintenance; in this case, Maintenance 4.0, and those features Al-Najjar, et al. [26] mention them: real-time communication, decentralization, fault finding, robotics, real-time information, intelligence, economy considerate, accessible, monitoring petrochemical process ability, precise conclusions, digitalized, petrochemical's key performance indicators consideration.

2. Conceptual Model

Suakanto, et al. [11] present a grounded theory asset management framework, depicted in Figure 1, which analyses asset lifecycle phases to ensure assets contribute value and align with organizational financial and strategic goals. Their purpose was to provide organisations with a systematic model that aligns asset management activities with organisational objectives by explicitly balancing value, cost, and risk across the entire asset lifecycle.

Grounded theory is widely recognised as an academically acceptable methodology because it provides a systematic means of uncovering complex relationships that are often hidden in dynamic environments [27-30]. As highlighted by Sembiring, et al. [31], grounded theory plays an important role in information systems research, particularly in contexts such as asset management, where interconnected factors of value, cost, and risk must be understood holistically. In their study, grounded theory has been employed in conjunction with the ISO 55000 standard as a best practice in asset management to explore the relationship between value, cost, and risk factors. As asset management operates in dynamic and multidimensional environments, grounded theory's incremental, systematic, and inductive nature makes it especially suitable for capturing situational complexity and generating actionable theoretical insights. The grounded theory model was based on the following research methodology steps: ontology

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(asset management theoretical perspectives), epistemology (theoretical of knowledge embedded in asset management theoretical perspective), axiology (knowing the field of studies which influences asset management interdisciplinary), rhetoric (processing the knowledge claims), methodology (a conceptual asset management framework).

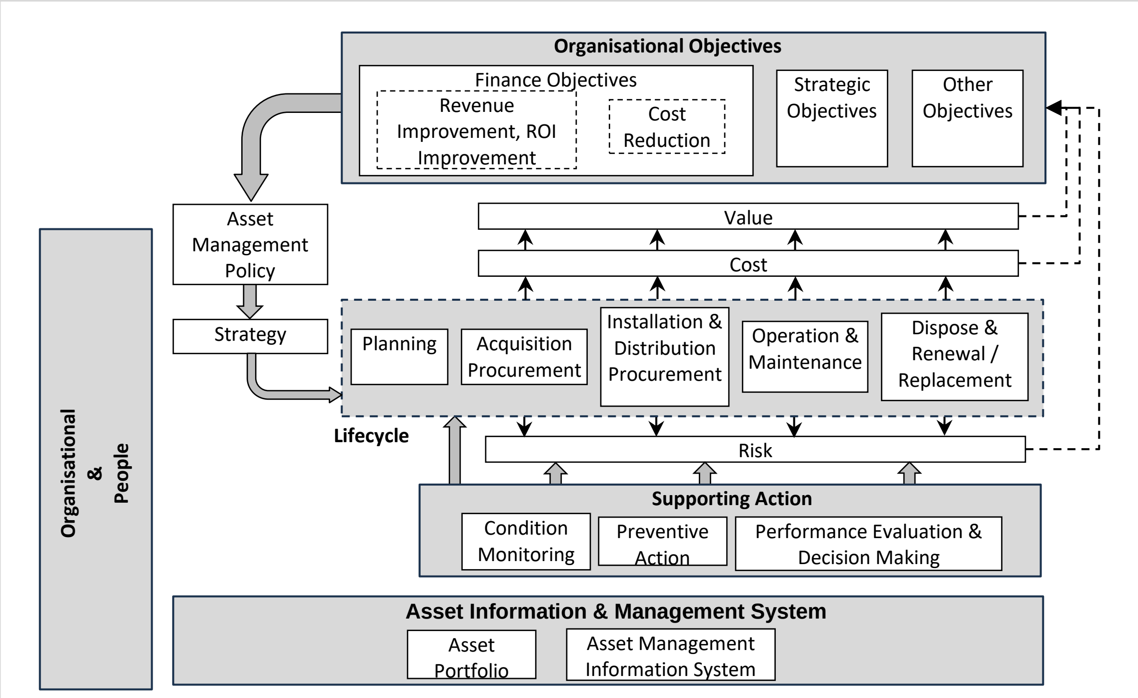

Figure 1: The grounded theory Asset Management Framework (AMF)
Source: Suakanto, et al. [11]

Suakanto et al.'s framework also exhibits notable limitations. First, as a conceptual model derived from grounded-theory interviews, it lacks quantitative evidence demonstrating improved asset performance or financial outcomes, leaving its effectiveness untested. Relatedly, the authors do not clearly describe the number or diversity of organisations studied, raising questions about how widely their findings can be generalised.

