Evaluating the progress of the South African Mining Industry in the transition towards Industry 5.0

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DECLARATION

I, Wilna Elizabeth Müller, hereby declare that this study, titled “Evaluating the progress of the South African Mining Industry in the transition towards Industry 5.0”, is my work, conducted under the guidance of Prof Liezl van Dyk at North-West University. To the best of my knowledge, this thesis contains no material previously published or written by another person except where due reference is made. This work has not been submitted for any degree or examination at any other university. All sources of information used have been duly acknowledged. Large language models (LLMs) are utilised as a tool for improving the clarity and conciseness of the thesis. The use of these models adhered strictly to the following tiers, ensuring that the intellectual integrity and originality of the research remain intact (Bekker, 2024).

Tier 2: Proofing tool - Written drafts were refined using specific prompts to correct spelling, grammar, register, tone, and style. This process was implemented after completing the research and analysis, ensuring that all content and critical thinking is the author's work. The LLM improved clarity and precision without compromising the originality of the study.

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It is emphasised that the use of LLMs in this thesis was restricted to improving language quality and presentation. The research, critical analysis, and original contributions remain entirely the author’s own work.

Signature: ____________________

Date: ___29 July 2025 ______

DEDICATION

To my husband Christoff, for your unwavering patience, encouragement, and support throughout this journey. Thanks to my family for standing with me every step of the way, and to God for granting me the strength and ability to complete this work.

To my little baby girl Liana, who was kicking in my tummy all the way through this — your quiet presence reminded me of the future I'm building, and you are now brightening our lives every day.

PREFACE

This thesis is the combination of a challenging and rewarding journey, motivated by my interest and experience in working and improving the South African mining industry through Industry 5.0 principles. My motivation to explore this evolving field comes from the pressing need to improve productivity, sustainability, and human-centric approaches within our local industry. Throughout the research process, I have encountered a wide range of challenges and opportunities currently faced by the South African Mining Industry. This work is the result of a dedicated journey of discovery and analysis, and I hope it contributes meaningful insights to the field.

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ABSTRACT

This thesis investigates the current state of Industry 5.0 adoption within the South African mining sector, focusing on the integration of advanced technologies with human-centric, sustainable, and resilient principles. Driven by the global shift toward Industry 5.0, which emphasises collaboration between humans and machines, the mining sector faces unique challenges, especially given the complex socio-technical landscape of South Africa. This study was motivated by the need to understand the opportunities and challenges associated with adopting Industry 5.0 principles within this critical sector of the South African economy.

The research follows a structured, phased qualitative approach that integrates a scoping review with an empirical investigation. The scoping review synthesised key Industry 5.0 components and maturity assessment practices to inform the development of an Industry 5.0 maturity framework. This framework guided the empirical phase, which involved semi-structured interviews with industry stakeholders. Interview responses were thematically coded using a priori categories, quantitised via a four-level maturity scale, and analysed through descriptive and visual methods. The study is grounded in Sociotechnical Systems (STS) Theory, emphasising the interaction between technological systems and human-centred factors in shaping transformation outcomes.

Key findings reveal a varied adoption landscape, with higher maturity levels in areas like sustainability but challenges in human-machine collaboration and resiliency. It also identifies a critical gap in digital fluency and change management, which impacts the readiness of the industry to embrace more advanced Industry 5.0 applications. The study's insights indicate that the industry is still largely rooted in an Industry 4.0 mindset. Recommendations highlight the importance of prioritising workforce training, flexible investment strategies, and stronger collaboration between operators and technology partners.

The study contributes a tailored Industry 5.0 framework emphasising the integration of human and machine collaboration, resilience-building, sustainable practices and worker, system and customer perspectives. It provides actionable recommendations for policymakers and industry leaders, focusing on workforce upskilling, investment in foundational infrastructure, and fostering a culture of innovation. By addressing these areas, the South African mining industry can position itself as a global leader in sustainable and human-centric mining practices. This research not only bridges the existing knowledge gap but also offers a roadmap for future studies and strategic planning, ensuring the mining sector's alignment with the evolving principles of Industry 5.0. It underscores the critical need for a balanced approach that harmonises technological progress with social and environmental priorities to achieve transformative growth.

