Exploring preventive maintenance strategies in the petrochemical industry through sixth industrial revolution technologies in Gauteng

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DECLARATION

I declare that the dissertation titled:

Exploring Preventive Maintenance Strategies in the Petrochemical Industry through Sixth Industrial Revolution Technologies in Gauteng

is my own original work. All sources used or quoted have been properly acknowledged through complete referencing and in-text citation. Furthermore, I confirm that this dissertation has not been previously submitted to any other institution for degree purposes.

Lutendo Gifton Mammburu

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ABSTRACT

The petrochemical sector is an asset-intensive safety-critical industry. Preventive maintenance is vital to ensuring reliability, safety and continued operations in South Africa. Understanding the impact on preventive maintenance in the petrochemical Industry in Gauteng is important.

The main aim of the study was to assess how Preventative Maintenance Strategies in Gauteng's petro-chemical industry are affected by the sixth industrial revolution 6IR technologies. Consequently, the objective of the study was to examine maintenance strategies of industrial operators, the level of adoption of 6IR technology in preventive maintenance strategies in the petrochemical industry as well as the organisational, technological and human enablers and constrains to effective adoption of 6IR technology by industrial players in preventive maintenance strategies.

The investigation of 6IR technology impacts on preventive maintenance was the main objective of the study. A qualitative exploratory research design was used in an interpretivist paradigm. The research was held with purposive selection of maintenance managers, engineers and technical specialists from petrochemical organisations in Gauteng.

Data was analysed through thematic analysis using computer-aided qualitative data analysis software to identify the recurring patterns, perception and experiences. According to organisations that implemented 6IR technologies, equipment reliability improved, and unplanned downtime reduced due to better decision-making and safety.

There are significant barriers posed by skills shortages, legacy systems, quality of data, financial constraints and resistance to change from organisations. The benefits of using 6IR technologies cannot be maximised unless they are backed by organisational processes, employee upskilling, and investments.

The research also suggests designing digital maintenance roadmaps; upskilling for maintenance specialists and employees; and enhancing digital data governance. Above all, the study casts light on enhanced leadership commitment to digital transformations.

Keywords: Preventive maintenance; Petrochemical industry; Sixth Industrial Revolution (6IR); Predictive analytics; Condition-based maintenance; Industrial IoT; Gauteng.

LIST OF ABBREVIATIONS

4IR	Fourth Industrial Revolution
6IR	Sixth Industrial Revolution
AECI	African Explosives and Chemical Industries
AI	Artificial Intelligence
AR	Augmented Reality
ATLAS.ti	A Qualitative Data Analysis Software
CAQDAS	Computer-Aided Qualitative Data Analysis Software
CBM C	Condition-Based Maintenance
CMMS	Computerised Maintenance Management System
DT	Digital Twin
ERP	Enterprise Resource Planning
IIoT	Industrial Internet of Things
IoT	Internet of Things
IR	Industrial Revolution
MRO	Maintenance, Repair, and Operations
ML	Machine Learning

PM	Preventive Maintenance
POPIA	Protection of Personal Information Act (South Africa)
PPP	Public-Private Partnership
QDA	Qualitative Data Analysis
RCM	Reliability-Centred Maintenance
SCADA	Supervisory Control and Data Acquisition
SOPs	Standard Operating Procedures
TAM	Technology Acceptance Model
TBM	Time-Based Maintenance
TIR	Technology Integration Readiness
WEF	World Economic Forum
XAI	Explainable Artificial Intelligence
XPM	Explainable Predictive Maintenance

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1 CHAPTER ONE: ORIENTATION TO THE STUDY

This section provides an overview of the study by outlining the research context, background, and rationale for investigating preventive maintenance strategies within the petrochemical industry in Gauteng. It introduces the relevance of Sixth Industrial Revolution technologies and establishes the foundation for the research problem

1.1 Introduction

In today's rapidly evolving industrial landscape, the reliability and uninterrupted operation of plant systems are critical to the success, safety and efficiency of organisations. Within the petrochemical industries, the maintenance department plays a pivotal role in ensuring the integrity and performance of plant systems that support core operations. Preventive maintenance strategies are a cornerstone of modern asset management are essential for safeguarding critical assets, minimising unplanned downtime, and enhancing operational efficiency (Fore & Msipha, 2010:18; Martins *et al*., 2020:17).

With the advent of Sixth Industrial Revolution (6IR) technologies, maintenance practices have undergone significant transformation. Smart technologies, automation, predictive analytics, and the Industrial Internet of Things (IIoT) are reshaping how preventive maintenance is planned and executed (Peter *et al*, 2023:16; McKinsey, 2022:21). Industry 6.0 technologies enable real-time monitoring, predictive maintenance, reliability centred maintenance and data-driven decision-making, which significantly enhance asset performance and operational reliability. This research aims to explore the impact of Industry 6.0 technologies on preventive maintenance strategies within the petrochemical industries in Gauteng region. The study seeks to analyse how these technological advancements influence the Maintenance Department's management, strategic planning, and execution, ultimately optimising the reliability and performance of plant systems.

By investigating emerging technologies currently deployed in maintenance departments, identifying potential areas for improvement, and assessing their impact on plant system reliability, this research highlights the crucial role of Industry 6.0 in modernising maintenance strategies. The findings provide insights into how Gauteng petrochemical

companies can leverage these innovations and technologies to enhance operational resilience, improve efficiency, and ensure seamless and uninterrupted delivery of products and services (Chen, Lu, Jiang & Xing *et al*., 2020:841-851).

The significance of this study extends beyond the confines of petrochemical sectors, influencing broader industrial landscapes. As industries worldwide seek to reduce costly disruptions, enhance safety, and improve sustainability, the adoption of advanced technological solutions in preventive maintenance strategies becomes a key enabler of competitiveness and long-term success. By examining best practices and offering actionable recommendations, this study contributes to the evolving field of industrial asset management and serves as a guide for organisations navigating the challenges of integrating Industry 6.0 technologies into maintenance operations (Prince & Ubani, 2024:20).

In the context of industrial operations, effective preventive maintenance strategies are essential for ensuring the reliability and longevity of plant systems. However, while preventive maintenance is widely recognised as an initiative-taking asset management approach, its precise application within specialised industries such as the industrial gas and petrochemical sectors in Gauteng region requires closer examination. Despite its acknowledged importance, uncertainties remain regarding the optimal design, implementation, and assessment of preventive maintenance practices in this technologically advancing environment (Fore & Msipha, 2010:18).

Plant systems in industrial gas and petrochemical plants are fundamental to the production, storage, and distribution of gases and chemicals. Any failure in these systems can result in severe consequences, including production halts, safety hazards, regulatory non-compliance, and substantial financial losses. Although preventive maintenance strategies are already in place, their alignment with the specific objectives of Gauteng regional petrochemical companies in the era of Industry 6.0 needs further investigation. Assessing the effectiveness of current methodologies, identifying their limitations, and exploring opportunities for improvement through digital transformation is essential to optimising resource utilisation and reducing operational risks (Martins *et al*., 2020:17).

Through an empirical analysis of how Industry 6.0 technologies influence preventive maintenance strategies, this study aims to provide practical recommendations for

optimising maintenance practices within Gauteng's industrial gas and petrochemical industries. By fostering innovation and encouraging the adoption of emerging technologies, the research supports the industry's commitment to operational excellence in maintenance management. This study reinforces the perspective that maintenance is not merely an operational cost but a strategic investment in reliability, safety, and sustainable industrial growth (Peter *et al*., 2023:16).

1.2 Problem statement

As digital transformation accelerates, the integration of Industry 6.0 technologies such as predictive analytics, automation, and the Industrial Internet of Things (IoT) is increasingly portrayed as essential for improving plant reliability and operational efficiency in asset-intensive industries (Peter et al., 2023:16; McKinsey, 2022:21). However, within the petrochemical industry in Gauteng, persistent challenges such as unplanned downtime, maintenance inefficiencies, inconsistent asset performance, and rising maintenance costs continue to occur, even where preventive maintenance methodologies are formally implemented. This raises concerns regarding the actual effectiveness of existing maintenance strategies and the extent to which advanced digital technologies are being meaningfully adopted in practice.

Although existing studies emphasise the importance of analysing maintenance methodologies and assessing the adoption of advanced solutions to generate evidence-based insights that improve decision-making and asset performance (Chen, Lu, Jiang & Xing et al., 2020:841–851), there remains limited empirical evidence on how predictive maintenance, reliability-centred maintenance (RCM), and condition-based maintenance (CBM) frameworks are operationalised within the Gauteng petrochemical context. While predictive maintenance enabled by data-driven condition monitoring has been shown to improve maintenance accuracy and reduce costs in global industrial settings (Prince & Ubani, 2024:20), it is unclear whether similar outcomes are being realised locally. Organisational, technological, and skills-related constraints may limit the effectiveness of these approaches, despite their theoretical advantages.

Consequently, a gap exists between the growing advocacy for Industry 6.0-enabled preventive maintenance strategies and their actual impact on maintenance performance

within Gauteng's petrochemical industries. Assessing the role of RCM and CBM frameworks within this context is therefore necessary to understand how preventive maintenance strategies can be refined to meet evolving operational demands (Fore & Msipha, 2010:18). Addressing this gap is critical to ensuring that investments in advanced maintenance technologies translate into improved operational resilience, safety performance, and sustainability rather than remaining aspirational

1.3 Objectives of this study

This section outlines the primary and secondary objectives that guide the study. The objectives specify what the research seeks to achieve in relation to understanding, analysing, and evaluating the influence of Sixth Industrial Revolution technologies on preventive maintenance strategies.

1.3.1 Primary objective

The primary objective of this study is to explore how Sixth Industrial Revolution (6IR) technologies influence preventive maintenance strategies within the petrochemical industry in the Gauteng region, and to develop a context-specific conceptual framework to guide the effective adoption and integration of 6IR-enabled preventive maintenance practices.

1.3.2 Secondary objectives

To achieve the primary objective, the following secondary objectives must be realised:

- Explore how these strategies align with industry best practices and regulatory requirements.
- Analyse how maintenance performance is tracked, reported, and acted upon to drive continuous improvement.
- Assess whether the integration of Industry 6.0 technologies has improved maintenance efficiency or remains an untapped opportunity.

1.4 Research methodology

This section introduces the methodological approach adopted for the study, explaining the rationale for selecting a qualitative research method. It provides an overview of how data were collected and analysed to address the research objectives.

1.4.1 Research method

The research method refers to the methods or techniques used to conduct research (Bryman, Bell, Hirschon, Dos Santos, Du Toit, Masenge, Wagner, & Van Aardt, 2017:382). The methods can be out, quantitative or a combination of qualitative and quantitative (i.e. mixed method). Examples of research methods include structured or unstructured interviews, questionnaires, surveys and observations.

The study adopts a qualitative research approach, given the study's focus on real-world applications of 6IR-driven maintenance frameworks, a qualitative methodology is most suitable for gaining in-depth insights into maintenance management practices, technological integration, and operational challenges (Nordal & El-Thalji, 2020：55).

Exploratory nature of the study

- The integration of Industry 6.0 technologies into preventive maintenance is still evolving in petrochemical operations. A qualitative approach allows for a deep exploration of industry-specific challenges, opportunities, and readiness for digital transformation (Trento *et al*., 2018：54).
- Understanding how maintenance personnel perceive and engage with predictive analytics, IIoT-based monitoring, and AI-driven maintenance decision-making requires a contextual and interpretive approach (Spöttl & Windelband, 2021：56).

In-depth analysis of maintenance strategies

- Unlike quantitative methods, which focus on numerical performance indicators, qualitative research uncovers operational insights, maintenance philosophies, and organisational decision-making processes (Jimenez *et al*., 2020：48).

- Subject Matter expert interviews are used to assess how Industry 6.0 driven maintenance solutions are being implemented, their success factors, and the barriers to adoption (Nordal & El-Thalji, 2020：55).

Understanding organisational and technological barriers

- Research in predictive maintenance and digital asset management highlights that organisations face technical, financial, and workforce-related barriers to the 6th industrial revolution adoption (Ohalete *et al*., 2023：51).
- A qualitative research design enables the identification of these challenges by collecting first-hand accounts from maintenance managers, engineers, and technicians (Trento *et al*., 2018：54).

Practical industry application

- This study is industry-focused, aiming to provide practical recommendations for integrating smart maintenance solutions in petrochemical operations.
- By using qualitative methods such as semi-structured interviews and document analysis, the research offers actionable strategies tailored to industry-specific needs (Sorooshian & Panigrahi, 2020：49).

1.5 Research design

Research design refers to the procedural plan used by the researcher to answer the research questions in a valid, objective, accurate and economical manner. The main function of the research design is to explain how the research questions will be answered (Kumar, 2011:96).

Data Collection Methods:

- Semi-structured expert interviews with maintenance managers, engineers, and technical personnel.
- Analysis of company maintenance reports, performance logs, and downtime records to assess historical trends.

- Thematic analysis of industry best practices and regulatory frameworks to benchmark preventive maintenance strategies.

Data Analysis Approach:

- Qualitative content analysis was applied to interview transcripts and maintenance documentation.
- Emerging themes were categorised to identify key patterns in maintenance effectiveness, technology adoption, and operational challenges.

1.6 Population, sampling and sample size

This section defines the target population and explains the sampling strategy used to select participants. It also justifies the sample size in relation to the qualitative nature and objectives of the study.

1.6.1 Population

The target population for this study comprises maintenance personnel in the petrochemical industries in Gauteng region, with a specific focus on organisations operating within Gauteng and surrounding industrial regions. This area is recognised as a major industrial and chemical processing hub, hosting numerous large-scale operations that rely heavily on effective preventive maintenance to ensure operational continuity, safety, and efficiency.

The study specifically targeted personnel from organisations such as:

- Sasol (energy and chemicals conglomerate with integrated gas and petrochemical operations)
- Air Products South Africa (industrial gases supplier with onsite gas generation plants)
- Afrox (African Oxygen Ltd – provider of industrial and medical gases)
- Natref (National Petroleum Refiners of South Africa – joint venture between Sasol and TotalEnergies)

- Omnia Group (producer of chemicals, fertilizers, and explosives with large-scale petrochemical operations)
- AECI (specialty chemicals and explosives provider operating within petrochemical and mining sectors)
- Puregas (supplier of refrigerants, LPG, and speciality gases)

These organisations are selected based on their reliance on complex process systems, high-value assets, and critical maintenance dependencies, making them highly relevant for the exploration of preventive maintenance strategies influenced by Industry 6.0 technologies.

The target population for this study consists of maintenance personnel in the petrochemical industries in Gauteng, particularly those involved in the planning, execution, and implementing of preventive maintenance strategies. This includes:

- Maintenance managers responsible for overseeing preventive maintenance programs.
- Engineers (electrical, mechanical, and instrumentation) involved in designing, implementing, and optimising maintenance strategies.
- Technicians and planners who perform maintenance tasks and schedule interventions.
- Production personnel who interact with maintenance teams and experience the operational impact of maintenance practices.

To ensure relevant expertise and experience, inclusion criteria required participants to have at least one year of experience in their respective roles, ensuring familiarity with maintenance processes, equipment reliability, and the effectiveness of preventive maintenance strategies (Subedi, 2021：73). Temporary staff and contractors who do not have continuous exposure to maintenance operations are excluded.

1.6.2 Sampling method and size

A purposive sampling method is employed, specifically targeting individuals who have direct knowledge and experience in preventive maintenance. This approach ensures that participants provide rich, in-depth insights, rather than randomly selecting participants who may have limited engagement with maintenance processes (Akkaş & Meydan, 2023：74).

This study utilises a stratified sampling approach due to the small and specialised number of organisations operating within the petrochemical sector in Gauteng and surrounding regions, particularly Sasolburg, where the highest concentration of these industrial facilities is located.

The target population includes 5 to 10 mediums to large organisations in this sector; each actively engaged in preventive maintenance activities and integrating or considering sixth Industrial Revolution technologies. Organisations were stratified according to their core function, such as gas processing, petrochemical refining, or integrated operations. This stratification allows for comparative analysis across operational categories.

From each organisation, 3 to 4 individuals in key roles such as maintenance engineers, technical managers, or operations heads were invited to participate, resulting in a sample size of approximately 15 to 30 participants. This number is adequate for in-depth qualitative inquiry in a focused sector.

Data saturation was assessed during interviews. Saturation is expected to be reached when successive interviews no longer yield new themes or insights, and responses begin to repeat across different organisations. Based on existing qualitative research standards, it was anticipated that saturation would occur between the 15th and 25th interview, although all scheduled interviews were conducted to ensure comprehensive data coverage and representation across stratified organisational categories.

- It ensures representation across different roles and expertise levels, providing a comprehensive view of maintenance practices.

- It aligns with recommendations for qualitative research sample sizes, which prioritise depth over breadth, typically requiring 10–30 participants for saturation (Subedi, 2021：73).
- The size is manageable within the given research timeline while allowing for robust data collection.

1.7 Recruitment strategy

This section explains how participants were identified, approached, and invited to take part in the study. It outlines the procedures followed to ensure ethical, voluntary, and informed participation.

The recruitment strategy for this study is designed to ensure the participation of knowledgeable and experienced individuals from the petrochemical industries operating in Gauteng and surrounding regions. It focuses on personnel directly involved in the planning, execution, and implementing of preventive maintenance (PM) strategies, particularly in relation to Industry 6.0 technologies.

1.8 Organisational approval

This section describes the process followed to obtain formal permission from participating organisations. It confirms that the research was conducted with institutional awareness and approval.

Formal permission was obtained from the senior management (e.g., GM/MD) of selected companies including Sasol, Air Products, Afrox, Natref, Omnia, AECI, and Puregas. This ensures alignment with internal protocols and facilitates access to eligible participants. Treweek *et al*. (2011:5) emphasise that organisational-level support and early approval significantly enhance the credibility of the study and foster participant cooperation.

1.9 Participant engagement

This section outlines how participants were engaged throughout the research process. It explains how communication, clarification, and cooperation were managed to support effective data collection.

Upon approval, the researcher engaged maintenance and production personnel directly or through their departmental supervisors. Clear explanations were be provided about the study's purpose, scope, and the voluntary nature of participation. Recruitment materials included brief summaries and visual aids where applicable to support participant comprehension, as suggested by Treweek *et al.* (2011:5), who found that multimedia information improves recruitment quality and rate.

To ensure representativeness, inclusion criteria required participants to have at least one year of experience in a relevant maintenance role (technician, planner, engineer, and managers), while temporary staff or interns were excluded. This ensures a robust base of contextual knowledge from respondents.

1.10 Informed consent and ethical compliance

This section details the ethical principles underpinning the study, with particular emphasis on informed consent, confidentiality, and compliance with relevant ethical guidelines and legislation.

- Each participant: Received an information sheet detailing the study's objectives, procedures, data handling practices, and anticipated outcomes.
- Was invited to ask questions for clarity.
- Signed an informed consent form confirming their voluntary participation and understanding of their rights.

This aligns with recommendations from Treweek *et al.* (2011:2), who advocate for clear, concise participant information, supported by written and verbal communication, to improve trust and recruitment reliability.

1.11 Roles in the recruitment process

This section clarifies the roles and responsibilities of the researcher and participating organisations during the recruitment process. It ensures transparency and ethical accountability.

In accordance with ethical research principles and South African guidelines on institutional access, this study does not require a gatekeeper in the traditional sense, but

it does require formal organisational approval from the Managing Director (MD) or General Manager (GM) of each participating company. These individuals serve as the legitimate authorities empowered to grant access for research involving employees, as required for research conducted in institutional settings (Singh & Wassenaar, 2016:42).

Once written permission was granted, the researcher proceeded with participant engagement and data collection under the following ethical structure:

1.12 Researcher's responsibilities:

This section outlines the ethical and professional responsibilities of the researcher throughout the study. It highlights measures taken to ensure integrity, objectivity, and respect for participants.

- Each potential participant received a clear information sheet outlining the research objectives, their rights, and assurances of privacy and confidentiality.
- The researcher obtained informed consent from all participants prior to their involvement, emphasising that participation is voluntary, and withdrawal is allowed at any time without consequences.
- The researcher ensured that recruitment is transparent, respectful, and unbiased, especially in cases where professional relationships may exist between the researcher and participants.
- The researcher was responsible for designing the recruitment strategy, engaging with the and ensuring ethical compliance throughout the process (Creswell & Creswell, 2018:74).
- The researcher conducted data collection, analyse findings, and ensure that research outcomes align with the study's objectives of optimising preventive maintenance strategies through Industry 6.0 integration.

This structured recruitment approach ensures transparency, ethical compliance, and effective participant engagement, facilitating a comprehensive exploration of preventive maintenance strategies in Gauteng's petrochemical industries.

1.13 Informed consent process

This section explains the step-by-step process followed to obtain informed consent from participants. It ensures that participants were fully informed of their rights and the nature of the study.

The informed consent process for this research is designed to ensure that participants fully understand the study's purpose, procedures, potential risks, and benefits before providing their consent (Kadam RA 2017:107-112). This process upholds ethical research principles and guarantees that participation remains voluntary, confidential, and free from coercion.

Steps in the Informed Consent Process:

1. Organisational Permission:

   Prior to participant engagement, the researcher sought and obtained formal written permission from the Managing Director (MD) or General Manager (GM) of each participating organisation (e.g., Sasol, Air Products, Afrox, Natref, Omnia, AECI, Puregas).

   This permission authorised the researcher to engage employees for voluntary participation and organisational awareness was confirmed and support of the research.

1.14 Information sheet distribution:

This section describes how information sheets were distributed to participants. It explains how study objectives, procedures, and participant rights were communicated.