Despite its limitations, the framework's holistic integration of cost, value, and risk assessments across the asset lifecycle provides managers with a comprehensive view that many existing models lack. Its alignment with recognised standards, such as ISO 55000, the International Infrastructure Management Manual, and the people–process–technology approach, ensures compatibility with established practices, making it a practical starting point for organisations seeking to enhance asset management without redesigning their systems from scratch. Suakanto, et al. [11] state that future studies can build on their research to explore how the grounded theory asset management framework can be expanded into a more detailed model.

The conceptual asset management framework used in this study, Figure 2. is an expansion of the grounded theory asset management framework suggested by Suakanto, et al. [11] and tailored for the petrochemical industry. This involved developing a more detailed, comprehensive model that further clarifies and organises the complex elements of the grounded theory asset management framework, enhancing its practical applicability and depth.

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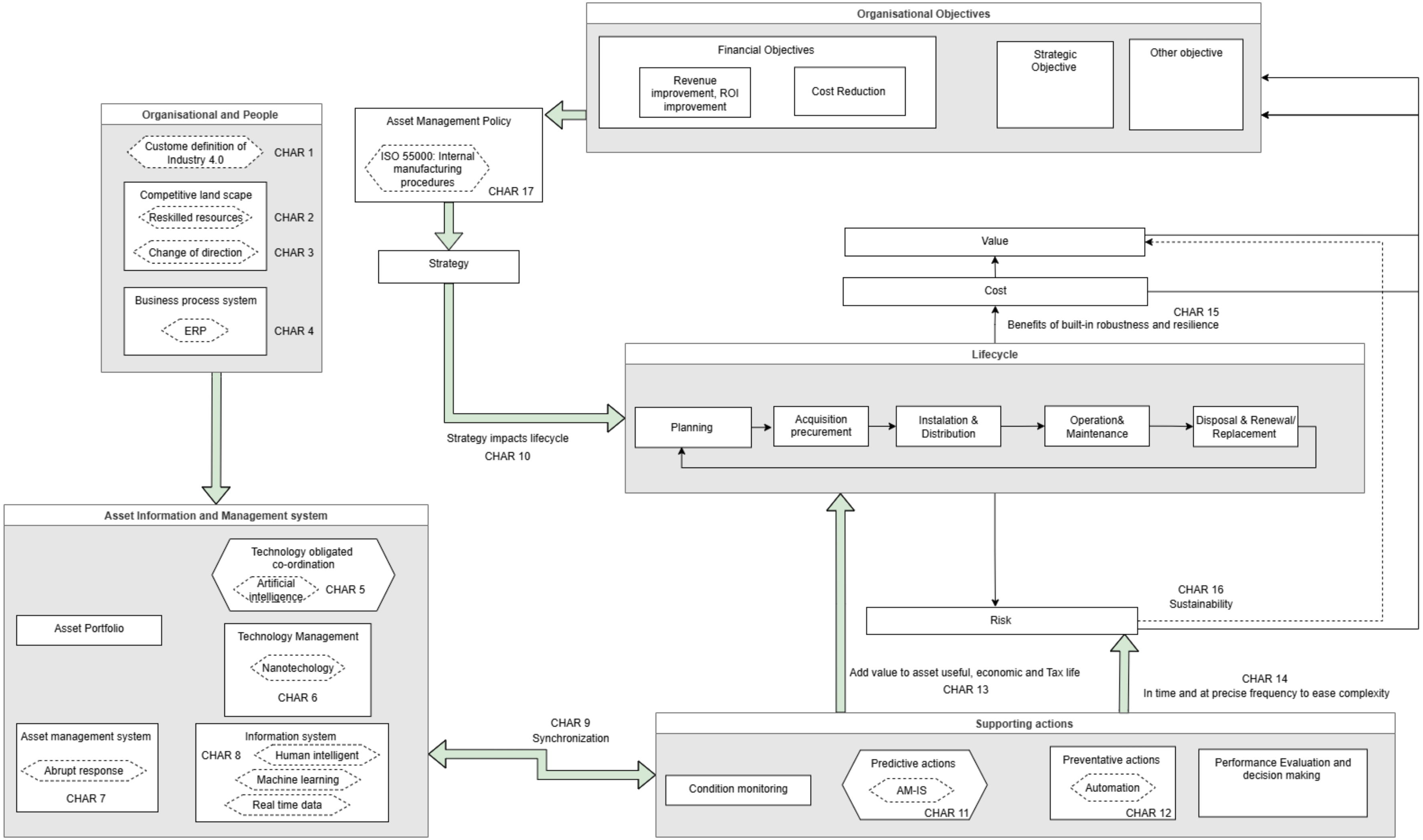