1. Each potential participant received a detailed information sheet explaining:
   - The research objectives and its relevance to preventive maintenance strategies in the petrochemical industries.
   - Expected time commitment and participation requirements.
   - Potential outcomes and contributions of the study.

2. Verbal Explanation and Clarification:
    - The researcher verbally explained the study, ensuring participants understand:
    - Their rights, including the ability to withdraw at any time without consequences.
    - Measures to protect confidentiality and anonymity in handling responses and data.
    - Participants would be encouraged to ask questions to clarify any concerns before proceeding.

3. Written Consent Agreement:
    - Once participants confirmed their understanding and willingness to participate, they signed a written consent form, officially granting their informed consent.

1.15 Data collection

This section outlines the data collection methods employed in the study, including interviews and document analysis. It explains how data were gathered to address the research objectives.

By definition, data collection is defined as the process of gathering, evaluating and analysing precise understandings for research using typical authenticated methods (Mazhar SA, Anjum R, Anwar AI, Khan AA.2021;10(1):6-10) Qualitative data collection methods were used to gain comprehensive insights into preventive maintenance strategies and the integration of technologies in the petrochemical industries in Gauteng region. The following methods were utilised:

Semi-Structured Interviews

- Conducted with maintenance managers, engineers, technicians, planners, and production personnel.
- Questions explored current preventive maintenance strategies, technological adoption, challenges, and improvement opportunities.
- Provide rich, in-depth qualitative data based on participants' experiences and perspectives.

Document Analysis

- Reviewing maintenance policies, historical maintenance records, standard operating procedures (SOPs), and performance reports.
- Identifies trends in equipment reliability, downtime, failure rates, and cost efficiency.
- Assesses the alignment of maintenance practices with industry standards and digital transformation initiatives.

1.16 Ethical considerations

This section discusses the ethical considerations associated with the study. It explains how participant privacy, confidentiality, and data protection were ensured.

Ensuring ethical integrity during data collection is a fundamental aspect of this research on preventive maintenance strategies and the impact of 6IR technologies in the petrochemical industries in Gauteng region. Ethical principles were strictly adhered to, particularly in compliance with the Protection of Personal Information Act (POPIA) to safeguard participants' rights, privacy, and confidentiality (South Africa, 2013).

1.16.1 Privacy protection

To protect participants' privacy and personal data, the following measures were implemented:

1. Informed and organisational Consent:

    - Prior to engaging with individual participants, formal permission was be obtained from each participating organisation (e.g. Sasol, Air Products, Afrox, Natref, Omnia, AECI, Puregas). This permission outlined the scope of the research, data access protocols, and how the findings will be used.
    - Each participant received a comprehensive information sheet describing the study’s purpose, scope, expected time commitment, data usage, and privacy safeguards.
    - Participants signed a consent form confirming their voluntary participation and understanding of their rights, including the right to withdraw at any time (Creswell & Creswell, 2018：74).

2. Anonymisation of Data:

    - Personal identifiers such as names, job titles, or locations were not recorded in the final dataset.
    - Instead, unique codes or pseudonyms were assigned to anonymise participants' information.

3. Secure Data Storage:

    - Digital data will be stored on password-protected servers and encrypted devices to prevent unauthorised access.
    - Physical documents will be kept in locked cabinets with restricted access.

4. Compliance with POPIA:

    - Data collection, storage, and processing will adhere to South Africa's Protection of Personal Information Act (POPIA) to ensure lawful and ethical data handling practices.
    - Final document and findings will be made available to the various organisation that were utilised or some other arrangement for making the document and its findings available.

1.16.2 Confidentiality of participants' data

The confidentiality of participants' data will be upheld through the following measures:

1. Restricted Access to Data:

    - Only the research team will have access to raw data, ensuring that no unauthorised individuals can view or manipulate it.

2. Data Encryption and Security:

    - Electronic files will be stored in encrypted folders with multi-layer authentication.
    - Hard copy records will be securely stored and destroyed after research completion.

3. Confidentiality in Reporting:

    - In research reports and publications, no identifying details will be disclosed.
    - Data will be aggregated and generalised to prevent the identification of any individual participant.

4. Academic and Public Access Statement:

    - This research is conducted for academic purposes and will be made available through the North-West University (NWU) library, public libraries, and online repositories.
    - Participants will be informed that the findings will be accessible in an anonymised format to ensure confidentiality while contributing valuable knowledge to the industry.

By adhering to strict ethical protocols, this study will ensure that participants' rights, privacy, and confidentiality remain protected while contributing to the advancement of preventive maintenance strategies in the Industry 6.0 era.

1.17 Trustworthiness

This section explains the strategies used to ensure the trustworthiness of the study. It addresses credibility, dependability, transferability, and confirmability.

In qualitative research, trustworthiness ensures that the study's findings are credible, transferable, dependable, and confirmable (Enworo, 2023:373-374). This study incorporates several techniques to enhance trustworthiness and ensure the accuracy and integrity of the research process.

1.17.1 Credibility (Internal Validity):

Credibility refers to confidence in the truth of the data and interpretations. To enhance credibility, this study employed member checking, where participants were given the opportunity to review interview transcripts and provide feedback on interpretations to confirm accuracy. A pilot study was also conducted to refine the interview questions and methodology, ensuring alignment with the research objectives. Additionally, prolonged

engagement with participants and triangulation using multiple data sources (e.g., interviews from diverse roles within the organisation) helped establish depth and authenticity.

1.17.2 Transferability (External validity):

Transferability refers to the extent to which findings can apply to other contexts. Though qualitative studies are not intended to be broadly generalised, this study provides thick descriptions of the research setting, participants, and processes to allow readers and other researchers to determine if the findings are relevant to their own settings. Describing the characteristics of participating organisations and individuals in detail will assist in achieving this.

1.17.3 Dependability (Reliability):

Dependability involves ensuring that the research process is logical, traceable, and well-documented. An audit trail was maintained, documenting all decisions, changes in direction, and reflections throughout the study. A clear record of the research methodology, data collection instruments, and coding decisions is provided to allow for replication or future studies in similar settings.

1.17.4 Confirmability (Objectivity):

Confirmability addresses the degree to which findings are shaped by the participants rather than researcher bias or interest. To ensure this, the researcher practiced reflexivity by maintaining a reflective journal, acknowledging their own assumptions and influence throughout the research. Peer debriefing and consultation with the research supervisor was used to validate the findings and interpretations independently.

1.18 Contributions

This section outlines the theoretical, practical, and policy contributions of the study. It explains how the research adds value to academic knowledge and industry practice.

1.18.1 Theoretical contribution

This study advances theoretical discourse on maintenance transformation by exploring the integration of Industry 6.0 technologies into preventive maintenance strategies within the Gauteng region petrochemical industries. It contributes to the conceptual development of Intelligent Maintenance Systems (IMS), Predictive Maintenance (PdM), and Maintenance 4.0, which emphasise real-time data analytics, cyber-physical systems, and the Internet of Things (IoT) for optimised asset performance (Nordal & El-Thalji, 2020:188-197). By examining the convergence of AI, machine learning, and big data analytics in Condition-Based Maintenance (CBM), the research enriches academic frameworks around digital maintenance architectures and intelligent decision-making in asset management (Goyal & Pabla, 2015:24-35; Wang & Wang, 2020:393-404).

1.18.2 Applied or practical contribution

The practical value of this research lies in offering industry-relevant insights into the operationalisation of Industry 6.0 technologies within maintenance departments. It illustrates how AI-powered predictive maintenance systems can be used to reduce unplanned downtime, optimise spare parts inventory, and improve equipment reliability and plant safety (Nordal & El-Thalji, 2020:188-197). South African companies such as Air Products, Sasol, Afrox, and Natref can apply these findings to streamline maintenance scheduling, implement sensor-based condition monitoring, and utilise real-time diagnostics. Studies in similar industrial contexts demonstrate that digital twins and machine learning algorithms support more accurate Remaining Useful Life (RUL) predictions, extending equipment lifespan and reducing operational risk (Goyal & Pabla, 2015:24-35).

1.18.3 Contribution to policies

This study supports policy development by highlighting the need for modernised maintenance frameworks aligned with Industry 6.0 standards, such as RAMI 4.0 and ISO 55000. It provides evidence for industrial policymakers and organisational leaders to update digital readiness policies, data governance frameworks, and maintenance workforce development strategies (Nordal & El-Thalji, 2020:188-197; Wang & Wang,

2020:393-404). The research also encourages the creation of incentive structures to promote technology adoption and ethical integration of AI and IoT in asset management, ensuring a safe, efficient, and competitive industrial maintenance landscape.

1.19 Limitations

This section revisits the limitations of the study, reflecting on how they may influence the interpretation of findings and suggesting areas for future research.

This study presents several limitations that should be considered when interpreting the findings:

1.19.1 Sampling bias in purposive sampling

While purposive sampling enables the researcher to engage with experienced maintenance personnel and decision-makers within industrial petrochemical companies, it may introduce selection bias. The sample may not reflect the full range of perspectives across departments, shifts, or organisational levels, potentially limiting the generalisability of the findings (Etikan *et al*., 2016:1–4).

1.19.2 Geographical scope

The study is primarily focused on organisations operating in Gauteng and surrounding regions, a key industrial hub in South Africa. However, the findings may not be generalisable to organisations outside this region or to those operating in different regulatory, economic, or technological environments (Bryman, 2014:181).

1.19.3 Managerial perspective bias

Most participants in this study are maintenance managers, engineers, and planners, which could result in a managerial bias. The exclusion of frontline technicians or operators may mean that the practical, hands-on challenges of adopting Industry 6.0 technologies in maintenance are underrepresented.

1.19.4 Subjectivity in qualitative research

Given the qualitative nature of this study, the findings are interpretive rather than causal. Insights are derived from participants' experiences and perceptions, and the interpretation of this data may be influenced by researcher subjectivity, even with careful thematic analysis and validation efforts (Suter, 2014:362–363).

1.19.5 Bias in semi-structured interviews

The reliance on semi-structured interviews may lead to social desirability bias or recall bias, where participants may provide responses, they perceive to be acceptable or favourable rather than completely candid (Merriam & Tisdell, 2015:187; Podsakoff, MacKenzie & Lee, 2003:879).

1.19.6 Technological challenges in online interviews

Due to scheduling and geographical dispersion, some interviews may well have been conducted via virtual platforms such as Microsoft Teams or Zoom. These platforms present challenges including connectivity issues, non-verbal communication gaps, or audio-visual disruptions that could compromise the clarity and depth of data (Carter *et al*., 2021:711–712). To mitigate these risks, the researcher ensured strong technical preparation, obtained consent for recording, and provided participants with clear guidance on how to navigate any disruptions.

1.19.7 Limitations of thematic analysis

While thematic analysis enables the identification of meaningful patterns, it may overlook unique or deviant insights that do not fit dominant themes. Moreover, the subjective nature of theme selection could introduce researcher bias, potentially affecting the neutrality of findings (Merriam & Tisdell, 2015:208).

1.20 Temporal relevance

This section explains the time-bound nature of the study and its relevance within a rapidly evolving technological environment. It acknowledges how future developments may influence the applicability of the findings.

This study captures a snapshot in time within a rapidly evolving technological landscape. As Industry 6.0 technologies continue to mature and new innovations emerge, the relevance and applicability of the findings may shift, particularly in light of changing organisational policies, skills development, and technology adoption rates (Saunders *et al*., 2019:147–148).

1.21 Dissertation format and layout

This section describes the structure and format of the mini-dissertation. It explains the rationale for adopting the mini-dissertation approach.

This research takes the form of a mini-dissertation, as it is best suited to a focused, time-sensitive investigation into the integration of Industry 6.0 technologies in preventive maintenance strategies. Based on the researcher's experience and academic guidance, this format allows for a comprehensive yet targeted examination of the research problem without the extended length required by full dissertations.

The mini-dissertation format supports in-depth analysis of a defined research question in this case, how Sixth Industrial Revolution (6IR) technologies such as IoT, AI, predictive analytics, and machine learning are shaping maintenance strategies in high-risk industrial sectors. Its concise structure demands a focused methodology and streamlines narrative, both of which enhance analytical clarity and ensure the research remains tightly aligned with the objectives.

This format also provides several practical advantages:

- It facilitates efficient time management, allowing for completion within a limited academic period.
- It reduces the stress and cognitive load often associated with lengthy academic writing projects, making it ideal for working professionals or part-time students.

- It enhances the researcher's ability to write with precision and academic discipline, a valuable skill in both academic and professional contexts.

Moreover, the mini-dissertation format aligns with the academic structure and expectations of institutions like North-West University and is well recognised for its academic rigor, despite its shorter length. As emphasised by (Putri & Saputra, 2021:1), a well-executed mini-dissertation still requires full adherence to scientific principles specifically the ontological, epistemological, and axiological dimensions of academic inquiry.

This format will support a clear, well-structured, and methodologically sound exploration of how 6IR technologies are transforming preventive maintenance strategies in the Gauteng petrochemical sectors, offering both theoretical insights and practical recommendations.

Chapter 1: Introduction

This chapter provides the foundation of the research. It introduces the research problem, background, and rationale for investigating the integration of Industry 6.0 technologies into preventive maintenance strategies. The problem statement, research objectives, and questions are clearly articulated, along with a brief overview of the petrochemical context in Gauteng. The chapter concludes with a summary of the methodology and the structure of the study.

Chapter 2: Literature review

This chapter presents a comprehensive review of existing scholarly literature related to preventive maintenance strategies and the influence of 6th industrial technologies such as AI, IoT, machine learning, and big data analytics. It explores global and local studies on predictive maintenance, smart asset management, and Maintenance 4.0. The literature review identifies key themes, gaps in existing research, and relevant theoretical frameworks to ground the study.

Chapter 3: Research methodology

Chapter 3 outlines the qualitative research design used to explore how Industry 6.0 is reshaping maintenance practices. It describes the research paradigm, data collection methods (e.g., interviews and document analysis), sampling strategy, and data analysis techniques such as thematic analysis. Ethical considerations including consent, confidentiality, and compliance with POPIA are also discussed. This chapter sets the foundation for the trustworthiness and rigor of the research process.

Chapter 4: Data presentation and analysis

This chapter presents the findings derived from the empirical research, particularly the semi-structured interviews with maintenance professionals and management staff in selected organisations. The data is categorised into themes and subthemes to reflect the realities of preventive maintenance in a digitalised industrial environment. This presentation establishes the basis for interpreting the implications of 6IR technologies on current maintenance practices.

Here, the findings are analysed and interpreted in relation to the literature reviewed in Chapter 2. The chapter discusses key patterns, trends, and discrepancies identified in the data. Theoretical and practical insights are explored, including how Industry 6.0 tools are transforming maintenance strategies, influencing decision-making, and shaping workforce readiness.

Chapter 5: Conclusions and recommendations

This chapter summarises the main conclusions drawn from the study and provides practical recommendations for industrial organisations, maintenance managers, and policymakers. Recommendations focus on enhancing preventive maintenance through the effective adoption of Industry 6.0 technologies. Guidance for future research is also provided based on identified gaps.

The final chapter also addresses the limitations of the study, including methodological, contextual, and data-related constraints. It also suggests future research directions to extend understanding in areas such as long-term impact assessment, digital skills development, and cross-sector adoption of predictive maintenance technologies.

1.22 Chapter Summary

In Chapter 1, a solid foundation was established indicating that it is worthwhile to investigate whether the use of 6IR technologies might reasonably affect preventive maintenance in the Gauteng petrochemical sector. The chapter has elaborated the research problem, discussed the primary and secondary objectives and the justification for the use of qualitative research design to understand complicated organisational, technological and operational situations. The study population, sampling strategy and recruitment process and ethical evidence has been clearly defined.

Also, it discussed the limitations of the study, explained the expected contributions and outlined the overall mini-dissertation structure. Overall, the frame an investigation which is fitting and purposefully aligned for the literature review in Chapter 2 that will explore the theoretical and empirical context of preventive maintenance and 6IR.

This research, exploring preventive maintenance strategies in the petrochemical industry through the sixth industrial revolution technologies in Gauteng sets the foundation for a critical investigation into how smart technologies are reshaping maintenance practices in one of the country's most asset-intensive and operationally demanding sectors.

Through the comprehensive development of this dissertation, several key components have been addressed to guide the successful execution of the study. The background and problem statement clearly highlight the need for more efficient, digitally integrated

preventive maintenance solutions in an industry where equipment reliability directly impacts safety, productivity, and profitability. The research objectives and questions have been crafted to focus specifically on the effectiveness, implementation, and organisational readiness for 6IR technologies such as AI, IoT, machine learning, and predictive analytics within the maintenance environment.

This chapter has introduced the research context, problem statement, objectives, and methodological approach, thereby establishing the foundation for the study; the next chapter presents a comprehensive review of the literature related to preventive maintenance strategies and Sixth Industrial Revolution technologies.

2 CHARPTER TWO: LITERATURE REVIEW

This chapter reviews existing scholarly literature related to preventive maintenance strategies and the influence of Sixth Industrial Revolution (6IR) technologies. It establishes the theoretical and conceptual foundations of the study, identifies key themes, and highlights gaps in the current body of knowledge that justify the need for this research.

Building on the research context and problem outlined in Chapter 1, this chapter reviews relevant literature to establish the theoretical and conceptual foundations of preventive maintenance and Sixth Industrial Revolution technologies.

2.1 Introduction

The petrochemical industry plays a critical role in South Africa's economy, particularly within Gauteng, where large-scale production facilities supply essential raw materials to multiple sectors. However, the operational demands of this industry present significant challenges due to complex, high-risk equipment and continuous production cycles, which require robust preventive maintenance (PM) strategies to ensure safety, reliability, and efficiency.

In recent years, technological advancements have shifted the focus from traditional time-based maintenance to intelligent, predictive, and autonomous strategies, driven by innovations associated with the Sixth Industrial Revolution (6IR). As noted by Zhong *et al*. (2023:2) the increasing integration of artificial intelligence, digital twins, and predictive analytics has transformed the landscape of equipment health monitoring and maintenance scheduling.

Preventive maintenance is essential in mitigating catastrophic failures and unplanned downtimes, especially in sectors like petrochemicals, where equipment reliability directly impacts production safety and environmental sustainability. According to (De Jonge *et al*. 2019:106-123), preventive maintenance remains a central strategy in ensuring system availability, but its success increasingly depends on embedding data-driven tools that optimise maintenance intervals and resource allocation.

Within the Gauteng, the rapid push towards smart industrial systems and digital transformation introduces both opportunities and challenges. While 6IR technologies such as IoT-enabled sensors, cloud-based systems, and AI-driven predictive models promise significant efficiency gains, many facilities still operate legacy systems with limited digital integration. As highlighted by Chen *et al.* (2020:1-11), transitioning to predictive and autonomous maintenance frameworks requires not only technological investment but also workforce upskilling and robust data governance models.

This study therefore seeks to explore how 6IR technologies can enhance preventive maintenance strategies within Gauteng's petrochemical sector by examining existing frameworks, assessing technology readiness, and identifying barriers to adoption

2.2 Gauteng regional industrial

This section provides an overview of the Gauteng industrial environment, with specific focus on the petrochemical and industrial gas sectors. It contextualises the study by highlighting regional characteristics, operational pressures, and infrastructure conditions that influence maintenance practices.

2.2.1 Overview of Gauteng's industrial base

Gauteng Province, although the smallest in South Africa by land area, is the country's economic and industrial hub, contributing approximately 34% to the national GDP. It encompasses dense clusters of manufacturing, petrochemical, engineering, and services industries across urban nodes including Johannesburg, Tshwane, Ekurhuleni, and the Vaal Triangle. These clusters are supported by a sophisticated network of transport and logistics infrastructure, which includes major roadways, rail links, freight hubs, and the OR Tambo International Airport, all functioning to support both domestic and global market access (Gauteng Provincial Government, 2021:7).

2.2.2 The industrial complex and strategic position

The industrial complex within Gauteng is defined by the co-location of heavy industries such as petrochemical plants, steel production, and industrial gas suppliers within shared development zones. These arrangements enable integrated supply chains, enhancing

operational efficiency by providing downstream industries – including automotive manufacturing, healthcare, and food processing – with consistent and timely access to critical inputs such as fuel, feedstocks, and industrial gases (Gauteng Provincial Government, 2021:8).

A case in point includes the strategic Vaal region, where petrochemical and industrial gas producers supply critical components directly to nearby manufacturing hubs via pipelines and tankers. However, such interdependence increases systemic risk, meaning equipment failures can propagate disruptions across multiple industries. This necessitates advanced preventive maintenance systems, especially as Gauteng aims to remain Africa's competitive industrial gateway (Gauteng Department of Economic Development, 2021:32; Vaal Development Planning Report, 2025:14).

2.2.2.1 The Vaal Triangle as a heavy industry hub

The Vaal Triangle, encompassing Vereeniging, Vanderbijlpark, and Sasolburg, is one of South Africa's most significant heavy industrial regions. It is historically known for its concentration of steel production (e.g., ArcelorMittal South Africa in Vanderbijlpark), petrochemicals (e.g., Sasol in Sasolburg), and industrial gas production facilities.

- Steel production: Vanderbijlpark's steel plants remain major consumers of industrial gases such as oxygen, nitrogen, and argon for blast furnace operations, cutting, and welding. Substantiate all statements.
- Petrochemical operations: Sasol's plants in Sasolburg produce synthetic fuels and chemicals that require hydrogen, oxygen, and nitrogen as feedstocks and process gases.
- Industrial gas producers: Afrox (Linde) and Air Products operate production plants in the region, supplying gases to steel mills, chemical producers, and other manufacturing facilities via pipeline networks and bulk road delivery.

This concentration of high-energy, high-throughput industries makes the Vaal Triangle particularly sensitive to equipment failures, process interruptions, and maintenance delays. Given the safety-critical and high-value nature of operations, integrating Sixth

Industrial Revolution (6IR) preventive maintenance technologies in this region could yield substantial efficiency and safety gains.

2.2.2.2 Regional opportunities and pressures

The Gauteng Vaal industrial belt benefits from a concentration of skilled technical labour, established logistics networks, and proximity to key suppliers that support large-scale petrochemical, steel, and industrial gas operations (Gauteng Provincial Government, 2021:7; Vaal Development Planning Report, 2025:14). These advantages have historically enabled the region to function as one of South Africa's most important heavy industrial hubs.

However, the region simultaneously faces several structural and operational pressures that directly affect maintenance performance and asset reliability. A significant proportion of industrial infrastructure in steelworks, petrochemical plants, and gas production facilities is ageing, increasing the likelihood of equipment degradation, unplanned failures, and higher maintenance costs (Martins et al., 2020:17; Nordal & El-Thalji, 2020:188). In addition, facilities operating in high-pollution zones such as the Vaal Triangle are subject to stringent environmental compliance requirements, particularly relating to emissions control, process safety, and environmental monitoring (Department of Forestry, Fisheries and the Environment, 2022).

Energy supply instability, driven largely by national electricity load-shedding, further disrupts continuous production processes and places additional stress on critical equipment, exacerbating maintenance challenges in asset-intensive operations (McKinsey, 2022:21; Council for Scientific and Industrial Research, 2023). At the same time, global competitiveness pressures compel petrochemical organisations to optimise plant uptime, reduce operational costs, and improve reliability in order to remain viable within international supply chains (Porter & Heppelmann, 2015:65; Prince & Ubani, 2024:20).

The interaction between these regional opportunities and pressures underscores the strategic importance of advancing preventive maintenance strategies within Gauteng's petrochemical sector. As organisations seek to modernise operations, comply with increasingly rigorous environmental and safety standards, and mitigate

risks associated with ageing infrastructure and energy disruptions, there is growing urgency to adopt more intelligent, data-driven maintenance approaches. These conditions create a compelling context for the exploration of Sixth Industrial Revolution (6IR) technologies as enablers of resilient and sustainable maintenance practices.

2.2.2.3 Strategic role of 6IR in the region

Within Gauteng's and the Vaal Triangle's high-density industrial environment, Sixth Industrial Revolution (6IR) technologies offer significant potential to address persistent maintenance and reliability challenges through intelligent, predictive, and autonomous capabilities. The integration of IoT-enabled condition monitoring systems enables real-time tracking of critical assets such as compressors, cryogenic distillation units, and high-pressure pipelines, allowing early detection of abnormal operating conditions and equipment degradation (Lee, Bagheri & Kao, 2015:18; Zhong et al., 2023:2).

Advanced artificial intelligence and machine learning-based predictive analytics further support maintenance decision-making by identifying failure patterns, estimating remaining useful life, and prioritising maintenance interventions before catastrophic failures occur (Chen et al., 2020:841–851; Del Giudice et al., 2021:70). In hazardous or inaccessible environments common in petrochemical operations, robotics and drone technologies enable remote inspections, reducing safety risks to personnel while improving inspection accuracy and frequency (Spöttl & Windelband, 2021:56).

Digital twin technology plays a strategic role by creating virtual representations of physical plant systems, allowing maintenance teams to simulate operating conditions, test maintenance scenarios, and optimise maintenance intervals without disrupting production (Tao et al., 2019:240; Nordal & El-Thalji, 2020:190). These capabilities are particularly valuable in regions such as Gauteng, where production continuity, safety compliance, and cost control are critical performance drivers.

By leveraging these 6IR technologies, petrochemical organisations in Gauteng and the Vaal Triangle can enhance operational reliability, reduce unplanned downtime, and strengthen compliance with stringent safety and environmental standards. In doing so, 6IR-enabled preventive maintenance supports the region's continued role as South

Africa's industrial heartland while enabling a transition toward more resilient, sustainable, and intelligent industrial operations (World Economic Forum, 2023:23).

2.3 Historical literature of Industrial Revolutions

This section traces the evolution of industrial revolutions from the First to the Sixth Industrial Revolution. It provides historical perspective on how technological advances have progressively transformed industrial operations and maintenance practices.

2.3.1 First Industrial Revolution (1760–1840)

Haradhan (2019:377) states that the industrial industry originated from England. The industrial revolution (1760-1840) was a period marked by important socio- economic changes in the country. Before the Industrial Revolution, work was primarily manual labour done by humans. Ashton indicated that the industrial revolution created new chemical manufacturing processes, improved iron production, made waterpower better, extended the use of steam power, and resulted in machine tool development. The iron and textile industries helped in these transformations. English blacksmith Thomas Newcomen (1664 – 1729) was able to create a technical advance in 1712. The steam engine (historically called the atmospheric engine) (Sinclair, 1907:11). According to the claim application, the engine was designed to use coal to generate power to pump water from coal mine shafts. In the year 1776, Scotsman James Watt made significant improvements to. laboratory in Glasgow. Because of Watt's innovations, the engine was able to make good use of large quantities of energy stored in coal. The invention and enhancing of the steam engine provided great advantages during the Industrial Revolution (Clark, 2007:39-72). The coal-driven iron engine became indispensable. Consequently, coal was important during the Industrial Revolution. This development sped up the early modern industrial age throughout the world and sparked revolutions in textile, mining, steam-powered railway, shipbuilding, steel and other economic activities. It resulted in the growth of big urban areas, industry, and infrastructure in several sectors (Atteberry *et al*., 2023). The agricultural revolution that mechanised agriculture during the First Industrial Revolution changed the availability of food and working conditions (Skilston & Hovsepian, 2018:7). According to Wan *et al*. (2024:1), the transition allowed for urban expansion and industrial infrastructure establishment, allowing for urbanisation.

The major historical occurrence, known as an industrial revolution, took place in local, regional, national and continental and global contexts. These technologies reshaped views of what society holds valuable. The progress helped in social, cultural, political, and geopolitical aspects. Moreover, it helped with the shift from agrarian to industrial economies of Europe and America. Economic historians define the transition as a structural transition. The. The late 19th century saw the start of the second Industrial Revolution.

During the Second Industrial Revolution, the primary energy source transitioned from coal to electricity, enabling the development of new industrial processes. This period saw significant technological innovations including the internal combustion engine and chemical breakthroughs such as synthetic dyes, which transformed manufacturing capabilities. Additionally, advancements in rail transport and telegraph communication enabled faster transfer of goods and information across regions (Stearns, 2020:3).

Simultaneously, mass production methods gained prominence; Henry Ford's introduction of the assembly line in automotive production became a hallmark of industrial efficiency. This shift also changed labour patterns, with large numbers of workers migrating from rural agricultural sectors to urban industrial centres driving urban growth and expansion of the middle class (Stearns, 2020:4).

The Second Industrial Revolution also marked the rise of large corporations, sophisticated financial institutions, and stock markets, laying the foundation for modern capitalist economies. In response to harsh working conditions, early labour laws were enacted to protect factory workers and regulate working environments. Collectively, these technological, economic, and social shifts paved the way toward global industrialisation and modern economic systems (Li, 2022:1–2).

The Second Industrial Revolution enabled the rise of large corporations, advanced financial systems, and stock markets that laid the foundations for the modern corporate economy. During this period, labour laws and regulations began to emerge in response to harsh working conditions and excessive work hours imposed on factory workers. Overall, this era represented a major shift in technology, economy, and social structures paving the way toward industrialisation and the development of industrial economies (Stearns, 2020:5; Li, 2022:2).

2.3.2 Second Industrial Revolution (1870–1914)

The Second Industrial Revolution came to fruition in the late 19th century. It marked the changeover from coal-powered steam to electricity. Due to better transportation and communication system (particularly air, rail and sea) low cost and high value goods can be exported on mass scale (Kaggwa, 2018:2). The Second Industrial Revolution saw considerable improvement in transport and communication infrastructure - railroads, the telegraph, steamships, cable - Jensen (1993:834), Ford Motors invented assembly line, which was one of the most important inventions during the Second Industrial Revolution (Abdin, 2019:1). The revolution brought forth the principles of large production and mass manufacturing up to the middle of the 20th century. The prominent players of the Second Industrial Revolution included European countries such as the United Kingdom, France, Italy, and Germany (Abdin, 2019:1). During this time, the U.S. economy emerged as the world's economic leader. Kaggwa (2018:2) claims that the hallmark of the Second Industrial. The transition from labour-intensive to capital intensive manufacturing, which significantly improved productivity, distinguishes the revolution from the First. While fertilisers were formulated to improve output, the textile industry made advancements into the synthetic age. The oil and gas extraction sectors began at the same time as iron and coal mining, which was then accompanied by communication technologies, the telegraph and telephone (Abdin, 2019:1).

According to Mokyr (1998:13), the Second Industrial Revolution converted many technical systems from uncommon events to standard issues. In many cases, free markets had difficulties with reliably coordinating large-scale complex systems. Subsequently, governments and other major agencies intervened to put in place standardisations such as traffic rules, rail road gauges, typewriters keyboard, and energy voltages (Mokyr, 1998:2). Advances in industrial technology helped for mass production activity. The processes that were used in mass production and steam was replaced by chemical energy and electric energy. Furthermore, various industrial technics and technological innovations are put in place to meet the demand that is continuously increasing by setting up the automated processes of manufacture which save up on manpower thereby improving efficiency.

In the 1870s, the invention of automatic signalling, air brakes, and knuckle couplers transformed railway operations, while the Bessemer and open-hearth processes

revolutionised steelmaking and enabled large-scale, high-quality steel production (Mokyr, 1998:2–3). Over the same period, landmark innovations such as the telephone, electric light, and typewriter reshaped communication and everyday life, and the introduction of structural steel and elevators made possible the first generation of skyscrapers in rapidly growing cities (Stearns, 2020:3–5). By the 1890s, new technologies including the phonograph, motion pictures, and the widespread use of electric generators supported the diffusion of modern household appliances such as refrigerators and washing machines, gradually displacing older water- and steam-powered systems and paving the way for the internal combustion engine and early automobiles (Atteberry *et al*., 2023; Stearns, 2020:4–5). At the same time, long-distance communication was transformed by the laying of transatlantic telegraph cables and, later, the rapid diffusion of Alexander Graham Bell's telephone from 1876 onward, which enabled near real-time communication between Europe and North America and accelerated business coordination across continents (Mokyr, 1998:2; Stearns, 2020:4).

2.3.3 Third Industrial Revolution (1950s–2000s)

The third industrial revolution (3IR) started around the 1950s, with the change of mechanical and analogue electronic technology to digital electronics. IR3 was ushered in by the further developments of nanotechnology, biotechnology, information technology, printer technology, artificial intelligence and robots. (Haradhan, 2021:241) The transition from the Second Industrial Revolution to the Third Industrial Revolution was driven through innovations in Information and Communications Technologies and the incorporation into manufacturing processes (Kaggwa, 2018:3). The Third Industrial Revolution brought about an increase in industrial production through automated production, advanced information and technology computer technology. The revolution has affected the energy, telecommunications, and transport sectors. Additionally, it also impacted several other sectors, especially ICT, knowledge, defence, health, education, advanced manufacturing, finance and administration (Sorooshian & Panigrahi, 2020:910; Taj and Zaman (2022:300). This evolution gave rise to a digital economy that creates and trades goods and services through digital channels. The Third Industrial Revolution (3IR) is the digitalisation of economies (Rifkin 2021:1). The 2023 digital economy is characterised by innovative methods of production, exchange, and digital distribution and sales of products and services, e-commerce, etc. One of the most notable aspects of the

Third Industrial Revolution was the rise of the online shop that wiped out various vacancies in retailing. Source The Third Industrial Revolution was characterised by the transformation of communication systems, visuals, sounds, physical objects, and biological systems into pure information. Source. Later, this information reshuffled into large, interrelating networks like complex ecosystems. Integrated digitalisation permitted crossing borders. Thus, differentiation is blurring across physical, digital, and biological worlds Rifkin (2021:3) According to (Naboni & Paoletti, 2015:20), the Third Industrial Revolution was a new development characterised by a growing use of digital manufacturing technologies which diversify production. This gave rise to an alternative open-source fabrication ecosystem that contests the standard. Architecture is among the declared contributions of the 3rd Revolution (Naboni & Paoletti, 2015:21).

As per Tod (2018), Rifkin outlined five pillars that supported the third industrial revolution (TIR), which were not outdated.

i. The transition to renewable energy.
ii. Make the buildings environmentally friendly micro-power plants that can collect renewable energy onsite.
iii. To store the surge of fluctuating energy sources, hydrogen and other storage technologies are used in all buildings and infrastructure.
iv. The electricity grids of each continent can become an energy Internet akin to the Internet through the use of Internet technology.
v. Change vehicles to electric plug-in and fuel cell cars need closing paragraph

2.3.4 Fourth Industrial Revolution (2010s–Present)

The Fourth Industrial Revolution (Industry 4.0) emerged in the 2010s, characterised by the integration of cyber-physical systems, the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and advanced robotics into manufacturing and other sectors. It emphasises smart factories, predictive maintenance, and real-time data-driven decision-making. Technologies such as blockchain, augmented reality (AR), and 3D printing have enabled new business models, while cloud computing and edge computing support scalable, flexible operations. Industry 4.0 aims to create autonomous, interconnected systems capable of adapting to changing demands with minimal human intervention.

According to Van Dam (2017:10), Fourth Industrial Revolution started in 2012 with cyber-physical systems, it presented numerous possibilities for humans and machines alike. A cyber physical system is a mechanism used to control or monitor using computer algorithms as a primary element. During this period, new technologies like the Internet of Things (IoT), artificial intelligence (AI), robots, blockchain, biotechnology and quantum computing came to the fore (Chourasia *et al.*,2022:445). The Fourth Industrial Revolution (4IR) referred to the ways of manufacturing when new technologies started to blur the lines between the physical, digital and biological worlds. As technology progressed, these advances enhanced factories across robotics, data analysis, and disruptive business models. The period changed healthcare, finance, industry and education. Moreover, the alterations significantly improved efficiency and production (Rotatori *et al*., 2021:100). Still, it also brought challenges that include worries about job lose, data privacy, cyber-hacking and need for labour re-skilling. The revolution changed worldwide economies and cultures, creating possibilities for great development and innovation requiring a new way of coping with complexity. Robots in factories are likely to take away people's jobs, as they will do all the work instead of people (Oosthuizen, 2022:2). There is a growing economic productivity from the growing robots in human shares in many industries (International Federation of Robotics, 2017:2-3). With modern technology, industrial robots are becoming more progressive and efficient. The beginning of the Fourth Industrial Revolution (4IR) is an era where robots and humans will work together, linking their tasks and using intelligent sensors to create smooth human-machine interfaces (Graupner, 2021:3). The Internet of Things, the Internet of Services and cyber-physical (or virtual-physical) systems will be the foundation of the Fourth Industrial Revolution. Many companies are joining the movement and utilising many methods to improve productivity, increase competitiveness and make financial gains (Trauth-Goik, 2021:64).

2.3.5 Fifth Industrial Revolution (5IR)

The Fifth Industrial Revolution (5IR) marks a shift from technology-focus of the Fourth Industrial Revolution to the integration of human ingenuity and collaboration with machines.

The Fourth Industrial revolution gave priority to automation, artificial intelligence and internet of things. On the other hand, the Fifth Industrial Revolution relies on a more

human-centred framework that seeks to enhance technology in a manner that is sustainable, ethical and socially beneficial (Tyagi *et al*., 2024:6). The revolution anticipates a work where people and robots work together to develop solutions that boost economic growth and address global problems such as climate change, inequality and wellbeing (George and George, 2020:211). 5IR highlights the importance of making technology custom-fit so that it improves the quality of life and empower employees instead of displacing them. The Fifth Industrial Revolution (5IR) has seen significant technological advances in various fields, such as collaborative robots (cobots). These cobots work together with humans, assist workers across a variety of fields, biotech and work on improving health and life span, and the development of alternatives to renewable energy that are deployed to solve environmental problems (Ziatdinov *et al*., 2024:6). This society is basically referring to the way organisations and governments are behaving in this current phase, it is also responsible for being ethical, accountable, and more aware for a better future. Ziatdinov *et al.* (2024:6) state that the Fifth Industrial Revolution (5IR) goes beyond technological advancement, which is an essential component. Instead, it aims to employ technological advancement to prove a more equal and better world for all. (Wang & Siau, 2019:66). The 5IR will improve the quality of life of all in India. The 5IR will really transform the country and make it a better place for all. This may cause some pain to certain classes. 5IR will reduce tensions and improve productivity. The future cannot be predicted but it will make things better for all. The significance of the Fifth Industrial Revolution is its ability to optimise and simplify routine operations related to business and industry and even in education and healthcare among many other arenas. According to Bhandurge and Bhide (2021:2), companies that put used shop floor trackers will enhance productivity, efficiency, and quality at the company while reducing waste and mismanagement. The combination of HI and AI which refers to human intelligence and artificial intelligence enhanced healthcare/medical practice.

2.3.6 Sixth Industrial Revolution (6 IR)

Yadav *et al.* (2022:1457), state that visionary leaders, experts and scholars expect the Sixth Industrial Revolution (IR 6.0) to commence around the year 2050. At that juncture, human intelligence (HI) along with artificial intelligence (AI), renewable cloud energy and drone 3D printing will merge for increasing production and operations of several heavenly

bodies including that of the moon. To achieve this the working together of humans, AI, and the 3D printings by drone with the support of satellite and Industry robots will be done.

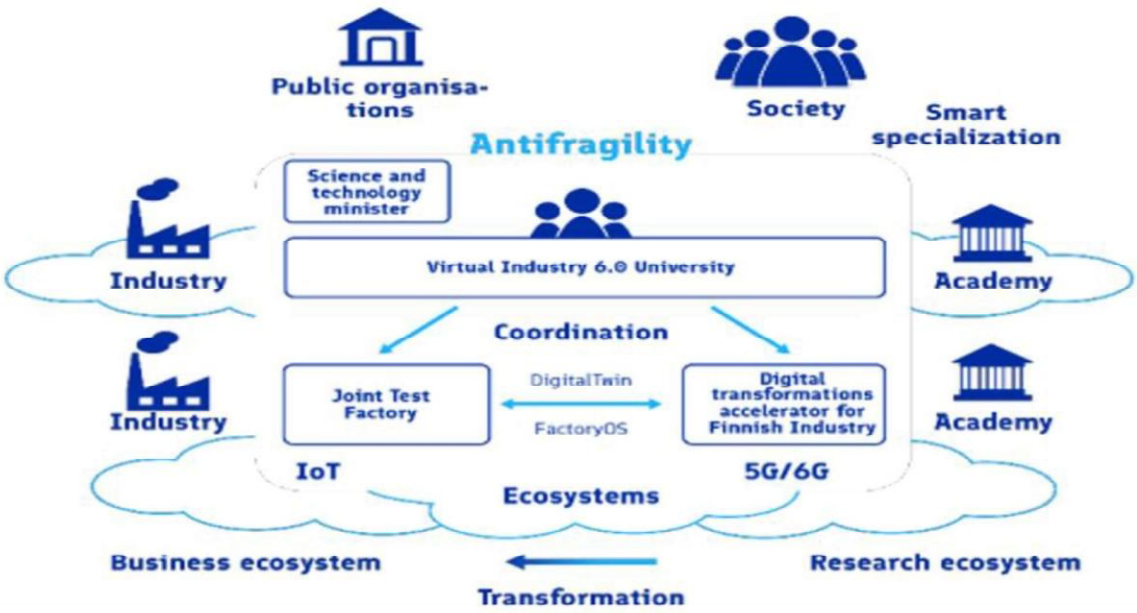

Figure 2.1 Sixth Industrial Revolution representation **Source:** Yadav *et al.,* (2022: 1457).

According to Yadav *et al*. (2022:1457), the revolution will help in overseeing the Automatic Mechanical Industry (ARI) systems in the atmosphere by quantum radar technology, similar to what is being done for aeroplanes. Depending on quantum, solar, cloud, planetary nuclear depend systems are based on so many renewable energies. As science grows advanced, HI, AI, unlimited cloud energy sources, satellites, production line robots are becoming more like human beings. Cooperation of sustainable cloud energy, satellites, computers, robots and human intelligence will be more in demand. Additionally, this will educate the sustainable universe together. As robots become more integrated into society, it's important to understand how people interact with and respond to computers that take decisions or function as authorities, such as in military or medical environments. Based on the regressive path leading to it, cohabitation robots will be the norm in the sector by the end of the next industrial revolution (Yadav *et al*., 2022:1457). Yadav *et al*. (2022), further state that previous revolutions based on technological automation and tailor-made manufacturing are likely to produce monolithic production facilities, where different AI algorithms connected to the same machine are simultaneously performing various tasks to produce for consumer demand.

2.4 Features of the Sixth (6th) Industrial Revolution.

This section discusses the defining features of the Sixth Industrial Revolution, including advanced artificial intelligence, sustainability-driven technologies, digital governance, and human–machine collaboration. It explains how these features extend beyond previous industrial paradigms.

2.4.1 Advanced Artificial Intelligence.

The rise of Artificial Intelligence (AI) in the early 21st century is a significant event in human history because larger computer capacity, large data availability, and more efficient algorithms (Groumpos, 2021:467). Things that were only a part of science fiction have now come out in the open, affecting industries everywhere and every aspect of modern life. Artificial intelligence can be a game-changing technology that will impact several sectors, including manufacturing. (Ota & Necula, 2023:14). The main reason behind AI development at present time has been algorithmic innovation. Ahmed *et al*. (2023:13521) state that some machine learning techniques such as CNNs, RNNs, and GANs have advanced to the stage where they can perform tasks such as image recognition, natural language processing, and autonomous decision-making. Also, advancement of reinforcement learning in which machines are taught how to act in a particular environment has made the industry a great place to work.