Figure 2: A Conceptual Maintenance 4.0 Asset Management Framework

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The aim is to ensure the successful implementation of Maintenance 4.0, which encompasses the petrochemical industry, not limited to assets, but includes asset support and service systems to emphasise creating value-added networks. The expansion of Suakanto et al.'s grounded theory asset management framework followed a structured process. The four sub-categories of the original framework, organisational and people factors, asset information and management systems, asset supporting actions, and organisational risk and objectives, were analysed using recent literature that the original framework did not explicitly address. After which, each emergent theme from the literature was aligned with one of the four sub-categories in the grounded framework and a corresponding proposition was formulated.

Expansion of sub-category	Proposed characteristic	Proposition and Characteristic	Supporting literature for the addition of characteristics
A. Organizational and people	• Customized definition of Industry 4.0 • Competitive landscape: Re/skilled resources • Competitive landscape: Organizational ability to change direction • Business process system: ERP	• P1 (CHAR 1) • P1 (CHAR 2) • P1 (CHAR 3) • P1 (CHAR 4)	[3, 32-36]
B. Asset information and management system	• Technological obligated coordination: Artificial intelligence • Technology management: Nanotechnology • Asset management system: Abrupt response • Information systems: Human intelligence, machine learning, and real-time data • Synchronization between supporting action and Asset management • Asset lifecycle is decided through organizational strategy	• P2 (CHAR 5) • P2 (CHAR 6) • P2 (CHAR 7) • P2 (CHAR 8) • P3 (CHAR 9) • P3 (CHAR 10)	[36-39]
C. Supporting actions	• Predictive actions: AM-IS • Self-dependent preventative actions: Automation	• P4 (CHAR 11) • P4 (CHAR 12)	[3, 31, 40-43]
	• Asset has a useful life, economic life, and tax life determined by supporting actions • Risk is a result of probability and consequences: the time factor from the supporting acting eases complexity while the opposite hinders organizational objectives	• P5 (CHAR 13) • P5 (CHAR 14)	[12, 44-50]
D. Organizational risk and objective	• The benefits of asset resilience and robustness are the result from asset life cycle and are of value linked to organisational objectives • Sustainability is a result of Risk which can be perceived as value to the organisation • Asset management policy is an enabling strategy for organisation aligned with organisational objective purpose.	• P6 (CHAR 15) • P7 (CHAR 16) • P8 (CHAR 17)	[12, 51, 52]

Table 1: Proposed characteristics of the expansion of the model's sub-categories

The conceptual asset management framework was built upon 8 propositions that provided characteristics for each sub-category of the petrochemical industry. Table 1. lists the characteristics of each sub-category with the 8 propositions.

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- P1: The requirement for successful Maintenance 4.0 implementation depends on the organization and people's culture.
- P2: The requirement for successful Maintenance 4.0 implementation depends on the organizational information and knowledge used to manage assets.
- P3: Organizational strategy, asset lifecycle, and supporting actions are factors that influence asset information and management systems.
- P4: The requirement for successful Maintenance 4.0 implementation depends on supportive actions consistent with organizational asset management.
- P5: Asset lifecycle, Risk, and Organizational objectives are factors that influence the impact by supporting actions.
- P6: Risk and Organizational objectives are factors that influence Asset lifecycle
- P7: Sustainability is a result of risk that can be perceived as valuable to the organization.
- P8: Asset management Policy and strategy influence organizational objectives.