Figure 2.2- The transformational journey of the Industrial Revolution
Source: Chourasia *et al.* (2022:445)

2.4.2 Sustainability and green technologies.

Green technologies are solutions and techniques that are more than an environmental technology. As per Wu and Strezov (2023:1), green is the complement of sustainability and friendliness for the environment, economy, societies and technologies. Green tech is the application of new technology that can help repair environmental damage and improve sustainability. This is an important development in technology, as it alters the ways that technological resources are conceived, produced and used. The goals are reducing environmental impacts and improving sustainability development (Wu & Strezov, 2023:1). Sustainable Development Goals and achieving sustainability are now more aligned with green technology.

The Sustainable Development Goals (SDGs) are the next global development framework after the Millennium Development Goals that were first proposed in 2000. They were proposed by the United Nations General Assembly (UNGA) in 2015 under the 2030 Agenda for Sustainable Development (Ali *et al*., 2023:2). Green technologies are not simply a collection of different technologies. As reported by the World Bank Group (2022), the most alarming problem the world faces today is severe food crisis. Similarly, other challenges are widespread environmental pollution; drawdown of energy and resources; global impacts of multiple diseases; and extreme climate changes. These obstacles make the formation of different interdisciplinary green technologies a must (Wu & Strezov, 2023:1). Advancement and upgradation of green technology necessitate workable green solutions that inspire large areas of future development. Green technology will create new links between man and nature and facilitate a new global community. Simply put, green tech includes all the technologies or techniques used to reduce harmful effects on the environment and to be able to use natural resources wisely.

These reasons make its utilisation necessary for solving ongoing issues of pollution, resource scarcity and climate change (Guo *et al.,* 2020:2). The development and implementation of Green Tech technologies rely on several fundamental ideas in support of eco-friendly moves. Energy efficiency refers to the optimised use of energy that reduces waste and results in increased output. Green technology refers to energy-efficient lighting, devices, and smart energy management systems that minimise the impact of energy on the environment. We must find alternatives for fossil fuels since they are limited, and pollution is one of the main results. We can use the sun, wind, water, and biomass for this purpose.

Technologies that harness renewable resources such as solar panels, wind turbines, and hydroelectric power plants are essential in reducing greenhouse gas emissions and mitigating climate change. Greenhouse gases like carbon dioxide are major contributors to air pollution and global warming. Green technology represents an innovative combination of urban planning, engineering techniques, and industrial processes aimed at minimising environmental impacts. For example, advancements such as solar heating systems, electric vehicles, and more efficient industrial processes are increasingly being

adopted to reduce CO_2 emissions and support sustainable development (Sharma *et al*., 2024:69).

2.4.3 Global collaboration and digital governance.

According to Matsiliza (2022:66), the Sixth Industrial Revolution (6IR) framework associates the emergence of a global project with the need for digital governance to foster international collaboration between organisations and states to curb the explosion and rapid delivery of technologies. To create, apply and regulate tech like the blockchain, AI and biotechnology, there is a need for global collaboration as they are gaining importance in the world economy.

Now that the world has entered an era of global cooperation, the significance of cooperative research, designing, and standard setting has been realised more than ever before. Nations and organisations are collaborating increasingly in sectors such as artificial intelligence, renewable energy, cyber security and healthcare to share technological solutions (Goswami, 2024). Tackling world problems such as economic injustice, pandemic preparedness and climate change will need global collaboration.

We must play out the potential impact of breakthrough technologies designed through this. Moreover, cooperation can help ensuring advancement of technology equally benefits developed and developing countries. Digital governance includes the infrastructure, rules and regulations put in place to oversee the ethical use, security and privacy of digital technologies. Taddeo (2020:173) explains that with digital technologies playing an embedded role in every corner of society, ranging from data protection and e-government to smart cities and driverless cars, it is evident that the governance models assuring responsible use allow for the prioritisation. We must build governance frameworks that guard against abuse of data, stop the monopolisation of digital resources, and preserve public confidence in the everyday tools powering society. One major issue of digital governance is balancing innovation with regulation.

Not enough governance can lead to a violation of privacy, cybersecurity threats, or ethical issues, especially on the part of AI and data-driven technologies. Yet, over-governance can hinder innovation and limit technical development (Raab, 2020:1). To ensure that the

digital environment is open, safe, and fair to everybody, we need international cooperation to coordinate our efforts. It helps nations to align on ethical principles, rules on data protection legislation, and artificial intelligence rules (Díaz-Rodríguez *et al*., 2023:1). By working together towards governance, countries and institutions can ensure global distribution of benefits and minimise risks of misuse of digital tools of the 6IR. As Taddeo (2020:175) notes, the ongoing interchange, trust, and engagement with shared ethical principles will be paramount as the global digital landscape shifts.

2.5 Significance of the Sixth (6th) Industrial Revolution.

This section examines the significance of the Sixth Industrial Revolution in modern industrial systems. It highlights its implications for productivity, sustainability, governance, and workforce transformation, with relevance to asset-intensive industries.

During COVID-19 pandemic the world was struggling with manufacturing, supply, and demand for goods and services, and other essentials. The worldwide crisis has made businesses, organisations and service providers rethink how they produce goods, deliver customer service, manage the supply chain, integrate the circular economy and digitalisation (Alonso-Munoz *et al*., 2021:6). Yet, it is noticed through all the various phases of the history of the industrial revolution that certain industries could have triggered the primary change. Likewise, companies should be prepared for the digital governance movement in a flexible and predictable environment.

According to Van de Boer-Visschedijk *et al.* (2021:22), because of cooperation with sustainable cloud energy, satellites, PCs, robots and human insight, human knowledge (HI), computerised reasoning (AI), limitless cloud energy and other human-like abilities will ultimately become more significant, commonly edifying the manageable universe. We seek to lessen the stress on Earth's resources by using the ones of other planets we find, and human insight (HI). We will keep looking for more planets and things to use from space to use what we have in the universe for the good of man and nature. As robots become more present in our everyday lives, understanding how people interact with machines that make judgments and act authoritatively, such as military or medically used robots, will prove crucial.

A World Economic Forum (2023:23) report indicates that these technologies can cut greenhouse gas emissions and boost job opportunities in the green economy. Also, circular economy models will be evolved under this 6th Industrial revolution with purported recycling, reusing and reducing impact over the planet. Combining AI and machine learning with industrial processes is yet another key aspect of the 6IR and allows organisations to operate at new levels of efficiency and productivity. AI systems have access to huge amounts of data. This helps in optimising operations, making better decisions, and enhancing the quality of products.

According to Del Giudice *et al.* (2021:70), this technological revolution not only improves operational efficiency but also allows new business models, such as the platform economy and intelligent manufacturing, to be created. The changes will transform labour market. With their advent, workforce need new skills. Educational institutions will need restructuring to meet their demand. In addition, the 6IR focuses on digital and physical convergence, which creates smart cities as well as driverless systems. The Internet of Things allows for smooth communication between devices and systems to play a very important role in it. The city uses technology to manage the city infrastructure efficiently and keep it safe. As cities become more urbanised, they must implement technology which helps them manage resources and improves citizen's lives (Mohanty & Kumar, 2021:143).

This trend pertains to urban issues and sustainable economic growth and development. While 6IR has huge benefits, there are still challenges impeding equitable results. When machines and technology are used in place of human workers, it affects jobs, it raises socio-economic inequalities and issues, which in turn raises concerns. A McKinsey Global Institute report (2017:4-6) states that the technology can create new jobs; however, it can also significantly disrupt existing ones. The industry and policy makers should come together to find ways to reskill and upskill the workforce so that the unskilled population suffers the least. Besides, artificial intelligence and data privacy issues that governments should focus as they can build trust while using technology for humanity. Now add a paragraph that links the above to the following below. We need a logical flow or as we also know it the Golden Thread.

2.6 Preventive Maintenance Strategies in Petrochemical Industries

This section reviews preventive maintenance concepts and frameworks applicable to petrochemical operations. It examines traditional and advanced maintenance approaches, including time-based, condition-based, reliability-centred, and predictive maintenance strategies.

2.6.1 Preventive maintenance (PM)

The petrochemical industry plays a critical role in South Africa's economy, particularly within Gauteng, where large-scale production facilities supply essential raw materials to multiple sectors. However, the operational demands of this industry present significant challenges due to complex, high-risk equipment and continuous production cycles, which require robust preventive maintenance (PM) strategies to ensure safety, reliability, and efficiency.

In recent years, technological advancements have shifted the focus from traditional time-based maintenance to intelligent, predictive, and autonomous strategies, driven by innovations associated with the Sixth Industrial Revolution (6IR). As noted by recent studies, the increasing integration of artificial intelligence, digital twins, and predictive analytics has transformed the landscape of equipment health monitoring and maintenance scheduling (Zhong *et al.,* 2023:3).

Preventive maintenance is essential in mitigating catastrophic failures and unplanned downtimes, especially in sectors like petrochemicals, where equipment reliability directly impacts production safety and environmental sustainability. According to De Jonge *et al*. 2019:106-123), preventive maintenance remains a central strategy in ensuring system availability, but its success increasingly depends on embedding data-driven tools that optimise maintenance intervals and resource allocation.

Within Gauteng, the rapid push towards smart industrial systems and digital transformation introduces both opportunities and challenges. While 6IR technologies such as IoT-enabled sensors, cloud-based systems, and AI-driven predictive models promise significant efficiency gains, many facilities still operate legacy systems with limited digital integration. As highlighted by Chen *et al*. (2020:1-11), transitioning to

predictive and autonomous maintenance frameworks requires not only technological investment but also workforce upskilling and robust data governance models.

This study therefore seeks to explore how 6IR technologies can enhance preventive maintenance strategies within Gauteng's petrochemical sector by examining existing frameworks, assessing technology readiness, and identifying barriers to adoption.

2.6.2 Relevance to preventive maintenance in petrochemical facilities

The Sixth Industrial Revolution (6IR) marks a significant paradigm shift in industrial operations, characterised by the fusion of digital, physical, and biological systems to create highly autonomous, sustainable, and human-centric production environments. As noted by (Xiong *et al*., 2021:3755–3757), the 6IR extends the innovations of Industry 4.0 and 5.0 by focusing on seamless human-machine collaboration, sustainable energy systems, and AI-driven autonomous decision-making.

For industries such as petrochemicals, 6IR provides transformative capabilities through smart interconnected systems that can predict failures, reduce downtime, and optimise asset performance. Chen *et al.* (2020:1-11) emphasise that data-driven decision frameworks enabled by artificial intelligence, cloud computing, and digital twins are at the heart of intelligent maintenance strategies. These technologies allow for predictive models that anticipate degradation and optimise intervention timing.

Several advanced technologies form the foundation of 6IR in the petrochemical maintenance context:

- Artificial Intelligence (AI) and Machine Learning (ML)
  AI algorithms process real-time sensor data to predict equipment health. According to Zhong *et al*. (2023:2), machine learning-based predictive maintenance has demonstrated up to 40% reductions in unplanned downtime and 20% cost savings in critical process environments.

- Internet of Things (IoT) and Smart Sensors
  IoT devices enable real-time monitoring of critical assets. As highlighted by (Han *et al*. 2019:2) IoT-enabled predictive maintenance integrates heterogeneous

sensor networks with cloud-based analytics, allowing for condition-based maintenance that responds dynamically to equipment degradation.

- Digital Twins
  Digital replicas of physical systems simulate various operational scenarios to optimise maintenance scheduling. In petrochemical facilities, this capability significantly improves fault detection accuracy and reduces diagnostic times.

- Robotics and Autonomous Systems
  Autonomous robots perform hazardous inspections and maintenance tasks, reducing human exposure to dangerous environments.

- Cloud and Edge Computing
  Cloud infrastructure supports vast amounts of predictive maintenance data, while edge computing ensures faster decision-making directly at equipment locations.

6IR technologies revolutionise preventive maintenance strategies by shifting from reactive and time-based maintenance to predictive and prescriptive frameworks. This transition minimises human error, optimises maintenance schedules, and significantly reduces operational risks in high-pressure petrochemical environments.

In Gauteng, where petrochemical facilities are central to industrial production, these innovations provide opportunities to address persistent challenges such as equipment obsolescence, high downtime costs, and safety hazards. As (De Jonge *et al.,* 2019:106-123) note, industrial environments that integrate predictive analytics and smart monitoring technologies can achieve up to a 50% reduction in maintenance-related failures while improving workforce efficiency and safety.

2.6.3 Reliability centred maintenance

Preventive maintenance (PM) is a structured approach to ensuring equipment reliability by performing maintenance tasks before failures occur. In the petrochemical sectors, where unplanned downtime, equipment malfunctions, and safety hazards can result in severe financial losses, environmental damage, and reputational risks, adopting the right PM strategy is critical.

Historically, maintenance has evolved through several generations. First-generation maintenance (1940–1955) was largely reactive, where interventions were only made after breakdowns occurred. This approach, while simple, led to frequent downtime and high operational costs. Second-generation maintenance (1955–1975) introduced preventive maintenance, based on calendar-based schedules and periodic inspections. While it reduced failures, it often lacked alignment with actual equipment conditions, resulting in inefficiencies. By the third generation (1975–2000), predictive maintenance emerged, leveraging condition-monitoring tools such as vibration and thermal analysis to anticipate failures before they occurred. In the current era, predictive maintenance has advanced further into what is often called Predictive Maintenance 2.0, combining reliability-centred maintenance, high-quality data, and AI-driven models to optimise maintenance strategies (Sensemore, 2023:1-4).

Reliability-centred maintenance builds on this evolution by systematically analysing the functions of equipment, identifying potential failure modes, and prioritising maintenance actions based on risk and criticality. It integrates principles from preventive and predictive maintenance but goes further by linking maintenance tasks directly to operational reliability and safety outcomes. In petrochemical industries, this approach ensures that scarce resources are directed towards assets where failure would have the most severe consequences, thus supporting operational resilience and sustainability.

The Sixth Industrial Revolution (6IR) further accelerates the application of RCM through the integration of advanced technologies such as IoT-enabled sensors, machine learning, and digital twins. IoT facilitates continuous condition monitoring, providing real-time operational data such as temperature, vibration, and pressure, which can be fed into predictive analytics platforms. Machine learning models analyse these data streams to detect patterns and anomalies that precede failure, while digital twins create virtual replicas of physical systems to simulate different maintenance scenarios. Together, these technologies enable proactive decision-making, reduce downtime, extend asset lifecycles, and enhance safety (Zhang *et al*., 2022:4; Sensemore, 2023:5-7).

Additionally, the progression towards prescriptive maintenance represents the next stage beyond predictive and reliability-centred frameworks. By analysing real-time data against historical corrective actions, prescriptive maintenance provides specific

recommendations for interventions. In Gauteng's petrochemical clusters, where complex assets and high safety risks are involved, prescriptive maintenance reduces reliance on scarce expert technicians by embedding decision support into the system itself (Sensemore, 2023:8-9).

Thus, in the era of 6IR, RCM is no longer a static process but a dynamic, technology-enabled strategy that combines proactive scheduling with intelligent analytics. It represents a vital shift from maintenance being perceived as a necessary cost to being recognised as a strategic enabler of productivity, safety, and long-term competitiveness in petrochemical industries.

2.6.3.1 Time-based preventive maintenance (TBM)

Traditional PM frameworks rely on fixed schedules determined by manufacturer recommendations or industry standards. This approach assumes that equipment degrades uniformly over time. As observed by (De Jonge *et al.,*2019:106-123), time-based maintenance strategies are simple to implement but inherently inefficient, as they ignore the stochastic nature of component degradation.

While TBM is widely used in petrochemical facilities, it often results in over-maintenance or under-maintenance, leading to unnecessary costs or unexpected equipment failures. The integration of 6IR technologies provides a path to optimise TBM schedules by using predictive models to refine intervention intervals.

2.6.3.2 Condition-based maintenance (CBM)

Condition-Based Maintenance focuses on monitoring real-time equipment health through IoT sensors and predictive analytics. Instead of relying on static schedules, maintenance is triggered only when measurable indicators such as vibration, temperature, or pressure signal degradation.

Condition-Based Maintenance (CBM) leverages real-time data from distributed IoT sensors to detect degradation trends and schedule interventions accordingly. As demonstrated by Sutharssan *et al.* (2020:2), IoT-enabled sensor networks combined with cloud-based analytics provide a dynamic platform for responsive and predictive maintenance decision-making a model particularly relevant for high-risk sectors like petrochemical processing.

For petrochemical facilities in Gauteng, CBM is particularly valuable due to the high operational risks and the need to manage aging infrastructure. Integrating CBM with 6IR tools such as edge computing and digital twins allows operators to simulate failure scenarios and make proactive decisions.

2.6.3.3 Predictive maintenance (PdM)

Predictive maintenance leverages machine learning models and historical operational data to forecast when a failure is likely to occur. Zhong *et al*. (2023:2) note that machine learning-based predictive maintenance strategies reduce unplanned downtime by up to 40% and optimise maintenance costs by as much as 20%.

In the petrochemical context, PdM enhances safety by preventing catastrophic breakdowns, improving asset lifespan, and lowering operational expenses. Combining IoT-generated sensor data with AI algorithms enables facilities to anticipate failures days or weeks in advance.

2.6.3.4 Imperfect maintenance models

Not all maintenance restores equipment to its original condition; hence, imperfect maintenance optimisation strategies are increasingly applied. According to (Chen *et al*., 2020:1-11), optimising preventive maintenance under imperfect restoration conditions requires dynamic models that balance equipment downtime, resource constraints, and system availability.

This approach is particularly relevant to older petrochemical plants in Gauteng, where frequent partial repairs rather than full replacements are common due to cost and operational pressures.

2.6.3.5 Integrated preventive maintenance frameworks

The emergence of 6IR-enabled integrated maintenance frameworks allows operators to combine TBM, CBM, and PdM into a single, data-driven strategy. As stated by (De Jonge *et al.,* 2019:106-123), integrated frameworks that unify condition monitoring, predictive analytics, and autonomous decision-making enable organisations to move from reactive to prescriptive maintenance paradigms.

By integrating smart sensors, cloud-based analytics, and digital twins, petrochemical facilities in Gauteng can reduce equipment failures, enhance safety compliance, and improve cost efficiency.

2.6.4 Integration of sixth Industrial revolution (6IR) technologies into maintenance

The Sixth Industrial Revolution (6IR) transforms traditional preventive maintenance (PM) into smart, autonomous, and data-driven strategies. In petrochemical facilities, the integration of cutting-edge technologies enables real-time monitoring, predictive insights, and automated interventions that reduce equipment failures and optimise operational efficiency.

As Zhong *et al*. (2023:2) highlight, the synergy between IoT-enabled monitoring systems, machine learning, and cloud-based analytics allows for dynamic decision-making in maintenance scheduling, thereby significantly improving system availability and reducing downtime. This technological convergence forms the foundation for advanced PM strategies in high-risk environments like petrochemical plants.

2.6.4.1 Internet of Things (IoT) and smart sensors

IoT devices collect real-time operational data on vibration, temperature, pressure, and other critical parameters. According to Han *et al*. (2019:2), IoT-enabled condition-based maintenance continuously acquires equipment health data through heterogeneous sensor networks combined with cloud analytics, allowing for dynamic, data-driven interventions.

In Gauteng petrochemical facilities, where equipment operates continuously under extreme conditions, IoT-based monitoring ensures that maintenance triggers are data-driven rather than calendar-based, improving response times and reducing costly shutdowns.

2.6.4.2 Artificial Intelligence (AI) and Machine Learning (ML)

AI and ML models analyse historical and real-time data to predict equipment failures with high accuracy. Zhong *et al*. (2023:2) state that machine learning-based predictive maintenance reduces unplanned downtime by up to 40%, significantly improving asset availability and extending component life cycles.

These capabilities are particularly valuable in Gauteng's petrochemical sector, where critical production bottlenecks often result from unexpected equipment failures.

2.6.4.3 Digital twins

Digital twins create virtual representations of physical assets to simulate performance, degradation, and maintenance scenarios. According to Chen *et al*. (2020;1-11), digital twin-enabled maintenance frameworks provide operators with a predictive understanding of equipment health, enabling proactive decisions that minimise downtime.

For petrochemical facilities, this technology enables failure simulations before physical interventions, improving safety and maintenance precision.

2.6.4.4 Robotics and autonomous maintenance

Robotics enhance safety by performing maintenance tasks in hazardous environments, such as inspecting high-pressure pipelines or confined reactors. As De Jonge *et al*. (2019:106-123) observe, integrating robotics into preventive maintenance frameworks reduces human exposure to dangerous conditions while improving the precision and repeatability of repair activities.

This is particularly relevant to Gauteng plants that operate high-risk installations requiring non-invasive and remote inspections.

2.6.4.5 Cloud and edge computing

Cloud computing provides the computational power and storage needed to process vast volumes of maintenance-related data, while edge computing brings real-time decision-making closer to the equipment. According to Zhong *et al*. (2023:2), hybrid cloud-edge architectures enhance predictive maintenance by combining scalable analytics with rapid local responses to emerging failures.

In petrochemical facilities, where delayed decisions can lead to production losses or safety incidents, this integration enables immediate responses supported by global-scale analytics.

2.6.5 Preventive maintenance in petrochemical industries

The petrochemical industry operates in a highly complex, hazardous, and capital-intensive environment, where equipment failures can lead to significant safety risks, production losses, and environmental damage. Effective preventive maintenance **(PM)** strategies are therefore critical to sustaining operational reliability and ensuring compliance with safety regulations.

As noted by Sikorska *et al*. (2011:41), many assets in chemical and petrochemical plants operate under extreme conditions such as high pressures and temperatures increasing the risk of catastrophic failures if maintenance interventions are not timely or data driven.

2.6.5.1 Challenges in petrochemical maintenance

Petrochemical plants face multiple PM challenges, including:

- Aging Infrastructure
  Many facilities in Gauteng rely on decades-old equipment, making component obsolescence a persistent problem. According to Chen *et al*. (2020:9), aging systems often require partial rather than complete restorations, forcing maintenance teams to balance operational continuity with limited budgets.

- Safety and Compliance
  With stringent environmental and safety regulations, unplanned failures pose catastrophic risks. As De Jonge *et al*. (2019:232) state, integrated preventive maintenance approaches are essential for mitigating safety hazards and avoiding compliance violations in high-risk industrial sectors.

- High Operational Downtime Costs
  A single unplanned outage can cost millions in lost production. Predictive and condition-based maintenance enabled by 6IR technologies provides a solution by reducing unexpected disruptions. (Xu *et* al., 2021:5672–5673).

- Skills Gaps and Workforce Readiness
  Adopting AI-driven and IoT-enabled maintenance solutions requires significant upskilling of maintenance personnel. Chen *et al*. (2020:115-116) highlight that successful digital transformation in maintenance depends as much on workforce capability as on technological investment.

The subsequent section explores how Industry 6.0 technologies are poised to reshape preventive maintenance strategies in the petrochemical sector, potentially transforming these challenges into strategic opportunities for innovation, efficiency, and resilience.

2.6.5.2 Opportunities through 6IR-enabled strategies

The adoption of 6IR technologies transforms petrochemical PM into a proactive, data-driven process:

- Predictive Analytics for Failure Prevention

  Zhong *et al*. (2022:2) note that machine learning-enabled predictive maintenance can reduce unplanned downtime by up to 40% and lower maintenance costs by as much as 20% in process-intensive environments.

- Digital Twin Applications

  Digital twin simulations improve reliability by replicating operational conditions virtually before implementing physical interventions.

- IoT-Based Continuous Monitoring
  Real-time condition monitoring enables early fault detection, reducing safety risks and improving regulatory compliance.

- Autonomous Inspection and Robotics
  Robotics are increasingly deployed for inspections in hazardous environments, improving workforce safety and enhancing inspection accuracy.

6IR-enabled preventative maintenance offers a transformative opportunity for the petrochemical sector to shift from reactive and time-based interventions to intelligent, automated, and data-informed strategies. By integrating predictive analytics, digital twins, IoT-driven monitoring, and autonomous inspection technologies, organisations stand to significantly enhance operational reliability, reduce unplanned downtime, and optimise resource allocation. These technologies not only strengthen asset performance but also advance safety outcomes and regulatory compliance positioning the industry for resilient and future-ready operations in an increasingly competitive and digitised landscape.

2.6.5.3 Relevance to Gauteng petrochemical facilities

In Gauteng, where petrochemical production forms the backbone of South Africa's industrial output, PM strategies are directly tied to economic sustainability and workforce safety. However, adoption of advanced frameworks remains uneven due to technological readiness gaps. As Chen *et al*. (2020:1-11) observe the transitioning to predictive and prescriptive maintenance frameworks requires addressing organisational, cultural, and infrastructure barriers in parallel with deploying technological solutions.

Integrating AI, IoT, digital twins, and robotics into PM frameworks offers Gauteng facilities opportunities to improve efficiency, reduce environmental risks, and extend the life cycles of critical assets.

2.7 Research gaps

This section synthesises the reviewed literature to identify gaps in existing research. It highlights areas where empirical evidence is limited, particularly regarding the practical adoption of 6IR-enabled preventive maintenance within the South African petrochemical context.

2.7.1 Contextual research aps in the South African petrochemical sector

A key gap lies in regional applicability. While studies such as those by Mashaba and Mathaba (2025:4) address maintenance strategies in the petrochemical sector, their geographic focus is mainly Asia and North America. They explicitly note, a noticeable dominance of literature originating from the Asian and North American continents suggests a need for further research in other continents like Africa to understand contextual nuances comprehensively.

This underscores the lack of localised studies on petrochemical preventive maintenance under 6IR conditions in Africa, and specifically Gauteng. Such a focus could reveal region-specific barriers, resource constraints, and adaptation needs.

2.7.2 Scaling from component-level to system-level maintenance insights

Much of the literature, such as the work by Miller and Dubrawski (2020:2), focuses on predicting failures for individual components. They emphasise that methods that are

effective for forecasting risk and informing maintenance decisions regarding individual components do not readily scale to provide reliable sub-system or system-level insights.

The petrochemical industry relies on highly integrated systems where failures in one part can cascade. This suggests a gap in holistic, system-level preventive maintenance models informed by 6IR technologies.

2.7.3 Limited exploration of human and organisational factors

Digital transformation isn't just about technology it's deeply rooted in people, culture, and organisational processes. As highlighted by Lambert-Torres *et al*. (2023:6), most studies explore relationships between individual technologies and specific practices without considering the broader organisational context or multiple concurrent technologies, resulting in limited systemic insights and lack of empirical validation. This mirrors the tendency to neglect factors such as training, culture, and leadership commitment, each of which is critical for the successful adoption of 6IR technologies in maintenance environments.

2.7.4 Insufficient focus on explainable, trustworthy predictive systems

As maintenance systems become more AI-driven, explainability and user trust become critical. Cummins *et al*., (2024:2) address this in the context of AI, Explainable predictive maintenance (XPM) human operators need to trust the predictive system. This attracts XAI to introduce explainability and interpretability into the predictive system.

Yet there's limited research on how explainable AI can be integrated into maintenance systems within petrochemical in Gauteng.

2.7.5 Challenges in implementing IoT and digital technologies in Petrochemical Assets

The petrochemical industry often operates with legacy infrastructure that resists digitisation. As Brachman *et al*. (2020:4) noted, the difficulty in retrofitting older systems with modern IoT components, combined with uncertainty over data integrity and high upfront implementation costs, remains a significant hurdle in industries with ageing

infrastructure such as petrochemicals. Bridging digital and analogue systems remains a real-world challenge, particularly in developing contexts.

Bridging digital and analogue systems remains a real-world challenge in petrochemical plants, particularly in developing contexts.

Table 2.1 provides a consolidated overview of the key research gaps identified in the literature on preventive maintenance (PM) within the petrochemical sector, particularly under the evolving influence of Sixth Industrial Revolution (6IR) technologies. The gaps span across contextual, technical, human, and infrastructural dimensions, highlighting limitations in regional focus, system-level maintenance models, and organisational readiness. Furthermore, emerging technologies such as Explainable AI (XAI) and IoT integration face practical barriers due to legacy infrastructure constraints and limited trust among operators. Addressing these gaps is critical to designing effective, context-specific maintenance strategies suitable for the petrochemical industry in regions like Gauteng.

Table 2.1: Summary of research gaps

Gap	Implication
Regional Focus	Need for localised studies examining 6IR-driven PM in African/Gauteng petrochemical sector.
System-Level Modelling	Lack of maintenance strategies addressing interdependent system dynamics, not just components.
Human and Organisational Factors	Organisational readiness and workforce capability receive insufficient attention.
Explainable AI (XAI)	AI-based predictive systems lack transparency, limiting trust among maintenance personnel.
Legacy Infrastructure Integration	Practical challenges of integrating IoT/6IR technologies into outdated industrial systems.

Source (own)

2.7.6 Alignment with research objectives

This study on Gauteng's petrochemical industry, is well-placed to fill these pivotal gaps. Specifically, it can:

- Generate contextually relevant insights for African petrochemical maintenance.
- Explore how 6IR technologies can be scaled system wide.
- Investigate how human and organisational factors influence adoption.
- Evaluate the role of explainability in predictive maintenance tools.
- Propose integration pathways for legacy systems transitioning to digital frameworks.

The identified research gaps highlight the need for a context-driven, system-wide understanding of 6IR-enabled preventive maintenance in Gauteng's petrochemical sector. By addressing underexplored areas such as local applicability, system-level integration, organisational readiness, explainable AI, and legacy system adaptation, this study aims to provide actionable insights and a more holistic framework for advancing maintenance practices in the region.

2.8 Chapter Summary

This chapter traced the evolution of industrial revolutions from the First to the emerging Sixth, showing how each wave of technological change has progressively reshaped production systems, labour, and maintenance philosophies. The Sixth Industrial Revolution, with its fusion of AI, IoT, digital twins, robotics, green technologies, and global digital governance, represents a decisive shift towards autonomous, sustainable, and human-centred industrial systems. Within this paradigm, maintenance is no longer a peripheral support function but a strategic, data-driven capability that underpins safety, reliability, and competitiveness.

Situated in this global trajectory, Gauteng and particularly the Vaal Triangle emerges as a critical industrial hub where heavy petrochemical, steel, and industrial gas operations are both opportunity-rich and risk-intensive. The literature shows that while 6IR technologies offer powerful tools for predictive, condition-based, and reliability-centred

maintenance, their adoption in petrochemical is constrained by legacy infrastructure, skills gaps, cultural resistance, governance deficits, and limited regional research. The review highlighted clear gaps in African and Gauteng-specific studies, system-level maintenance modelling, human and organisational dimensions, explainable AI, and the integration of IoT and digital technologies in ageing assets.

These insights provide a conceptual and contextual foundation for the present study. They justify the focus on Gauteng's petrochemical sector and motivate an empirical exploration of how 6IR technologies are understood, adopted, and operationalised in preventive maintenance practice. By responding directly to the identified gaps and aligning with the stated research objectives, the study seeks to move beyond abstract technological promise and generate grounded, context-sensitive knowledge that can inform more effective, trustworthy, and future-ready maintenance strategies in the region.

This chapter critically reviewed the body of literature surrounding preventive maintenance (PM) strategies, the integration of Sixth Industrial Revolution (6IR) technologies, and their application within the petrochemical industry in Gauteng.

The review revealed that traditional time-based PM strategies are increasingly inadequate for modern petrochemical operations due to aging infrastructure, high safety risks, and growing operational complexity. Advanced approaches such as predictive maintenance, condition-based monitoring, and digital twin-enabled simulations have emerged as viable solutions.

The integration of 6IR technologies including IoT, AI, machine learning, robotics, cloud-edge architectures, and digital twins was shown to enhance real-time monitoring, improve failure prediction accuracy, and support data-driven decision-making. These technologies provide petrochemical facilities with the tools to move from reactive and time-based interventions toward proactive and autonomous strategies.

However, several research gaps exist. Existing studies are heavily concentrated in developed economies, leaving limited contextual evidence for South African petrochemical facilities. There are also significant challenges related to scaling predictive systems from component-level to system-level, integrating emerging technologies with legacy infrastructure, and addressing human and organisational readiness for digital

transformation. Moreover, there is a growing need for explainable AI and trustworthy predictive frameworks to improve adoption in high-risk industrial environments.

This study positions itself to address these gaps by exploring how 6IR technologies can be effectively leveraged to strengthen preventive maintenance frameworks within Gauteng's petrochemical industry, with a focus on enhancing safety, operational efficiency, and technological integration.

Having examined existing literature and identified key research gaps related to 6IR-enabled preventive maintenance, the following chapter outlines the research design and methodology employed to address these gaps.

3 CHAPTER THREE: RESEARCH DESIGN

This chapter outlines the research design and methodology employed to investigate the influence of Sixth Industrial Revolution technologies on preventive maintenance strategies. Following the literature review and identification of research gaps in Chapter 2, this chapter describes the research paradigm, design, and methodological procedures used to investigate the study objectives.

3.1 Introduction

This chapter outlines the research design and methodology adopted for the study titled: Exploring Preventive Maintenance Strategies in the Petrochemical Industry Through the Sixth Industrial Revolution Technologies in Gauteng.

The purpose of this chapter is to describe the philosophical assumptions, research design, and methodological choices that underpin the study. It explains why a qualitative exploratory approach was selected to gain deep insights into how petrochemical companies in Gauteng are integrating Sixth Industrial Revolution (6IR) technologies into preventive maintenance (PM) strategies. The chapter discusses the research paradigm, data collection techniques, sampling strategies, data analysis procedures, trustworthiness considerations, and ethical principles guiding the study.

Given the dynamic technological environment and complexity of maintenance strategies in petrochemical industries, a qualitative approach provides an opportunity to explore meanings, experiences, and perceptions within specific contexts (Nowell *et al*., 2017:2). The approach is especially suitable for this study as it seeks to understand how industry practitioners interpret and implement 6IR-driven preventive maintenance strategies rather than test predetermined hypotheses.

3.2 Research paradigm

This section explains the research paradigm guiding the study and justifies the selection of an interpretivist perspective.

This study is grounded in the interpretivist paradigm, which focuses on understanding the subjective meanings and lived experiences of individuals within their natural settings.

Interpretivism assumes that reality is socially constructed and context-dependent, making it suitable for exploring how petrochemical professionals perceive and adopt emerging technologies in maintenance (Alharahsheh & Pius, 2020:39).

This paradigm emphasises the importance of rich, detailed data from participants, where meanings are co-constructed through interaction (Alharahsheh & Pius, 2020:40). Qualitative research relies on participants' views to uncover motivations, challenges, and contextual influences rather than aiming to generalise findings through statistical methods (Igwenagu, 2016:16). This framework supports the use of methods such as semi-structured interviews and document analysis, enabling a deeper understanding of experiences, organisational contexts, and the adoption of preventive maintenance technologies.

3.3 Research philosophy

This section explains the research paradigm guiding the study and justifies the selection of an interpretivist perspective.

In qualitative research, the philosophical foundation shapes how knowledge is created, interpreted, and validated. Two central paradigms are positivism and anti-positivism (also called non-positivism or interpretivism).

Positivism emerged in the 19th century through the work of Auguste Comte, who argued that knowledge should be grounded in observable facts and empirical evidence rather than speculation (Ayeni, Saman & Kasimu, 2019:21). Positivism emphasises objectivity, value-free inquiry, and the use of scientific methods such as quantification and hypothesis testing to establish universal truths (Padmanabhan & Gafoor, 2011:19–20, cited in Ayeni *et al*., 2019:21). In this view, reality exists independently of the researcher and can be measured and explained through systematic observation and mathematical analysis (Ayeni, Saman & Kasimu, 2019:22–23).

By contrast, anti-positivism (or interpretivism) challenges the idea that social phenomena can be studied in the same way as natural sciences. It argues that human behaviour is subjective, context-bound, and shaped by values, beliefs, and experiences (Alessandrini, n.d:4, cited in Ayeni *et al*., 2019:22). Anti-positivist scholars maintain that meaning is

socially constructed and can best be understood through qualitative approaches such as interviews, participant observation, and document analysis (Ayeni *et al*., 2019:24). The aim is not generalisation, but deep understanding of context-specific realities (Bennett, 1996:123, cited in Ayeni *et al*., 2019:24).

Furthermore, neo-positivist or post-positivist approaches recognise the limitations of both paradigms, proposing that objectivity is never absolute and that bias must be acknowledged. Knowledge is therefore seen as provisional and open to reinterpretation (Buddharaksa, 2010:1–3, cited in Ayeni *et al*., 2019:25).

For this study on exploring preventive maintenance strategies in the petrochemical industry through the sixth industrial revolution technologies in Gauteng, an anti-positivist paradigm is most suitable. This is because the research seeks to explore the lived experiences, perceptions, and interpretations of engineers, technicians, and managers in relation to technology adoption and maintenance practices. Such insights cannot be reduced to numerical measurements alone but require understanding of context, meaning, and interpretation (Ayeni *et al*., 2019:24–25).

The interpretivist stance allows the researcher to uncover how stakeholders perceive the opportunities and challenges of 6IR technologies such as IoT, AI, and digital twins in preventive maintenance. This aligns with the qualitative methodology of semi-structured interviews and document analysis, which emphasise depth over breadth, and meaning over measurement.

3.4 Research approach

This study adopts a qualitative exploratory research approach to gain a deep understanding of how Sixth Industrial Revolution (6IR) technologies are influencing preventive maintenance strategies within Gauteng's petrochemical industry. According to Nowell *et al*. (2017:2), qualitative approaches are particularly suited to studies that aim to explore complex social phenomena where limited prior research exists.

The exploratory nature of this study allows flexibility to investigate how maintenance practitioners interpret, adopt, and implement data-driven maintenance strategies, particularly when incorporating advanced technologies such as IoT, artificial intelligence,

and predictive analytics. Unlike quantitative approaches that focus on measuring relationships between variables, this study prioritises rich, descriptive insights into participants' perceptions and lived experiences (Sandelowski, 2000:334-340).

Furthermore, a qualitative exploratory approach is appropriate because the integration of 6IR technologies into preventive maintenance within the South African petrochemical context is still emerging, and little is known about the patterns, practices, and challenges within local industries (Creswell & Poth, 2018:42-44). (This makes it essential to explore subjective meanings rather than test predetermined hypotheses).

3.5 Research design

This study employs a qualitative exploratory case study design to investigate the integration of Sixth Industrial Revolution (6IR) technologies into preventive maintenance strategies within the Gauteng petrochemical industry

This study focuses on multiple petrochemical facilities within Gauteng, treating each organisation as a unit of analysis. This multi-site case study approach enables comparison between organisations, thereby uncovering patterns, variations, and unique insights regarding maintenance transformation in diverse operational settings.

The chosen design aligns with the study's objectives by enabling an exploration of industry-specific technological adoption, organisational practices, and contextual challenges in a sector where little prior research exists.

3.6 Population and sampling strategy

This section defines the study population and explains the sampling techniques used to select participants with relevant experience and expertise.

3.6.1 Study population

The target population for this study comprises maintenance managers, engineers, technicians, and reliability specialists working within petrochemical facilities in the Gauteng region. These participants were chosen because they are directly involved in the design, implementation, and execution of preventive maintenance (PM) strategies

and are likely to provide rich insights into the role of Sixth Industrial Revolution (6IR) technologies in shaping these practices.

3.6.2 Sampling method

The study employs purposive sampling, which is commonly used in qualitative research to deliberately select participants who possess specific knowledge and experience relevant to the research objectives. As Patton (2015:264) explains, purposive sampling focuses on information-rich cases from which the researcher can learn a great deal about the central issues of the study.

This sampling strategy ensures that participants are selected based on their direct involvement in preventive maintenance planning, execution, and decision-making within the petrochemical industry.

3.6.3 Sample size

The study employs a stratified purposive sampling strategy, which ensures representation across key sub-groups within the petrochemical sector while still selecting participants based on relevant expertise. This approach allows the researcher to intentionally recruit participants from different petrochemical companies and occupational roles (e.g., maintenance engineers, reliability specialists, plant managers) to ensure diversity in perspectives related to 6IR-driven maintenance practices.

The sample comprised of between 12 and 15 participants. In qualitative research, the purpose is not to generalise statistically but to reach data saturation, where no new themes or insights emerge during analysis. According to Guest, Bunce, and Johnson (2006:65), saturation often occurs within the first twelve interviews, indicating that this sample size is sufficient for exploratory qualitative studies seeking depth and variation across strata.

3.6.4 Inclusion and exclusion criteria

To ensure the selection of participants who can provide meaningful and contextually valid insights, this study applies explicit inclusion and exclusion criteria consistent with

qualitative research best practices (Palinkas *et al*., 2015:533-544). These criteria help refine the sample to individuals with substantive experience and direct involvement in preventive maintenance and digital transformation initiatives within the petrochemical industry. This rigorous selection approach supports the goal of gathering rich, relevant data to answer the research questions effectively.

Inclusion criteria:

- Participants must be employed in petrochemical facilities located in Gauteng.
- Participants must be directly involved in maintenance strategy planning, decision-making, or operational execution.
- Participants must have a minimum of three years of relevant industry experience in maintenance, reliability, or digital transformation roles.

Exclusion criteria:

- Administrative or support staff without direct technical or operational involvement in maintenance activities.
- Individuals not engaged in equipment reliability, condition-based monitoring, predictive maintenance, or technological implementation for maintenance improvement.
- People who are not employed in the petrochemical industry.

By applying these criteria, the study ensures alignment between participant experience and the research objectives while minimising the inclusion of individuals whose roles may not yield relevant insights. This deliberate approach to participant selection enhances the quality and credibility of findings, aligning with recommendations for purposive and criterion-based sampling in qualitative inquiry (Gentles *et al*., 2015:1772-1789).

3.7 Data collection methods

This study uses two primary data collection techniques: semi-structured interviews and document analysis. These methods are appropriate for an exploratory qualitative

approach as they allow the researcher to collect rich, in-depth information and gain insights into participants' perceptions, experiences, and contextual realities.

3.7.1 Semi-structured interviews

Semi-structured interviews will be the primary data collection method. This approach provides flexibility by combining a set of guiding questions with the ability to probe deeper into emerging issues during discussions. According to Kallio *et al*. (2016:2955), semi-structured interviews enable researchers to collect comparable data while maintaining the flexibility to explore individual perspectives in depth.

The interviews will focus on:

- Participants' experiences with preventive maintenance strategies.
- The role of Sixth Industrial Revolution (6IR) technologies in maintenance planning and execution.
- Challenges and opportunities in integrating advanced technologies such as IoT, AI, predictive analytics, and digital twins.

Interviews were conducted face-to-face or via secure virtual platforms, depending on participant availability, and each lasted approximately 20 to 30 minutes. With informed consent, interviews were audio-recorded and later transcribed verbatim for thematic analysis.