3. Research Methodology

Within Section 2, a conceptual asset management framework for the petrochemical industry was developed, as shown in Figure 2. The validation of the proposed framework was undertaken through a structured quantitative survey designed to test the 17 characteristics associated with the seven theoretical propositions of the framework. Each characteristic was transformed into a survey item, enabling respondents to express their level of agreement with its relevance to the adoption of Maintenance 4.0 in the petrochemical industry. A six-point Likert scale was employed to avoid central tendency bias, thereby ensuring clearer distinctions in respondent perceptions. This approach was deemed suitable for an exploratory validation of the conceptual framework, providing initial empirical evidence of its applicability. While the validation process does not constitute final proof of the framework, it establishes a credible foundation for future confirmatory studies using advanced methods such cross-sectoral testing.

The study was conducted within one of the largest operating energy and chemicals organizations in the South African petrochemical industry. The organization has over 17,000 employees and multiple operations, namely chemicals, fuels, market distribution, and research. The data acquisition was limited to two of this organization's Operating Model Entities (OME).

The sample population in this study comprised reliability engineers, data scientists, asset management leads, process engineers, and technicians, representing key phases of the asset lifecycle. Technicians provided insights into the operational maintenance stage, while engineers offered technical support, reflecting the asset lifecycle's design, acquisition, and disposal stages.

A web-based questionnaire was completed using Qualtrics to enable respondents to complete the survey online through links sent via email requesting participation. The survey began with a consent form explaining the purpose, ethical and confidential information to the respondent, and a request to participate in volunteering. The data was collected over two months, with follow-ups during the data collection process. The results extracted were analysed using Excel, Qualtrics statistics feature, and Mini Tub for written results.

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Questionnaire contents were categorised into general information and validation of the asset management framework for the petrochemical industry. General information regarding the respondents entailed organizational occupation, demographics profile, and experience level. The questionnaire complied with the University of Pretoria's ethical clearance and approval process, and organizational authorisation was obtained before data collection. The anonymity of respondents was secured through the confidentiality procedure guided by the University and the organization's procedure, with results reported as a collective.

4. Results

379 individuals were identified as the sample population, and 45 questionnaire responses were received, equaling a response rate of 12%. Two of the responses received were discarded for being incomplete; therefore, 43 were reserved for analysis.

The details of the respondents, including the spread of functional roles such as process, maintenance, production, technical support, and management, and lead roles, were well represented. Aligned with the organizational hierarchy structures, leads and managers are the lowest, 7% and 14%, respectively. The engineers represented 60%, while the technicians and technologists represented 19%.

The experience level in maintenance management is deemed significant when collecting data from working professionals; the experience factor is the skills and knowledge measured by councils or committees and industries in levels. The level of experience is measured in years and categorised for group analysis. The wide range of participants in the survey was selected to cater to varying levels of knowledge and skill from the maintenance generation viewpoint and framework. Results in the lowest participation, with 19% of participants having more than ten years of working experience, and the highest is a split between less than two years and between 5-10 years of working experience, represented by 30% each; the middle was the participants of between 2-5 years represented by 21%.

4.1 An asset management framework for the petrochemical Industry

The validation section required respondents to validate the proposed characteristics of the sub-categories through a 6-point Likert Scale, with six being strongly agree. Each question was framed in such a way as to ask if the respondent strongly disagreed, disagreed, slightly disagreed, slightly agreed, agreed, or strongly agreed that the characteristic is required for the petrochemical industry to adopt an asset management framework for successful Maintenance 4.0 implementation. The mean, Coefficient of Variation (CV%). For acceptance, the characteristic's mean needed to be aligned with slightly agree and higher, thus a mean higher than or equal to 3 and a CV% value below 30% to indicate a relatively low variability in the data.