3.8 Data analysis

This study employs qualitative data analysis (QDA), specifically thematic analysis, to interpret the data collected from semi-structured interviews and document analysis. Qualitative data analysis goes beyond organising raw material; it is a systematic process of transforming unstructured textual data into meaningful insights by identifying themes, relationships, and underlying meanings. As noted by Mezmir, (2020:5), qualitative data analysis is the classification and interpretation of linguistic material to uncover both explicit and implicit structures of meaning-making. This makes it highly suitable for the

current study, which seeks to uncover how Sixth Industrial Revolution (6IR) technologies influence preventive maintenance strategies in South Africa's petrochemical industries.

The process began with familiarisation, where the researcher carefully reviews interview transcripts and organisational documents to gain an initial sense of patterns. This was followed by coding, in which important segments of the data are labelled to capture their essence. According to Saldana (2013, cited in Mezmir, 2020:8), coding is not merely a technical procedure but an interpretive act that connects raw data to conceptual ideas. Through iterative cycles of coding, themes were refined and organised into categories.

Next, the study employed data display and thematic mapping to organise these categories into broader thematic frameworks aligned with the research objectives. This stage highlights recurring issues such as digital readiness, technology adoption, and maintenance optimisation, which directly relate to the integration of 6IR technologies. As suggested by Creswell (2009, cited in Mezmir, 2020:11), thematic frameworks allow researchers to link data back to research questions in a systematic and transparent way.

Finally, the interpretation and conclusion drawing stage synthesised the results into meaningful insights that answer the study's research questions. This involves identifying convergences and divergences across interviews and documents, triangulating evidence to strengthen trustworthiness. As emphasised by Bryman and Burgess (1994, cited in Mezmir, 2020:7), interpretation must be rigorous and transparent so that readers can trace how findings were developed.

By following this structured and iterative process, the study ensures that its data analysis remains flexible yet rigorous. This enhances credibility, dependability, and trustworthiness (Mezmir, 2020:12) and guarantees that findings reflect participants lived experiences while being grounded in the data.

3.8.1 Data preparation

All interviews were audio-recorded (with participant consent) and transcribed verbatim to ensure accuracy. Transcripts were reviewed alongside field notes and relevant organisational documents.

3.8.2 Coding process

The data analysis follows Braun and Clarke's six-step framework:

1. Familiarisation with the data – Reading transcripts repeatedly to understand the content.
2. Generating initial codes – Identifying meaningful statements and grouping them into categories.
3. Searching for themes – Combining related codes into potential themes.
4. Reviewing themes – Refining and validating themes by comparing them with the dataset.
5. Defining and naming themes – Assigning concise labels that capture the essence of each theme.
6. Producing the report – Integrating final themes with supporting participant quotes and organisational evidence.

3.8.3 Use of qualitative analysis software

Atlas.ti Software was used to systematically manage, organise, and code interview transcripts during the data analysis process. These tools support the efficient retrieval, categorisation, and visualisation of qualitative data, enhancing transparency and rigor in thematic exploration. As noted by Zamawe (2015:2), the use of CAQDAS such as Atlas.ti improves the efficiency of analysis by enabling systematic coding and exploration of patterns in large amounts of text data. Similarly, Woods, Paulus, Atkins, and Macklin (2016:5) emphasise that software-aided qualitative analysis ensures a dependable audit trail, which strengthens methodological transparency and credibility.

Alongside CAQDAS tools, this study leverages artificial intelligence (AI) platforms such as ChatGPT and Gemini as supplementary tools for instance, to support summarisation of coded themes or assist in refining thematic interpretations. These AI tools do not replace human interpretation but help enhance efficiency during preliminary analysis

phases, consistent with current guidance on integrating AI ethically into qualitative research workflows (Saldaña & Omasta, 2021).

3.8.4 Triangulation

Findings from interviews will be cross validated with document analysis to ensure consistency and strengthen credibility. This process provides a richer understanding of how petrochemical companies integrate 6IR technologies into preventive maintenance strategies.

3.9 Trustworthiness

Ensuring trustworthiness in qualitative research is fundamental to guaranteeing that the findings are credible, dependable, transferable, and confirmable. According to Gunawan (2015:10), trustworthiness in qualitative inquiry is established when the researcher provides transparent and auditable practices that enable readers to judge the rigor of the study. This framework builds on the criteria developed by Guba and Lincoln, which highlight credibility, dependability, transferability, and confirmability as essential elements.

Credibility relates to the confidence in the truth of the data and is enhanced through strategies such as member checking, triangulation, and prolonged engagement with participants (Gunawan, 2015:11). Dependability emphasises the stability of research findings over time and can be strengthened by detailed documentation of the methodological process. Transferability addresses the extent to which findings can be applied to other contexts and is supported by providing rich, thick descriptions of the research setting and participants. Confirmability ensures that findings are shaped by the participants' perspectives rather than researcher bias, achieved through audit trails and reflexivity.

Gunawan (2015:11) notes that triangulation, systematic coding, and detailed transcription are critical in minimising bias and enhancing rigor. By applying these strategies, this study ensures that its findings are trustworthy and offer meaningful insights into the integration of Sixth Industrial Revolution technologies in preventive maintenance strategies.

3.9.1 Credibility

Credibility refers to the confidence in the accuracy of the findings. To enhance credibility, this study applies data triangulation by combining semi-structured interviews with document analysis. Member checking was also conducted, allowing participants to review and validate their interview transcripts to ensure authenticity and correctness (Nowell *et al*., 2017:2).

3.9.2 Transferability

Transferability ensures that findings can be applied to similar contexts. This will be achieved by providing rich, thick descriptions of the research setting, participant experiences, and organisational contexts. As (Tracy, 2010:837-851) states, detailed contextual accounts enable readers to evaluate the applicability of findings in other settings.

3.9.3 Dependability

Dependability refers to the stability, consistency, and reliability of the research process over time, ensuring that if the study were repeated under similar conditions, comparable results would be obtained. To achieve this, the researcher will maintain a comprehensive audit trail that documents every stage of the research process, including the design framework, interview protocols, coding strategies, and decisions made throughout data collection and analysis.

According to Chowdhury (2015:148), dependability in qualitative research can be strengthened by providing clear and transparent records of how the study was conducted, enabling other researchers to understand and, if necessary, replicate the process. This involves demonstrating that changes in the research process are well-documented and justified, ensuring the internal logic of the study remains intact despite contextual or methodological adjustments.

In this study, dependability is established through careful documentation, peer debriefing, and consistent application of thematic analysis procedures, thus ensuring the findings are grounded in a transparent and reproducible research process (Chowdhury, 2015:150).

Confirmability

Confirmability refers to the degree to which the findings reflect participants' views rather than researcher bias. To achieve this, the study employs reflexivity through a reflective journal and maintain audit trails to ensure transparency. As Morse (2015:121) asserts, confirmability is achieved when interpretations are grounded in data rather than the researcher's personal assumptions.

3.10 Ethical considerations

Ethical integrity is a cornerstone of this research, ensuring the protection of participants' rights, privacy, and dignity throughout the study. This research complies with the ethical guidelines set by the university's research ethics committee and adhere to principles of informed consent, confidentiality, voluntary participation, and data protection. See also permission teller to conduct this study, with ethics number NWU-00786-25-A4 (Annexture 4)

3.10.1 Informed consent

Before participation, all respondents received a detailed information sheet explaining the study's purpose, procedures, and potential risks. Written consent was obtained to ensure participants fully understand their involvement. As Creswell and Poth (2018:42-44) note that informed consent ensures participants voluntarily decide to take part in research based on adequate information.

3.10.2 Voluntary participation

Participation in this study was entirely voluntary, and participants were able to withdraw at any stage without penalty. No coercion or undue influence was applied to secure participation.

3.10.3 Confidentiality and anonymity

Confidentiality and anonymity are essential principles in qualitative research to protect participants' identities and ensure ethical integrity. In this study, participants'

confidentiality is preserved by assigning unique codes during transcription and analysis, rather than recording their personal details. Audio recordings, transcripts, and any organisational documents will be securely stored on password-protected devices accessible only to the researcher.

Kang and Hwang (2023:2–3) emphasise that protecting anonymity and confidentiality is crucial for safeguarding participants from potential harm, maintaining their trust, and ensuring the credibility of research outcomes. Confidentiality involves safeguarding personal information shared during the research process, while anonymity refers to collecting data without linking it to identifiable participants. Both principles are particularly important in qualitative studies, where sensitive organisational and personal insights are shared. By adhering to these ethical standards, the study not only protects participants' dignity but also strengthens the validity and trustworthiness of the findings (Kang & Hwang, 2023:4–5).

3.10.4 Data protection and storage

Data was stored in compliance with the Protection of Personal Information Act (POPIA) in South Africa. Interview recordings and documents will be encrypted and retained for a maximum of five years before secure disposal.

3.10.5 Institutional approval

Prior to data collection, the researcher obtained ethical clearance from the university's ethics committee and sought formal permissions from participating petrochemical facilities.

3.11 Thematic analysis methodology

The study employs **reflexive thematic analysis** according to the six-phase framework proposed by Braun and Clarke. This approach is widely used in qualitative research due to its systematic yet flexible nature for identifying and interpreting patterns within data (Braun & Clarke, 2006:87). Their model enables both semantic and latent analysis and supports deep engagement with participant narratives during coding and theme development.

The six stages include:

1. Familiarisation with the data – Transcribing interviews, reading and re-reading transcripts, noting initial insights.
2. Generating initial codes – Systematically organising meaningful segments of data across the dataset.
3. Searching for themes – Combining codes into potential themes that capture patterns relevant to the research question.
4. Reviewing themes – Refining themes for coherence and alignment with coded data and full datasets.
5. Defining and naming themes – Conducting detailed analysis of each theme and developing clear labels.
6. Producing the report – Integrating the analysis into a cohesive narrative that addresses research objectives.

This reflexive and iterative approach supports the generation of rich thematic insights by emphasising the researcher's active role in interpreting meaning beyond descriptive content. As Braun and Clarke (2022:7) caution, careful reflexive practice helps avoid common pitfalls such as coding-for-coding's sake or superficial theme development.

3.11.1 Role of Atlas.ti, NVivo and other AI tools in data analysis

To strengthen the systematic rigor and transparency of thematic analysis, this study incorporates qualitative data analysis software (QDAS), including Atlas.ti complemented by artificial intelligence (AI) platforms such as ChatGPT and Google Gemini. These tools collectively enhance data management, coding efficiency, and analytic depth throughout the interpretive process.

- Efficient Data Management: Both software packages allow for the secure storage and organisation of large volumes of qualitative data, including interview transcripts, audio files, and organisational documents.

- Systematic Coding: The researcher can apply, modify, and manage codes digitally, ensuring consistency and transparency in the coding process. The software also allows for visualising connections between codes.

- Theme Development: Atlas.ti facilitate clustering and linking of codes into higher-order categories, supporting the identification of themes and subthemes.
- Query and Search Functions: Advanced features such as text search, code co-occurrence analysis, and word frequency queries provide deeper insights and triangulate emerging patterns.
- Audit Trail: All coding decisions, annotations, and memos are stored within the software, creating a transparent record that strengthens dependability and confirmability.
- Visualisation Tools: Features such as concept maps, networks, and matrices help illustrate relationships among codes and themes, providing a clearer picture of complex data.

According to Zamawe (2015:14), Software facilitates efficient coding and retrieval of qualitative data, enabling researchers to link themes and insights systematically. Similarly, Woods *et al*. (2016:600) note that, Atlas.ti support transparency through an inherent audit trail, which preserves all coding decisions and analytic memos to strengthen confirmability and dependability within the research process. This supports the reflexive thematic analysis approach proposed by Braun and Clarke (2006:89), which emphasises iterative coding and theme refinement grounded in rich, contextualised data.

The integration of AI-powered tools such as ChatGPT and Gemini allows for automated support in tasks like summarisation, pattern recognition, and refinement of emerging themes. While not replacing the interpretive role of the researcher, these tools offer additional analytic lenses in line with emerging practices that support multimodal qualitative research (Braun & Clarke, 2022). Used ethically, they enhance efficiency during the iterative process without compromising methodological integrity or human reflexivity (Hani-Morgan, 2020).

3.12 Chapter summary

This section has demonstrated how the combined use of Computer-Assisted Qualitative Data Analysis Software (CAQDAS) tools like Atlas.ti and NVivo, alongside emerging AI platforms such as ChatGPT and Google Gemini, enriched the data analysis process in this study. By integrating these tools, the research achieved not only systematic rigor and transparency but also enhanced interpretive richness and analytic efficiency. The tools supported consistent and auditable coding, enabled sophisticated thematic development, and offered corroborative insights through intelligent search and visualisation features.

The interplay between human reflexivity and technology-driven assistance supported by Braun and Clarke's iterative thematic analysis approach ensured that the findings remained grounded in the authentic lived experiences of participants. While AI never replaced the critical role of the researcher, it supplemented the process through efficient summarisation, pattern recognition, and conceptual refinement. This methodological fusion underscores the value of combining structured qualitative analysis tools with AI to improve the dependability, credibility, and transferability of qualitative research in the contemporary digital era.

This chapter detailed the research methodology employed to explore the influence of Sixth Industrial Revolution (6IR) technologies on preventive maintenance strategies in Gauteng's petrochemical industry. Rooted in the interpretivist paradigm, the qualitative exploratory case study design was chosen to gain deep, contextual insight into how industry practitioners perceive and implement emerging technologies such as predictive analytics, IoT, and AI-driven maintenance systems. Purposive sampling was used to identify information-rich participants like engineers and maintenance managers, with data gathered through semi-structured interviews and document analysis. These approaches provide flexibility and depth, allowing for the uncovering of complex experiential and organisational dynamics surrounding technological transformation in maintenance.

Thematic analysis, supported by software such as Atlas.ti, was selected as the primary analytical method, following Braun and Clarke's six-step (2022:1-12) framework to systematically identify patterns across the data. Measures to ensure trustworthiness such as triangulation, member checking, audit trails, and reflexivity were integrated throughout the research process. Ethical considerations including informed consent, confidentiality,

and data protection, in compliance with the POPI act and institutional guidelines, were rigorously applied. Overall, this chapter established a scholarly and methodologically sound foundation for exploring the intersection of 6IR and preventive maintenance within a sector undergoing digital transformation.

This chapter has detailed the research methodology adopted for the study; the next chapter presents and analyses the empirical findings derived from the data collected.

4 CHAPTER FOUR: PRESENTATION OF FINDINGS

This chapter presents and analyses the findings derived from the empirical data collected through interviews and document analysis. The findings are organised into themes that reflect participants' experiences and perceptions of 6IR-enabled preventive maintenance.

Based on the research design and data collection procedures outlined in Chapter 3, this chapter presents and analyses the findings obtained from the empirical investigation.

4.1 Introduction

The author utilised an ATLAS.ti-inspired approach to import and analyse the transcribed interview data from maintenance professionals in the petrochemical industry. A total of 15 text documents were imported and analysed. These documents comprised transcripts from various roles, including Maintenance Managers, Planners, Engineers, Technicians, and Production Supervisors. An ATLAS.ti-style coding function was used to code these 15 documents.

The coding procedure was subsequently followed by the identification of the most relevant concepts and themes pertaining to the study. It was difficult but necessary for the author to select only the concepts and themes most relevant to the research questions of this study. The ATLAS.ti approach initially generated codes assigned to quotations extracted from the text documents and organised these under distinct code categories, some of which served as the research themes. The approach also extracted unique concepts from the transcripts; several stood out in the context of the research. An overview of these concepts is provided in section 4.2 and is followed by a detailed unpacking of the results from the thematic analysis in section 4.3. Throughout section 4.3, illustrative quotes from the transcripts are reported before the author's own analysis. This is done in order to stay as close as possible to the reported experience of the professionals themselves and to centre their lived experience and reporting. Section 4.4 concludes this chapter.

4.2 Concepts

This section presents the key conceptual categories that emerged from the qualitative data analysis. These concepts were derived through the coding and categorisation of interview transcripts using computer-aided qualitative data analysis software. They

represent recurring ideas, patterns, and relationships identified in participants' responses and form the foundation for the thematic analysis presented in Section 4.3.

The initial coding process generated a broad range of concepts related to preventive maintenance practices and 6IR technology adoption. As illustrated in Figure 4.1, frequently occurring concepts included predictive maintenance, skills gap, technology, digital tools, and digital downtime. The prominence of these concepts indicates their centrality to maintenance transformation within the petrochemical context.

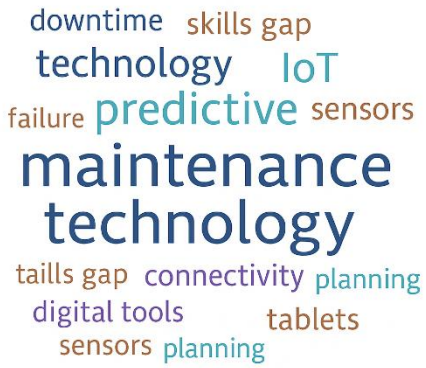

Figure 4,1: ATLAS.ti concepts cloud

Source: Own compilation using ATLAS.ti (2025)

4.3 Thematic analysis

Guided by the research questions, a network was generated for each theme (category code), and every single code and its associated quotes were inspected to determine relevance. Most codes were merged to focus the analysis and discussion on key subthemes within the major themes. Flowing from this process, the following code categories, which served as the research themes, were identified. Each theme is built up of the most relevant codes, which will be discussed in depth in the sections to follow. Many of the themes are interrelated but will be dissected and discussed initially as silos, focusing on the subthemes and the associated quotes.

- **Theme: Definitions and strategies**-proactive intervention, reliability and longevity, time-based, condition-based

- **Theme: Effectiveness**-reduced failures, Better Planning, Unplanned Breakdowns, Execution Issues
- **Theme: Industry 6.0 adoption and impact**- IoT and monitoring, predictive tools, efficiency gains, technical issues, human factors
- **Theme: Readiness, skills and training**-Moderate readiness, lagging readiness, digital literacy, generational resistance, uneven training, needed training
- **Theme: Alignment and policies-** Strong link, cross-department tension, traditional only

Employing multi-code quotes allowed the researcher to discover thread that runs through the rich tapestry that is the professionals lived experience. The first-hand accounts of their own roles and challenges provided the researcher with a formidable foundation upon which a lighthouse of knowledge may be built to shine a light on this field, with its unique dynamics and challenges. Neither should the analysis nor the reporting overlook the digital skills gap code serving as the golden thread. In the following sections, the themes are unpacked as follows: a diagram visualising the theme and its constituent codes is presented, multiple illustrative quotes are reported verbatim before the author's own analysis, and a discussion paragraph follows each set of quotes. This structure allowed for an authentic narrative to emerge from the self-reported experience.

4.3.1 Theme 1: Definitions and strategies

The relationships between identified concepts were further analysed to form conceptual categories. Figure 4.2 presents the category code network, demonstrating how definitions, strategies, and effectiveness are interconnected within participants' narratives.

This theme comprised main codes: Proactive Intervention, Reliability and longevity, Time-based, and Condition-based.

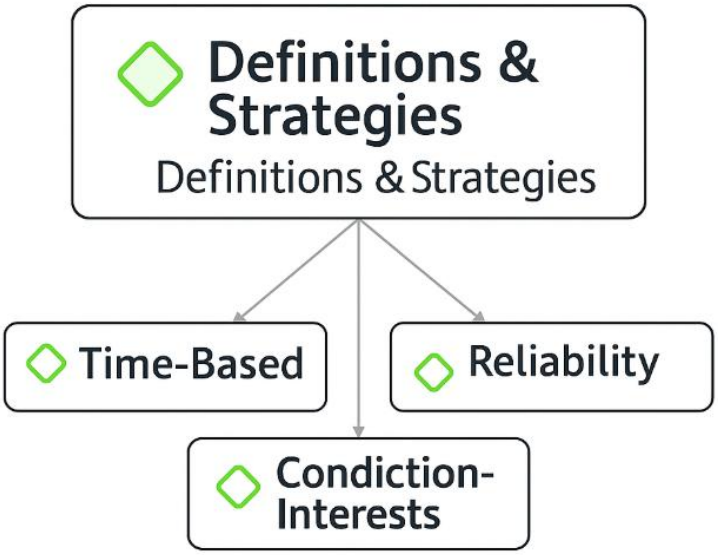

Figure 4.2: ATLAS.ti Category code network: Definitions and strategies

Source: Own compilation using ATLAS.ti (2025)

4.3.1.1 *Definitions and strategies: Proactive intervention*

> *"It's the systematic approach of servicing equipment before it fails—essentially identifying early signs of wear and taking corrective action before a breakdown happens." — Mechanical engineer*

> *"Preventive maintenance is basically doing maintenance to try and prevent a failure. So instead of leaving the equipment to run until it fails and then only start to try and fix it…" — Reliability engineer*

"It's about catching faults early, like spotting a leaking seal or unusual vibration before it turns into a breakdown." — Maintenance technician

"What I can say it helps us actually for with the assets that we work on. So what it does for us, it help us with the availability and the reliability of the plant…" — planner

The professionals interviewed agree that preventive maintenance is fundamentally proactive, focusing on intervening before failures occur. This aligns with standard reliability engineering principles in high-risk environments like petrochemical plants, where early detection prevents cascading failures and catastrophic incidents.

4.3.1.2 *Definitions and strategies: Reliability and longevity*

"To me, it's proactive servicing of assets to extend their life and minimise unplanned downtime. The aim is to intervene before the equipment fails, rather than after." — Maintenance Manager

"What I can say it helps us actually for with the assets that we work on… it help us with the availability and the reliability of the plant or all the assets that we work on…" — Planner

"Preventive maintenance, in simplest format, is a maintenance strategy whereby we do some different intervention in terms of inspections… The goal is to prevent the machines from premature failures…" — Mechanical maintenance manager

Reliability and asset longevity emerged as core outcomes of PM. Professionals consistently linked proactive interventions to sustained plant availability, reflecting a strategic rather than tactical view of maintenance.