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Organizational and People	Mean	CV %	Code	Validation
Definition Maintenance 4.0 and culture impact the organization's outcome	5.16	12.40%	CHAR 1	Accepted
Organization's competitive landscape, there is a re/skilled resource associated with Industry/Maintenance 4.0.	4.63	24.19%	CHAR 2	Accepted
An organization's ability to adapt, change, and change direction is a key feature of Industry/Maintenance 4.0.	5.07	20.11%	CHAR 3	Accepted
ERP (*Enterprise Resource Planning/SAP)* is a business process systems that merge critical data, which has an impact on the success, adoption, and implementation	4.63	26.78%	CHAR 4	Accepted

Table 2: Statistical results for organizational and people characteristics

Asset Information and Management System (AM-IS)	Mean	CV %	Code	Validation
Management must have organizational information and knowledge to coordinate technological non-natural(artificial) intelligence for the success of Industry/Maintenance 4.0.	5.02	17.13%	CHAR 5	Accepted
Technology management changed with technology development: the use of Nanotechnology in an organization is the indicator of Industry/Maintenance 4.0, as it must be programmed to imitate human intelligence.	4.02	33.33%	CHAR 6	Not accepted
Asset management systems are required to make abrupt responses (decision-making) for success in Industry/Maintenance 4.0.	4.86	22.48%	CHAR 7	Accepted
Human intelligence, Machine learning, and real-time data from asset information systems have an impact on the successful adoption and implementation of Industry/Maintenance 4.0, which can be deemed critical.	5.21	12.28%	CHAR 8	Accepted
Successful Industry/Maintenance 4.0 has an unsynchronized asset management system and asset supporting actions.	3.74	36.89%	CHAR 9	Accepted*
Asset lifecycle has uncertainties inherent from the Organization's decisions.	4.67	21.63%	CHAR 10	Accepted

Table 3: Statistical results for Asset Information and Management System (AM-IS) Characteristic

**The survey question for (CHAR 9) was intentionally phrased negatively as "successful Industry/Maintenance 4.0 has an <u>unsynchronised</u> asset management system and asset supporting actions", and the survey results showed respondents did not agree with it (mean = 3.74, CV = 36.89 %). The rejection does not imply that synchronisation between asset management and supporting actions is rejected. Rather, it underscores the opposite: respondents strongly believe that synchronised asset management systems and support functions are necessary for successful Maintenance 4.0. Therefore, CHAR 9 is accepted.*

Asset supporting actions	Mean	CV %	Code	Validation
Organizations that are successful in implementing Industry/Maintenance 4.0 have an Asset Management Information System as a driver for predictive actions.	5.12	13.4%	CHAR 11	Accepted
Organizations that are successful in implementing Industry/Maintenance 4.0 have complete preventative action through self-dependent systems (automation).	4.77	17.40%	CHAR 12	Accepted
Asset useful life, economic life, and tax life are determined by the asset supporting actions in Industry 4.0 Organization.	4.67	23.74%	CHAR 13	Accepted
The time factor from supporting action influences the complexity of the Risk associated with that asset.	4.86	16.87%	CHAR 14	Accepted
Asset resilience and robustness are the characteristics of asset benefits realized through asset lifecycle.	5.14	13.61%	CHAR 15	Accepted

Table 4: Statistics results for Asset supporting actions Characteristic

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Organizational Risk and Objectives	Mean	CV %	Code	Validation
Organizational sustainability is a result of balanced organizational risk management and perceived value awareness of the Organization, which influences organizational objectives.	4.95	18.38 %	CHAR 16	Accepted
Successful Industry/Maintenance 4.0 organizations perceive Asset Management policy (ISO 55000X) as a barrier to organizational strategy.	3.63	37.19 %	CHAR 17	Not accepted

Table 5: Statistical results for Organizational Risk and Objective Characteristics

5. Findings

The conceptual asset management framework for the petrochemical industry consisted of 4 sub-categories and 17 characteristics. The respondents accepted 15 out of 17 characteristics to be a requirement for the petrochemical industry to adopt an asset management framework for successful maintenance 4.0 implementation. Additionally, these characteristics provided insight into the underlying propositions on which the asset management framework for the petrochemical industry was built. This resulted in the conclusion of propositions shown in Table 6 and the final framework in Figure 2.