4.3.1.3 *Definitions and strategies: Time-based*

"We follow weekly and monthly inspection checklists, do lubrication, and use handheld vibration monitors for rotating equipment." — *Maintenance technician.*

"We use a mix of time-based inspections and condition-based monitoring. For example, vibration analysis and oil sampling are routine for rotating machines." — *Maintenance manager.*

> “We stick to weekly, monthly, and annual checklists. Recently, we’ve also started using condition-monitoring tools…” — *Maintenance technician.*

Time-based scheduling remains a foundational strategy, particularly for non-critical assets. While reliable, it is increasingly supplemented by data-driven methods, indicating a transitional phase in maintenance philosophy.

4.3.1.4 *Definitions and strategies: Condition-based*

> “We use vibration analysis, oil analysis, and scheduled strip-down inspections for critical pumps and gearboxes.” — *Mechanical Engineer.*
>
> “We use calibration schedules, loop checks, and smart transmitter diagnostics. Increasingly, we’re shifting toward condition-based monitoring with IIoT-enabled instruments.” — *Instrumentation engineer.*
>
> “We also integrate condition-based monitoring data, which automatically generates work orders when a parameter crosses a threshold.” — *Maintenance planner.*

Condition-based monitoring represents the evolution of PM, leveraging real-time data to optimise interventions. This shift is most evident in critical rotating equipment like pumps and compressors.

4.3.2 Theme 2: Effectiveness

This theme comprised main codes: Reduced failures, better planning, unplanned breakdowns, and execution issues.

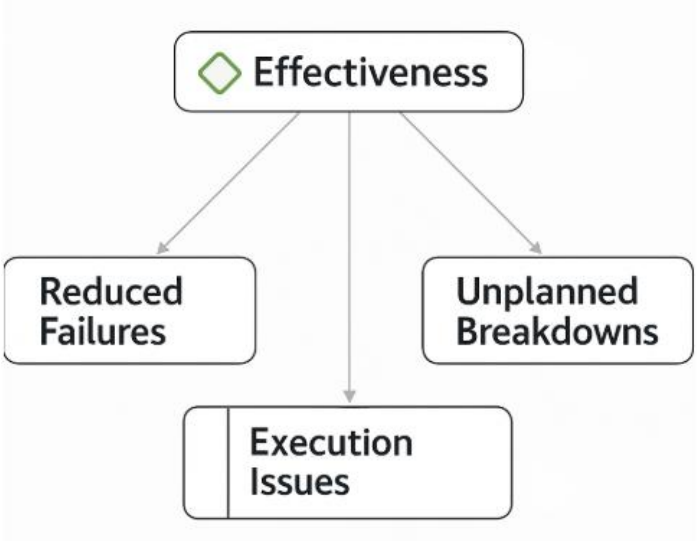

Figure 4.3: ATLAS.ti Category ode network: Effectiveness

Source: Own compilation using ATLAS.ti (2025)

4.3.2.1 *Effectiveness: Reduced failures*

"We've reduced gearbox failures by about 20% since implementing condition-based monitoring." — Mechanical engineer.

"They're fairly effective—we've managed to reduce major breakdowns by about 30% in the past five years." — Maintenance manager.

"We've been able to avoid catastrophic gearbox failures by intervening early." — Mechanical engineer.

Quantifiable reductions in failure rates validate PM strategies, particularly when condition monitoring is applied consistently.

4.3.2.2 *Effectiveness: Better planning*

"They're good at keeping us organised. The main issue is when unexpected breakdowns throw off the plan." — Maintenance planner.

"I can say probably within the organisation we are 70-75% there. However, we do have plans in place for the improvement…" — Planner.

"It has cut planning time significantly, maybe by 40%." — Maintenance planner.

PM enhances organisational efficiency and predictability, though full effectiveness remains aspirational due to external disruptions.

4.3.2.3 *Effectiveness: Unplanned breakdowns*

> *“They’re good for planned work, but unplanned breakdowns still disrupt schedules.” — Maintenance planner.*
>
> *“From my company's perspective, I don't think it's where it's supposed to be… some of the preventive maintenance items that normally kick out the reports are unnecessary.” — Mechanical maintenance manager.*
>
> *“The result of that is you get failures of equipment which you think is in a good condition, but it's not.” — Electrical manager.*

Despite gains, unplanned events remain a persistent challenge, often triggered by aging assets or execution gaps.

4.3.2.4 *Effectiveness: Execution issues*

> *“However, sometimes the execution is inconsistent—especially when production pressures lead to deferred maintenance.” — Mechanical engineer.*
>
> *“Systems are useless unless they're managed.” — Maintenance systems project.*
>
> *“The problem with the maintenance is it depends on artisans and if the artisans do not do it as required…” — Electrical manager*

Human and operational factors undermine execution, revealing that strategy alone is insufficient without discipline and alignment.

4.3.3 Theme 3: Industry 6.0 adoption and impact

This theme comprised main codes: IoT and monitoring, predictive tools, efficiency gains, technological issues, and human factors.

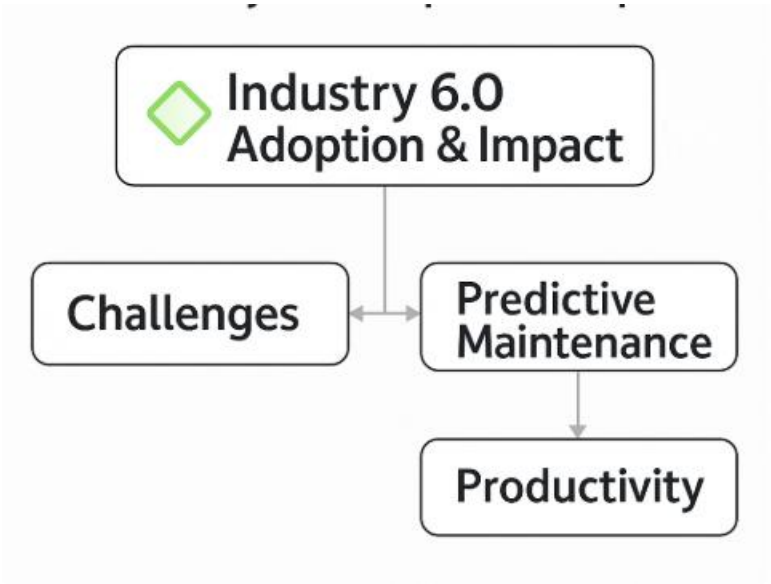

Figure 4.4: ATLAS.ti Category code network: Industry 6.0 adoption and impact

Source: Own compilation using ATLAS.ti (2025)

4.3.3.1 *Industry 6.0: IoT and monitoring*

> *"Yes, we've started using handheld IoT devices that connect to the cloud. I can scan equipment, and the data uploads instantly." — Maintenance Technician.*
>
> *"We've linked smart instruments into a central monitoring system that flags abnormal readings." — Instrumentation engineer.*
>
> *"We are using online monitoring to monitor some of the stuff online." — Electrical manager.*

IoT enables real-time visibility, transforming reactive maintenance into proactive oversight.

4.3.3.2 *Industry 6.0: Predictive tools*

> *"Yes, we've piloted AI-based predictive analytics on our pump systems. The software analyses vibration patterns…" — Mechanical engineer.*

“We also piloted predictive analytics last year, which showed promise in forecasting pump failures.” — Maintenance manager.

“We've got that system Process MD… it predicts certain things like a bearing temperature…” — Reliability engineer.

Predictive analytics marks the cutting edge of PM, offering weeks of advance warning on critical failures.

4.3.3.3 *Industry 6.0: Efficiency gains*

“It’s reduced my planning time by at least 40%. Also, it helps us order spare parts well in advance.” — Maintenance planner.

“It’s definitely reduced costs and unplanned downtime. Cost is the biggest one…” — Reliability engineer.

“We’ve been able to avoid catastrophic gearbox failures… It’s also saved money we no longer replace parts too early.” — Mechanical engineer.

Digital tools deliver measurable time and cost savings, particularly in planning and spare parts management.

4.3.3.4 *Industry 6.0: Technical issues*

“Connectivity and data accuracy. Sometimes sensors misread, and we waste time chasing false alarms.” — Maintenance planner.

“Data quality is a big issue. Sensors need to be calibrated regularly…” — Mechanical engineer.

“The biggest challenge is managing the data. There’s a(n) overflow of information, and not all of it is meaningful.” — Electrical engineer.

Infrastructure and data quality remain significant barriers to scaling Industry 6.0 solutions.

4.3.3.5 *Industry 6.0: Human factors*

“Some technicians don’t fully trust AI recommendations yet.” — Mechanical engineer.

“Some of the older guys resist the change.” — Maintenance technician.

“Currently we do have challenges and limitations because we don't have a full access…” — Planner.

Cultural resistance and lack of trust in automated systems slow adoption, even when technical benefits are clear.

4.3.4 Theme 4: Readiness, skills and training

This theme comprised main codes: Moderate Readiness, Lagging Readiness, Digital Literacy, Generational Resistance, Uneven Training, and Needed Training.

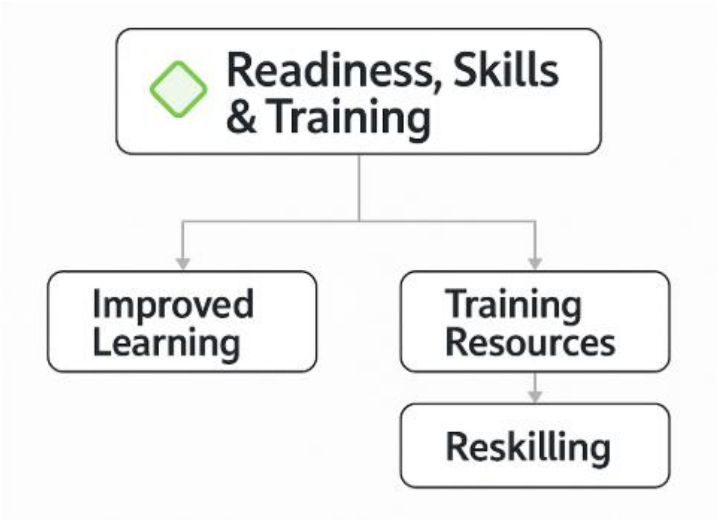

Figure 4.5: ATLAS.ti Category code network: Readiness, skills and training

Source: Own compilation using ATLAS.ti (2025)

4.3.4.1 *Readiness: Moderate readiness*

“I’d say moderate to high. Management is supportive, and we have budget for pilots…” — Mechanical engineer.

“I think we are 8 or one to 10.” — Planner.

“I’d say medium. Management is supportive, but budgets are tight…” — Maintenance manager.

Organisational readiness is generally positive, supported by leadership and pilot budgets.

4.3.4.2 *Readiness: Lagging readiness*

“In terms of AI, I think we are a bit far off…” — Reliability engineer.

“In terms of technologies, as a company, we're still a little bit behind.” — Mechanical maintenance manager.

However, advanced applications like AI remain distant due to data and infrastructure gaps.

4.3.4.3 *Skills: Digital literacy*

“Definitely. Many artisans prefer paper job cards. Moving them to digital tablets has been tough.” — Maintenance planner.

“Mechanical staff are excellent at hands-on work but often struggle with interpreting the digital analytics reports.” — Mechanical engineer.

“There's still a lot of gaps… especially on the technology space. We're still lagging behind.” — Mechanical maintenance manager.

A significant digital literacy gap continues, particularly among hands-on workers.

4.3.4.4 *Skills: Generational resistance*

“Some of the older guys resist the change.” — Maintenance technician.

“Some of the older technicians resist the change and prefer the old methods.” — Maintenance technician.

Resistance is often generational, with experienced workers favouring familiar paper-based systems.

4.3.4.5 *Training: Uneven training*

“Yes, we’ve rolled out digital skills training for artisans, but progress has been uneven.” *— Maintenance manager.*

“It's on in-house training actually… but like right now, we are basically trying…” — Planner.

“Not that I'm aware of. Not in my time in the company.” — Reliability engineer.

Training initiatives exist but lack consistency and reach.

4.3.4.6 *Training: Needed training*

“I’d push for training on digital tools to be mandatory, not optional.” — Maintenance planner.

“More hands-on training with the digital tools, and making sure we have proper Wi-Fi coverage…” — Maintenance technician.

“More training across levels. Engineers, technicians, and even operators need to understand what the data is telling us.” — Instrumentation engineer.

There is strong consensus that training must be compulsory, practical, and ongoing.

4.3.5 Theme 5: Alignment and policies

This theme comprised main codes: Strong link, cross-department tension, and traditional only.

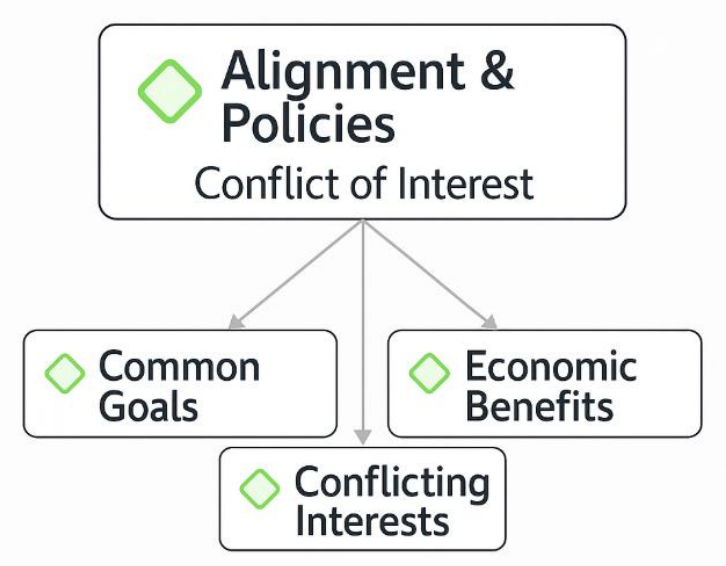

Figure 4.6: ATLAS.ti Category Code Network: Alignment and policies

Source: Own compilation using ATLAS.ti (2025)

4.3.5.1 *Alignment: Strong link*

“Yes. Our KPIs focus on safety, reliability, and OEE. Preventive maintenance directly supports all three.” — Maintenance manager.

“They do go hand in hand. The preventive maintenance is there to ensure that we don't have unnecessary breakdowns…” — Mechanical maintenance Manager.

“Maintenance strategies is(are) very important. If you do not keep the plant online, obviously the KPAs of the company will go down…” — Electrical manager.

PM is well-aligned with core KPIs when properly implemented.

4.3.5.2 *Alignment: Cross-department tension*

“Better alignment between maintenance and production KPIs. Right now, sometimes maintenance takes machines down at critical times…” — Production operator.

“Maintenance and production KPIs should be linked more closely. Right now, we sometimes pull in opposite directions.” — Production shift leader.

“Sometimes we only hear about scheduled downtime a day before, and that disrupts planning.” — Production supervisor.

Tensions arise when departmental priorities conflict, particularly around scheduling and communication.

4.3.5.3 *Policies: Traditional only*

“We follow ISO 55000 guidelines and company reliability standards. For digital tools, we’re still drafting formal policies.” — Maintenance manager.

“Not using new technologies. There are guidelines of how we need to do our preventive maintenance, but I don't think it's on the new technologies as yet.” — Mechanical maintenance manager.

“Not that I'm aware of.” — Reliability engineer.

Policies exist for traditional PM but are absent or underdeveloped for digital tools.

4.4 Chapter Summary

This chapter presented the findings of the qualitative investigation into the integration of preventive maintenance strategies and 6IR technologies in the petrochemical sectors of Gauteng. Through a structured ATLAS.ti-driven thematic analysis, rich insights were derived from the lived experiences of maintenance practitioners, highlighting not only successes and progress but also persistent challenges and systemic barriers.

Five core themes emerged:

- **Definitions and Strategies** revealed a shared understanding of preventive maintenance as proactive, with a gradual shift from time-based to condition-based methodologies, especially for critical assets.
- **Effectiveness** demonstrated tangible improvements in equipment reliability, planning efficiency, and cost savings, yet unplanned breakdowns and execution inconsistencies remain prevalent due to misalignment and resource constraints.
- **Industry 6.0 Adoption and Impact** showcased the promise of predictive tools, IoT-enabled monitoring, and AI analytics though full value realisation is hindered by technological barriers, data quality issues, and human resistance.
- **Readiness, Skills and Training** highlighted an uneven landscape: while leadership investment and pilot projects signal moderate organisational readiness, digital literacy gaps and generational resistance impede widespread adoption.
- **Alignment and Policies** underscored the strategic linkage between preventive maintenance and corporate KPIs, but exposed glaring divisions between departments and the absence of formal governance structures for emerging technologies.

Emerging from these findings is a dual narrative: one of technological potential and one of practical constraint. While the industry shows intent and incremental technological adoption, its readiness is fragmented across organisational, cultural, and infrastructural

dimensions. The recurring motif of digital skills gap serves as a binding thread that mediates both the success and limitations of technology-enabled maintenance.

Broadly speaking, the thematic analysis conducted on interview responses from maintenance professionals revealed that definitions and strategies, effectiveness, Industry 6.0 adoption, readiness and skills, and alignment with policies were common experiences shared by those interviewed. Professionals in the petrochemical sector all confronted challenges like skills gaps and technology integration during digital transitions. Where advancements like IoT and predictive analytics were piloted, many struggled with data accuracy, connectivity, and trust.

Within each theme, it is notable that the digital skills gap comes to the fore in different ways. During Industry 6.0 adoption (Theme 3), it is found that few fully trust AI recommendations due to interpretation challenges. Lack of readiness and training (Theme 4) was a main reason for this. Professionals often lacked cross-training, hindering full adoption. For those advancing, alignment and policies (Theme 5) improved outcomes. The skills gap did not reduce efforts; it highlighted needs for mandatory training. A few who noted gaps indicated that addressing them could enhance reliability and planning efficiency.

It is important, however, bearing in mind the holistic approach, that policies should be implemented comprehensively. Tablets for job cards can assist in digital transitions. Owning analytics skills can enable better predictions. Training investments can go a long way toward equipping professionals with these opportunities. It is important that policies embed digital tools within reliable infrastructure (e.g., plant-wide Wi-Fi) and support which make it feasible for adoption. These, and other conclusions and implications, can inform future practices in the sector.

This chapter has presented the key empirical findings of the study; the final chapter synthesises these findings with the literature, draws conclusions, and offers recommendations and a conceptual framework for practice.

5 CHAPTER 5: SYNTHESIS, RECOMMENDATION AND FINAL CONCLUSION

Drawing on the empirical findings presented in Chapter 4 and the literature reviewed in Chapter 2, this chapter synthesises the results, presents conclusions, and proposes recommendations and a conceptual framework for 6IR-enabled preventive maintenance.

5.1 Synthesis

The findings reflect a paradox of progress in Gauteng's petrochemical maintenance landscape: technological capability outpaces organisational readiness.

- PM strategic maturity is evident in the universal emphasis on proactivity and reliability-centred outcomes, with condition-based maintenance (CBM) leveraging vibration analysis and oil diagnostics to surpass traditional time-based approaches (Chen *et al*., 2020:841–851).
- Operational effectiveness, while improved through data-driven interventions, remains sub-optimal due to execution inconsistencies driven by production-maintenance tensions a systemic challenge in high-uptime environments (Zhang *et al*., 2022:823–838).
- Industry 6.0 adoption is in an embryonic phase, with pilot deployments of IIoT and AI analytics yielding tangible efficiency gains. However, infrastructural deficits (e.g., unreliable Wi-Fi, sensor calibration drift) and human factors (e.g., algorithmic distrust) perpetuate a feedback loop of underutilisation: Technical failure → competence gap → Eroded confidence (Sorooshian & Panigrahi, 2020:1024–1032).
- Organisational readiness is asymmetric: leadership endorses innovation, yet frontline artisans exhibit digital hesitancy, favouring analogue workflows. Training programmes, though present, lack standardisation, compulsion, and practical focus, rendering them inadequate for 6IR competency development (World Economic Forum, 2022).
- Governance and alignment represent the most critical bottleneck. Traditional PM is rigorously governed under ISO 55000, but cyber-physical systems operate in a policy vacuum, lacking SOPs for AI decision-making, data stewardship, or

cybersecurity in OT environments. KPI divergence with production incentivised for runtime and maintenance for compliance engenders adversarial scheduling and deferred interventions, undermining reliability (Zwetsloot *et al*., 2017:88–100).

Co-occurrence patterns position the digital skills gap as the pivotal mediating variable. When technological affordances align with human proficiency, operational excellence emerges; when misaligned, innovation stagnates. This dynamic, while globally observed, is exacerbated in the South African context by resource constraints, legacy infrastructure, and skills mismatches (Schwab, 2016).

5.2 Limitations of the study and directions for future research

While this study provided valuable insights into the integration of Industry 6.0 technologies into preventive maintenance practices within the petrochemical industries in Gauteng, it is not without limitations. Acknowledging these constraints provides context for interpreting the findings and highlights areas for potential future inquiry.

5.2.1 Methodological limitations

This research employed a qualitative approach using semi-structured interviews with five key maintenance stakeholders. While this method provided rich, in-depth insights, the sample size limits the generalisability of the findings. The participants, though diverse in role and experience, represent only a small fraction of the industry and do not fully capture the range of perspectives from other operational areas such as production, IT, or supply chain. Additionally, the study relied on self-reported experiences and perceptions, which are subject to participant bias or selective memory.

5.2.2 Contextual limitations

The study was conducted within a single geographic region (Gauteng) and focused specifically on companies within the petrochemical sector. As such, the findings may not fully reflect practices or challenges in other regions or sectors within South Africa or internationally. Technologies, resources, and maintenance cultures may differ significantly in industries such as power generation, mining, or manufacturing, which limits the broader applicability of the study’s conclusions.