Sub-category	Proposition	Result
Organizational and people	P1: The requirement for successful Maintenance 4.0 implementation depends on the organizational and people's culture.	Accepted
Asset information and Management systems	P2: The requirement for successful Maintenance 4.0 implementation depends on the organizational information and knowledge used to manage assets.	Partially accepted
	P3: Organizational strategy, asset lifecycle, and supporting actions are factors that influence asset information and management systems.	Accepted
Asset supporting actions	P4: The requirement for successful Maintenance 4.0 implementation depends on supportive actions consistent with organizational asset management.	Accepted
	P5: Asset lifecycle, Risk, and Organizational objectives are factors that influence the impact by supporting actions.	Accepted
Organizational risk and objectives	P6: Risk and Organizational objective are factors that influences Asset lifecycle	Accepted
	P7: Sustainability is a result of risk that can be perceived as valuable to the organization.	Accepted
	P8: Asset management Policy and strategy influence organizational objectives.	Not accepted

Table 6: Proposition testing

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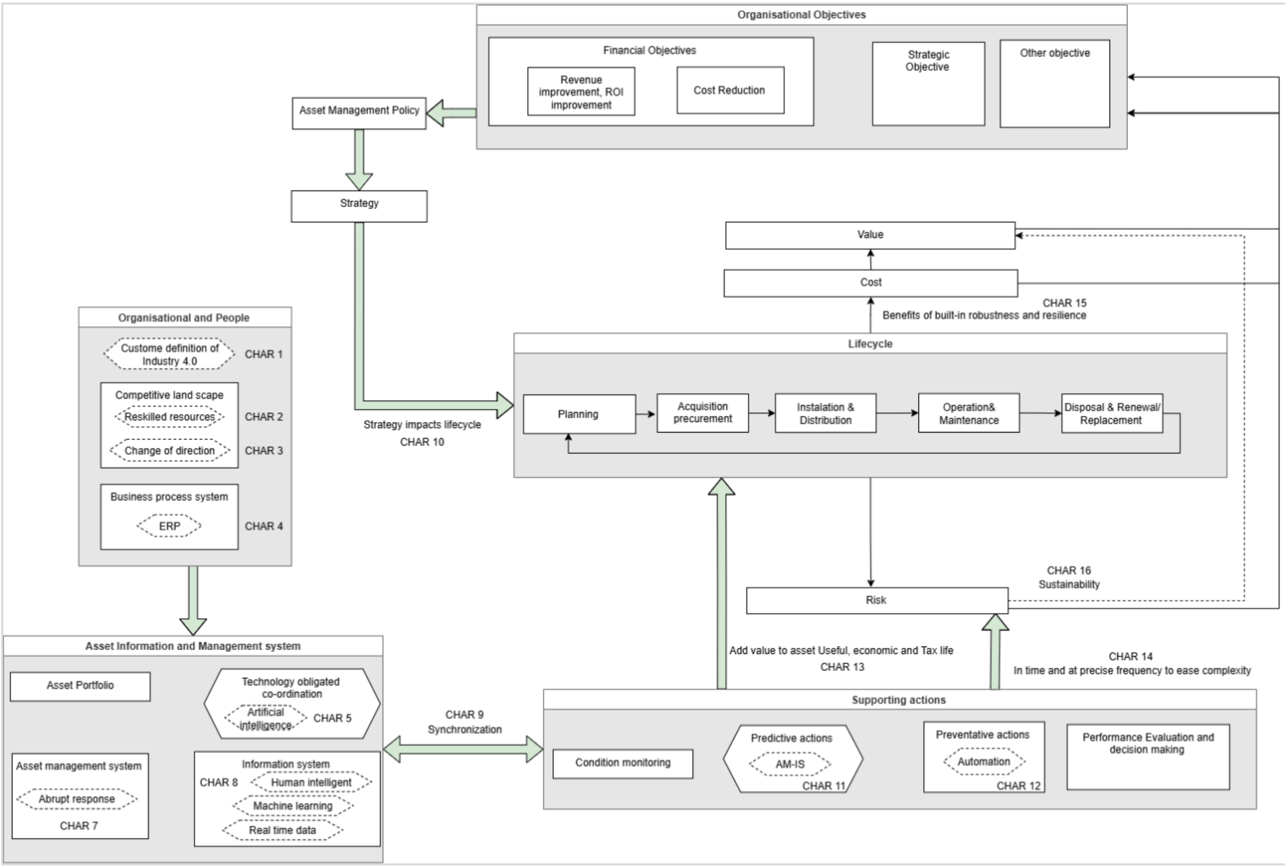