5.2.3 Data-related limitations

Access to digital systems and internal records was not within the scope of this study. Therefore, while participants referenced systems like Process MD, DCS platforms, and CMMS tools, the actual data from these systems such as performance metrics, maintenance logs, or AI diagnostic outputs was not reviewed or analysed directly. This constrained the ability to validate claims regarding efficiency improvements or cost savings associated with technology adoption.

5.3 Correspondence between literature and empirical findings

- **Technology adoption and maintenance outcomes**
  Both literature and empirical findings show that the transition from time-based to condition-based and predictive maintenance using sensors and diagnostics improves equipment reliability and reduces failures (Chen *et al*., 2020:843). Participants in this study confirmed that vibration analysis, oil diagnostics, and real-time tools like Process MD have materially improved uptime.

- **Human factors as critical enablers**
  The literature highlights the digital skills gap as a barrier to organisational transformation (World Economic Forum, 2022:4). Empirical findings echo this with frontline artisans showing hesitance toward automation and AI tools, consistent with Sorooshian and Panigrahi's (2020:1026) observation that competence gaps drive algorithmic distrust.

- **Infrastructure and systemic constraints**

  Schwab (2016:22), argues that Industrial Revolution technologies face adoption challenges in environments with legacy infrastructure and uneven connectivity. This was reflected in the study as participants cited unreliable Wi-Fi, outdated CMMS systems, and sensor calibration drift as persistent hindrances in rollout.

5.4 Differences between literature and empirical findings

- **Scale and implementation trajectory**

While global literature reports scaling of AI-driven PM across sectors (Zhong *et al.,* 2023:457), empirical findings from Gauteng industries showed that most initiatives remain pilot projects, struggling to achieve sustained implementation due to resource constraints and operational fatigue.

- **Organisational alignment and governance**

According to Zwetsloot *et al*. (2017:93), effective Industry 4.0/6.0 adoption demands clear policy frameworks and consistent leadership commitment. In contrast, this study highlighted that although senior leaders endorse digital initiatives, operational misalignment and KPI conflicts between production and maintenance still hinder execution.

- **Cultural readiness and trust in automation**

While much of the literature suggests growing acceptance of AI and automation in industrial settings, this study reveals a contrasting trend among frontline maintenance personnel in Gauteng. Technicians demonstrate significant scepticism toward AI-driven predictive tools often opting for traditional manual techniques due to fears of job displacement and concerns about opaque decision-making models (Xiong *et al.,* 2021:3754). This finding highlights a critical disconnect between technological advancement and workforce readiness that is largely overlooked in global narratives.

- **Sector-specific evidence gaps**

Existing research predominantly focuses on high-tech manufacturing sectors in Europe and Asia, such as automotive and electronics, where Industry 4.0 and AI integration are more advanced (Li, 2022:1–2). However, this study underscores the distinct challenges faced by petrochemical and industrial gas facilities in the South African context particularly in the Vaal Region and Gauteng Industrial Belt. These challenges include load-shedding, a shortage of digitally skilled technical workers, and strict environmental compliance a reality not adequately addressed in mainstream literature, which often assumes stable power grids and robust digital infrastructure.

5.5 Suggestions for future research

To build upon the findings of this study, future research is recommended in the following areas:

5.5.1 Long-term impact assessment

Given that much of the digital transformation within maintenance is still emerging, longitudinal studies could assess the long-term impact of Industry 6.0 technologies on maintenance performance, asset reliability, and organisational efficiency. These studies could explore how predictive analytics and AI-enabled decision-making evolve over time, particularly in environments with varying technological maturity.

5.5.2 Digital skills development and training

A deeper exploration of digital skills readiness across different job categories within maintenance such as technicians, engineers, and managerswould be valuable. Future research could investigate specific skill gaps, assess the effectiveness of digital upskilling programs, and evaluate how skills development influences technology adoption success.

5.5.3 Cross-sector comparative studies

Expanding the research to include comparative studies across sectors such as mining, energy, and manufacturing would offer broader insights into adoption patterns, barriers, and best practices related to Industry 6.0 maintenance. This could also help identify sector-specific regulatory influences or contextual enablers of successful predictive maintenance strategies.

5.5.4 Technology-driven culture and organisational change

Further research could examine organisational culture's role in enabling or hindering digital transformation in maintenance. Understanding how leadership support, change management practices, and employee engagement influence the adoption of advanced technologies will provide valuable insights for companies seeking to modernise their maintenance approaches.

5.6 Conclusion and recommendation

This study set out to explore the effect of preventive maintenance strategies in the petrochemical industry through the sixth industrial revolution technologies in Gauteng. Through qualitative data collected from key maintenance personnel including planners, managers, engineers, and specialists a comprehensive understanding of current practices, challenges, and opportunities was developed.

The findings suggest that while preventive maintenance is widely recognised and implemented as a critical component of operational reliability, the adoption of advanced digital tools and Industry 6.0 technologies remains limited. Across the five interviews analysed, most participants acknowledged the use of foundational digital systems such as online monitoring and predictive analytics. However, the integration of more advanced capabilities such as artificial intelligence, machine learning, and fully automated decision-support was identified as an untapped opportunity.

The study successfully meets its primary and secondary objectives:

1. **Objective 1**: Understanding the effect of Industry 6.0 technologies: The research revealed that Industry 6.0 technologies have begun to influence maintenance planning and execution mainly through online monitoring systems and condition-based maintenance approaches. However, full-scale adoption is hampered by digital skill gaps, limited data integration, and infrastructure challenges.
2. **Objective 2**: Alignment with best practices and regulatory requirements: Current preventive maintenance strategies align in principle with best practices, focusing on asset reliability, efficiency, and safety. However, gaps exist in formalising policies for digital integration, updating standard operating procedures, and ensuring alignment with emerging global standards.
3. **Objective 3:** Maintenance performance tracking and continuous improvement: Performance tracking is conducted but is largely basic and manually driven. There is limited use of digital tools for real-time performance measurement or predictive reporting. Opportunities for continuous improvement exist, particularly through better data capture during maintenance tasks and more advanced analytics.

4. **Objective 4:** Technology integration and efficiency gains:
   While the use of digital tools has demonstrated some efficiency gains such as earlier detection of equipment anomalies these benefits are not yet maximised due to incomplete implementation of full Industry 6.0 technologies. The potential of AI-driven insights and fully integrated predictive maintenance remains largely unexplored.

Recommendations

Building on these insights, this study recommends:

- Increasing investment in Industry 6.0 technologies and accelerating their integration into core maintenance functions.
- Designing structured digital upskilling programmes to close identified skill gaps.
- Digitising maintenance records, technical manuals, and reporting processes to support advanced analytics.
- Adopting digital workflows (e.g., tablets, barcode scanning) to replace manual job cards.
- Developing internal policies and change management frameworks to support technology adoption and cultural transformation.

5.7 Contributions of the Study

This study makes several important contributions at theoretical, practical, and policy levels by advancing understanding of how Sixth Industrial Revolution (6IR) technologies influence preventive maintenance strategies within the petrochemical industry in Gauteng.

5.7.1 Theoretical Contribution

From a theoretical perspective, the study extends existing maintenance and digital transformation literature by providing context-specific insights into the application of 6IR concepts within an asset-intensive, high-risk industrial environment. While much of the existing literature focuses on Industry 4.0 or presents conceptual discussions of advanced maintenance technologies, this study contributes empirical evidence from a South African petrochemical context. The study further contributes to maintenance theory by integrating concepts of predictive maintenance, condition-based maintenance, and reliability-centred maintenance within a 6IR perspective, thereby supporting the development of a conceptual framework that links technology adoption, organisational readiness, and maintenance performance.

5.7.2 Practical Contribution

Practically, the study offers actionable insights for maintenance managers, engineers, and decision-makers within petrochemical organisations. The findings highlight key enablers and barriers affecting the effective adoption of 6IR-enabled preventive maintenance, including skills readiness, data quality, organisational culture, and legacy infrastructure constraints. The proposed conceptual framework serves as a practical guide to assist organisations in assessing their readiness for 6IR adoption and in structuring maintenance strategies that improve reliability, reduce unplanned downtime, and enhance safety performance.

5.7.3 Policy and Industry Contribution

At a policy and industry level, the study contributes to discussions on digital transformation and maintenance governance within South Africa’s industrial sector. The findings support the need for aligned digital maintenance policies, targeted skills

development initiatives, and clearer guidance on ethical and sustainable deployment of advanced technologies. These insights may inform organisational policy formulation and contribute to broader industry efforts aimed at improving asset management maturity and operational resilience.

5.8 Implications of the Study

The findings of this study have several implications for maintenance practice, organisational leadership, and future research within the petrochemical industry.

5.8.1 Implications for Maintenance Practice

The study implies that petrochemical organisations should move beyond viewing 6IR technologies as standalone tools and instead integrate them into a coherent preventive maintenance strategy. Maintenance practices should increasingly be informed by real-time data, predictive analytics, and condition monitoring, supported by appropriate skills development and data governance structures. Failure to address these enabling conditions may limit the effectiveness of advanced maintenance technologies.

5.8.2 Implications for Management and Leadership

For senior management and organisational leaders, the study highlights the importance of strategic alignment between digital transformation initiatives and maintenance objectives. Leadership commitment, investment in workforce capability, and cross-functional collaboration are critical for successful implementation of 6IR-enabled maintenance strategies. Managers must also address resistance to change and ensure that technology adoption is accompanied by organisational and cultural transformation.

5.8.3 Implications for Policy and Skills Development

The study underscores the need for industry bodies, policymakers, and educational institutions to support the development of digital and analytical skills relevant to advanced maintenance practices. Structured training programmes, partnerships between industry and academia, and updated maintenance standards can facilitate more effective adoption of 6IR technologies within the petrochemical sector.

5.8.4 Implications for Future Research

The findings suggest opportunities for future research to explore quantitative assessments of 6IR-enabled maintenance performance, longitudinal studies on technology adoption, and comparative analyses across different industrial sectors or regions. Further research could also examine the long-term sustainability and ethical implications of advanced maintenance technologies.

5.6 Concluding Remarks

Preventive maintenance remains a foundational strategy for asset reliability in the petrochemical industries. The transition to Industry 6.0 offers unprecedented opportunities to enhance this strategy through intelligent systems, real-time insights, and autonomous diagnostics. While this transition is underway, the pace of adoption can be accelerated through strategic planning, investment, and skill development. The study highlights that the true promise of Industry 6.0 lies not only in technological capability but also in organisational readiness and collective mindset shift.

6 REFERENCE LIST

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7 ANNEXTURE 1: INFORMED CONSENT FORM

NWU®
NORTH-WEST UNIVERSITY
NOORDWES-UNIVERSITEIT
YUNIBESITI YA BOKONE-BOPHIRIMA

INFORMED CONSENT FORM

Dear Participant,

You are invited to participate in a research study that forms part of an academic requirement for a Master of Business Administration (MBA) degree at the North-West University. Please take the time to read the information below and feel free to ask the researcher or person explaining the research to you any questions you might have before you decide to participate. It is important to the researchers that you are fully satisfied that you clearly understand the purpose of this research and how you will be involved. Please note, your participation in this study is entirely voluntary and you are free to decline participation. Not participating in this study will not affect you negatively in any way. You are also free to withdraw from the study at any point, even if you do agree to take part now.

This study has been approved by the NWU Economic and Management Sciences Research Ethics Committee (EMS-REC) and will be conducted according to the ethical guidelines and principles of the North-West University and other international ethical guidelines applicable to this study.

Title of the study: Exploring preventive maintenance strategies in the petrochemical industry through the sixth industrial revolution technologies in Gauteng

Institution: NWU Business School

Ethics references number: NWU-00786-25-A4

Names and contact details of project staff:

Principle researcher:	**Study Supervisor:**
Lutendo Mammburu	Johan Coetzee
North-West University (NWU)	North-West University (NWU)
Email: 49824716@mynwu.ac.za	Email: 10306498@mynwu.ac.za

Purpose of the study

The purpose of this study is to explore how sixth Industrial Revolution (Industry 6.0) technologies, such as artificial intelligence (AI), the Internet of Things (IoT), predictive analytics, and machine learning are being integrated into preventative maintenance strategies of petrochemical sectors within the Gauteng Province, South Africa.

What participation involves

Should you agree to participate in the current study, you will undergo an interview of approximately 20–30 minutes at a suitable time that is convenient for all parties. The interview can be conducted in person or via a digital platform (e.g., Zoom or Teams). With your consent, the interview will be audio-recorded to ensure accurate transcription and analysis of data.

Confidentiality and data protection

Your identity will be protected through anonymisation (e.g., using codes instead of names). All collected data will be stored securely on password-protected devices. Data will be used strictly for academic purposes in the current study only and will stand in compliance with the Protection of Personal Information Act (POPIA). The final mini-

dissertation will be publicly available via the NWU Library Repository, but no personal identifiers will be included.

Risks and benefits

There are no foreseeable risks associated with your participation. Your input may contribute to improving maintenance strategies and adoption of technology in the industry.

Permission from organisation

This study is conducted with written approval from the participating organisation's senior management where participants are employed. Your participation is voluntary and separate from your professional responsibilities.

Consent statement by the participant

I, the undersigned, agree to take part in the research study titled above and declare that:

1. I have read and understood the information provided above.
2. I voluntarily agree to participate in this research.
3. I understand that I can withdraw at any time without penalty.
4. I give permission for the interview to be audio-recorded.

☐ Yes ☐ No

Participant Name: _____

Participant Signature: _____

Date: _____

Declaration by the researcher

I, Lutendo Mammburu, declare that:

1. I explained the information set out in this document to the undersigned participant.
2. I ☐ did / ☐ did not use and interpreter.
3. I encouraged the participant to ask questions and took adequate time to answer them.
4. I am satisfied that the participant adequately understands all aspects of the research as described above.

Researcher Name: _____

Researcher Signature: _____

Date: _____

8 ANNEXTURE 2: SEMI-STRUCTURED INTERVIEW QUESTIONS

SEMI-STRUCTURED INTERVIEW QUESTIONS

Section A: Participant Background

- Can you briefly describe your current role and responsibilities within the organisation?
- How many years of experience do you have in maintenance or operations in this industry?
- What types of preventative maintenance strategies are currently used in your facility?

Section B: Understanding of Preventative Maintenance

- How would you define preventative maintenance in the context of your organisation?
- What are the main goals of your organisation's preventative maintenance program?
- How effective do you think your current maintenance strategies are in preventing equipment failure or unplanned downtime?

Section C: Industry 6.0 Technologies in Maintenance

- Are you familiar with Industry 6.0 technologies (e.g., IoT, AI, machine learning, predictive analytics)? If so, which ones are currently used in your maintenance practices?
- How have these technologies influenced your maintenance planning, execution, or monitoring?
- What benefits or improvements have you observed (e.g., reduced downtime, improved asset reliability, cost savings)?
- Are there any challenges or limitations you've encountered in implementing these technologies?

Section D: Organisational Readiness and Skills

- How would you rate your organisation's readiness to adopt advanced technologies in maintenance?
- Have there been any training or upskilling initiatives related to digital maintenance tools or systems?
- In your view, is there a digital skills gap that affects the successful use of Industry 6.0 technologies in maintenance?

Section E: Strategic Impact and Policy

- How do preventative maintenance strategies align with the overall goals or KPIs of the organisation?
- Are there any internal policies or regulations that guide how maintenance is planned and executed using new technologies?
- What recommendations would you make to improve the effectiveness of preventative maintenance strategies through digital integration?

Section F: Closing

- Is there anything else you would like to add regarding the role of Industry 6.0 in maintenance within your organisation?
- Do you have any suggestions for future research or improvements in this area?

9 ANNEXTURE 3: PERMISSION TO CONDUCT ACADEMIC RESEARCH

Air Products South Africa (Pty) Ltd
Reg. No. 1969/003571/07
Silver Stream Business Park
1st Floor, Building 3, 10 Muswell Road South,
Bryanston, 2191
Private Bag 784090, Sandton, 2146
T +2711.570.5000
E info@airproducts.co.za
www.airproducts.co.za

AIR PRODUCTS

To: North-West University (NWU)
Business School

Attention: Lutendo Mammburu
MBA Candidate

RE: Approval to Conduct Academic Research at Air Products

Dear Mr, Mammburu,

This letter serves to confirm that Air Products South Africa – Onsite Department grants approval for you to conduct academic research titled:

"Exploring Preventive Maintenance Strategies in the Petrochemical Industry Through Sixth Industrial Revolution Technologies in Gauteng."

Permission is granted for you to conduct semi-structured interviews with selected employees within relevant departments, including Maintenance, Engineering, and Operations. Interviews may be conducted in person or online, depending on staff availability and operational needs.

This approval is granted subject to the following conditions:

1. Voluntary Participation: All participating employees must be informed that their involvement is voluntary.
2. Confidentiality: All information obtained must be treated confidentially. Neither employee identities nor the organisation's identity may be disclosed without written permission.
3. Academic Use Only: The information collected is to be used strictly for academic purposes related to your mini-dissertation and any related scholarly publications.

Directors: NP Mageza (Chairman); CAA Dos Santos (Managing); M Kara (Financial); S Nkonde; IJPL Bols*; R Sinath; NJ Williams; JB Escorihuela Urbina**
*Belgium **United Kingdom

Rev 2025-04

4. Operational Consideration: Research activities must be arranged in a way that does not interfere with normal operations at the facility.

We trust that your research will contribute meaningfully to academic insights and industry practices relating to maintenance and emerging technologies.

Kind regards,

Dumisa Gina
General Manager – Onsites
T: 011 570 5188

Signature:

Date: 10 October 2025

10 ANNEXTURE 4: ETHICAL LETTER

Private Bag X1290, Potchefstroom
South Africa 2520
Tel: 018 299-1111/2222
Fax: 018 299-4910
Web: http://www.nwu.ac.za
Senate Committee for Research Ethics
Tel: 018 299-484
Fezlwe.Mseleni@nwu.ac.za

11 August 2025

ETHICS APPROVAL LETTER OF STUDY

Based on approval by the **North-West University Economic and Management Sciences Research Ethics Committee (EMS-REC)** on 11 August 2025 , the Economic and Management Sciences Research Ethics Committee hereby **approves** your study as indicated below. This implies that the North-West University Senate Committee for Research Ethics (NWU-REC) grants its permission that, provided the special 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:	Exploring the effect of sixth industrial revolution technologies on preventative maintenance strategies in industrial gas and petrochemical industries in Gauteng Region		
Study leader/Supervisor (Principal investigator/Researcher:	Mrs J.C. Coetzee	**University no.:**	10306498
Student:	Mr L.G. Mammburu	**University no.:**	49824716
Ethics number:	N W U - 0 0 7 8 6 - 2 5 - A 4 Institution / Study number / Year / Status Status: S = Submission; R = Re-submission; P = Provisional authorisation; A = Authorisation		
Application type:	Single study - Postgraduate research	**Risk level:**	Low/minimal risk
Commencement date:	8/11/25		
Expiry date:	8/11/25		
Approval of the study is initially provided for a year, after which continuation of the study is dependent on receipt and review of the annual (or as otherwise stipulated) monitoring report and the concomitant issuing of a letter of continuation.			

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

None.

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 study leader/supervisor (principal investigator)/researcher must report in the prescribed format to the EMS-REC:*
  - *annually (or as otherwise requested) on the monitoring of the study, whereby a letter of continuation will be provided, 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 study leader/researcher must apply for approval of these amendments at the EMS-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 an external audit.*
- *The date of approval indicates the first date that the study may be started.*
- *In the interest of ethical responsibility, the NWU-SCRE and EMS-REC reserves the right to:*
  - *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 EMS-REC or that information has been false or misrepresented;*
    - *submission of the annual (or otherwise stipulated) 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.*
- *EMS-REC can be contacted for further information or any report templates through the secretariat. Botlenyana Maluleka (Botlenyana.Maluleka@nwu.ac.za/ +27 18 2852436) or the chair Prof Diana Viljoen-Bezuidenhout (Diana.Viljoen@nwu.ac.za / +27 16 9103403).*

The EMS-REC would like to remain at your service as scientist and researcher, and wishes you well with your study. Please do not hesitate to contact the EMS-REC or the NWU-SCRE for any further enquiries or requests for assistance.

Yours sincerely,

Prof Diana Viljoen-Bezuidenhout

Digitally signed by Prof Diana Viljoen-Bezuidenhout
Date: 2025.08.11 12:25:40 +02'00'

Prof Diana Viljoen-Bezuidenhout

Chairperson: NWU Economic and Management Sciences Research Ethics Committee

11 ANNEXTURE 5: EDITOR'S CERTIFICATE

CERTIFICATE OF EDITING: Dissertation submitted in fulfilment of the requirements for the degree *Masters in Business Administration* in at the North-West University

22 November 2025

CANDIDATE: LG Mammburu Student number: : 49824716

Title: Exploring preventive maintenance strategies in the petrochemical industry through the sixth industrial revolution technologies in Gauteng

orcid.org/0009-0007-8416-2734 **Supervisor: Mr JC Coetzee**

I have edited this dissertation and would certify that all aspects of the linguistic expression (grammar, style, paragraphing, spelling, and vocabulary) are now of a standard that is to be expected from a document at this level and of this nature.

I am totally satisfied with all the language aspects of the document as it now stands.

Professor Damian Garside
MA (Manchester) Ph D (Cape Town)
Associate Professor of Communication
NWU (Mahikeng Campus) (retired)
formerly: Senior Lecturer
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Professor Damian John Garside

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Date: 2025.11.22 20:16:40 +02'00'