Figure 2: A Maintenance 4.0 Asset Management Framework

Two characteristics (CHAR 6 and CHAR 17) and one proposition (P8) failed the acceptance criteria; their rejection is illuminating and reflects the state of practice within the petrochemical industry. The characteristic "technology management changed with technology development: the use of nanotechnology in an organisation is the indicator of Industry/Maintenance 4.0" (CHAR 6) received a mean of only 4.02 and a CV% (33.33 %), leading to its rejection. Respondents did not consistently perceive nanotechnology as an essential enabler of Maintenance 4.0. This may reflect the current maturity level of the South African petrochemical sector, where nanotechnology is still emerging and its integration into maintenance systems is not yet widespread. CHAR 17 asserted that "successful Industry/Maintenance 4.0 organisations perceive Asset Management policy (ISO 55000X) as a barrier to organisational strategy" and obtained the lowest mean (3.63) and the highest CV% (37.19 %). Consequently, the proposition that "asset management policy and strategy influence organisational objectives" (P8) was also not supported. The rejection suggests that, within the investigated organisation, policies are not considered obstacles; they provide a framework for governance and consistency.

Additionally, when analyzing each statement, the statements that the participants agreed with the strongest were:

- Human intelligence, Machine learning, and real-time data from asset information systems have an impact on the successful adoption and implementation of Industry/Maintenance 4.0, which can be deemed critical.

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- The way an organization and people (stakeholders) define maintenance 4.0 is a result of the organizational and people culture and has an impact on the organizational outcomes.
- Asset resilience and robustness are the characteristics of asset benefits realized through the asset lifecycle.

These statements complement the technology-focused predictive maintenance strategies of Mashaba and Mathaba [21] by providing the organisational architecture, governance, and human-centric elements required to realise technology benefits. These findings, along with the Maintenance 4.0 asset management framework, further contribute beyond existing predictive-maintenance models. Predictive-maintenance models typically focus on sensor deployment, data analytics, and machine-learning algorithms. They seldom address organisational readiness, cultural change or strategic alignment.

Conclusions

A conceptual asset management framework for the petrochemical industry to move towards maintenance 4.0 was developed. Through statistical analysis, 15 of the 17 proposed framework characteristics and 5 of the original propositions were validated, confirming that with minor amendments, the framework can be suitable as a structured approach for modernizing maintenance strategies within the petrochemical industry. In the context of adopting Maintenance 4.0, the successful implementation hinges on several critical factors. Integrating human intelligence, machine learning, and real-time data from asset information systems is vital, as these technologies enable predictive and data-driven decision-making essential for optimizing maintenance processes. Additionally, how an organization and its stakeholders define and approach Maintenance 4.0 is deeply influenced by the existing organizational culture, which impacts overall outcomes. Lastly, enhancing asset resilience and robustness throughout the asset lifecycle underscores the benefits of this framework, as resilient assets contribute to improved performance and long-term operational efficiency, aligning maintenance practices with organizational sustainability goals. Taken together, these validated insights offer clear guidance for workshop-level practice, encouraging maintenance practitioners and managers to merge digital tools with strategic organizational alignment to improve equipment reliability, operational efficiency, Maintenance 4.0 maturity and long-term sustainability in petrochemical operations.

The validation undertaken in this study does not claim to provide final proof of the proposed framework. Instead, it provides initial empirical support and practical validation within one of the most asset-intensive industries in South Africa, thereby demonstrating both relevance and applicability in a context where the adoption of Maintenance 4.0 is critical. The originality of the research lies in the expansion of a grounded-theory asset management framework and its subsequent validation in an industry-specific setting, which together provide statistically defensible evidence of the framework’s utility. This offers a more detailed and context-specific model, which is an improvement over the earlier framework and mark a clear progression from prior theoretical models to a robust, evidence-based Maintenance 4.0 framework. Nonetheless, the validation remains exploratory in nature, and further research is required to confirm and extend its generalisability. By doing so relatively low response rate from this study can be mitigated. Therefore, further research across multiple sectors is recommended to confirm the proposed framework's broader applicability and adapt its features to different industry needs.

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Author Contributions

Rina Peach: Formal analysis, data curation, writing—original draft, writing—review and editing, visualization, supervision and project administration.

Refilwe Matsha: Conceptualization, methodology, validation, formal analysis, investigation, data curation and visualization.

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Conflicts of Interest

The authors declare no conflicts of interest.

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