Keywords: Industry 5.0, human-centric, resilience, sustainability, maturity, framework

OPSOMMING

Hierdie tesis ondersoek die integrasie van Industry 5.0 in die Suid-Afrikaanse mynbousektor, met spesifieke fokus op die integrasie van gevorderde tegnologieë met mens-gesentreerde, volhoubare en veerkragtige beginsels. Gedryf deur die globale skuif na Industry 5.0, wat samewerking tussen mense en masjiene beklemtoon, staar die sektor unieke uitdagings in die gesig, veral binne Suid-Afrika se komplekse sosio-tegniese landskap. Die studie beoog om die geleenthede en uitdagings van hierdie oorgang te verstaan.

Die navorsing volg 'n gestruktureerde, gefaseerde kwalitatiewe benadering, insluitend 'n omvangbepalingsstudie van bestaande Industry 5.0-raamwerke en 'n empiriese ondersoek na die mynbousektor. Semi-gestruktureerde onderhoude met belanghebbendes evalueer die sektor se volwassenheid, geleenthede en hindernisse. Antwoorde op onderhoudsvrae is tematies gekodeer met behulp van voorafbepaalde kategorieë, gekwantifiseer volgens ’n viervlak-volwassenheidskaal, en ontleed deur middel van beskrywende en visuele metodes Sosio-tegniese Stelselteorie (STS) vorm die studie se grondslag, en beklemtoon die wisselwerking tussen tegnologie en menslike elemente vir suksesvolle integrasie en transformasie.

Die bevindings toon 'n uiteenlopende integrasie landskap, met hoër volwassenheidsvlakke in volhoubaarheid, maar uitdagings in mens-masjien samewerking en veerkragtigheid. Daar is ook 'n gaping in digitale geletterdheid en veranderingbestuur wat die sektor se gereedheid vir Industry 5.0-toepassings beïnvloed. Die insigte dui daarop dat die sektor steeds grootliks in 'n Industry 4.0-mentaliteit gewortel is.

Die studie stel 'n Industry 5.0-raamwerk voor wat die integrasie van mens-masjien samewerking, veerkragtigheid en volhoubare praktyke beklemtoon. Dit bied praktiese aanbevelings vir beleidsmakers en nywerheidsleiers, insluitend werksmag-opskoling, beleggings in basiese infrastruktuur en die bevordering van 'n kultuur van innovasie en samewerking. Deur hierdie uitdagings aan te spreek, kan die mynbousektor homself as 'n wêreldleier in volhoubare en mens-gesentreerde mynboupraktyke posisioneer.

Hierdie navorsing oorbrug nie net 'n bestaande kennisgaping nie, maar bied ook 'n padkaart vir toekomstige studies en strategiese beplanning. Dit beklemtoon die behoefte aan 'n gebalanseerde benadering wat tegnologiese vooruitgang met sosiale en omgewingsprioriteite harmoniseer om transformerende groei te bewerkstellig.

Sleutelwoorde: Industry 5.0, mens-gesentreerd, veerkragtigheid, volhoubaarheid, raamwerk

LIST OF ABBREVIATIONS

4IR	Fourth Industrial Revolution
AI	Artificial Intelligence
APC	Advanced Processing Control
AR	Augmented Reality
CEO	Chief Executive Officer
Cobots	Collaborative robots
CPPS	Cyber Physical Production Systems
DMR	Department of Mineral Resources
EDS	Enterprise Data Storage
ESG	Environmental, Social, and Governance
GDP	Gross Domestic Product
GISTM	Global Industry Standard on Tailings Management
IoT	Internet of Things
IR	Industrial Revolution
ISO	International Organisation for Standardisation
IT	Information Technology
LLM	Large language models
LDP	Learner Development Program
NWU	North West University
OEM	Original Equipment Manufacturer
PGM	Platinum Group Metals
PID	Proportional-Integral-Derivative
PLC	Programmable Logic Controller
POC	Proof of Concept
PPE	Personal Protective Equipment
PRISMA-ScR	Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews

RFID	Radio Frequency Identification
ROI	Return on investment
SATCAP	Successful Application of Technologies Centered Around People
SCADA	Supervisory Control and Data Acquisition
STS	Sociotechnical Systems Theory
TOE	Technology Organisation Environment Theory
XR	Extended Reality

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CHAPTER 1 INTRODUCTION

1.1 Introduction

The first chapter of this thesis provides a foundational understanding of Industry 5.0. It delves into the historical progression of industries, from Industry 1.0 to Industry 4.0, highlighting key technological advancements, societal changes, and the accompanying challenges that have shaped the industrial landscape. Industry 5.0, coined by the European Commission, emerges as a response to the limitations of Industry 4.0, emphasising human-machine collaboration and sustainable, socially beneficial practices.

Against this backdrop, the chapter presents the South African mining industry as a unique case for exploring Industry 5.0, due to its historical significance, economic importance, and ongoing challenges. Although the sector has begun integrating aspects of Industry 4.0, it remains constrained by issues such as high operational costs, outdated infrastructure, and limited workforce preparedness. Consequently, this research aims to assess the current state and maturity of Industry 5.0 adoption within the South African mining industry, identifying both opportunities and challenges. The research objectives and questions are detailed, with the aim of providing recommendations and guidance for the industry's transition to this next industrial phase. Finally, the chapter acknowledges the limitations of this study, particularly regarding the emerging nature of Industry 5.0 literature and its relevance within the South African mining sector.

1.2 Background

Significant technological advancements and corresponding societal changes have marked the evolution of the industry from its inception to the present day. Industry 1.0, which began in the late 18th century, was characterised by the use of steam and water power to mechanise production processes in industries such as mining, agriculture, and iron manufacturing (Mathur *et al.*, 2022). This era brought about significant industrial growth, but also posed challenges like pollution, long working hours, and poor working conditions (Apriliyanti, 2022).

In the late 19th century, Industry 2.0 emerged with the start of mass production powered by electricity. This period saw the rise of iron and steel production, railways, and turbines, utilising innovations such as conveyor belts and assembly lines (Mathur *et al.*, 2022). While this era significantly boosted production efficiency, it also led to job displacement as machines replaced human labour and brought about high operational costs (Apriliyanti, 2022). The 20th century introduced Industry 3.0, marked by the beginning of automated production and the integration of computers and IT systems (Luca & Dolga, 2021). This era focused on renewable energy, telecommunications, and wireless communication. Despite these advancements, challenges such as electronic waste and high power consumption have become prominent issues (Apriliyanti, 2022).

Entering the 21st century, Industry 4.0 revolutionised production by integrating artificial intelligence (AI), the Internet of Things (IoT), and smart factories. These intelligent systems spanned all production industries, enhancing efficiency and productivity across the board. However, new challenges arose, including the risks of cyber-attacks, extended working hours, and a significant skills gap in the workforce (Raja Santhi & Muthuswamy, 2023). Each industrial revolution has built upon the technological advancements of its predecessors, leading to increased productivity and innovation while also presenting new challenges that society must address. Due to the lack of Industry 4.0's focus on a strong emphasis on human interaction and collaboration, sustainable and ethical practices, and a beneficial drive for business and social success (Adel, 2022), these shortcomings have paved the way for the emergence of Industry 5.0.

The term "Industry 5.0" was coined by the European Commission to represent a new phase of industrialisation (European Commission, 2021). It builds on the technological advancements of Industry 4.0, with a stronger focus on human-machine collaboration, customisation, innovation, resilience, and sustainability, shifting the focus from economic value to social value and well-being (Xu *et al.*, 2021). It places the well-being of the industry worker at the centre of focus and emphasises the collaboration of human skills such as creativity, decision-making, and complex problem-solving with advanced technologies (Raja Santhi & Muthuswamy, 2023).

Various sectors are transitioning towards Industry 5.0, which emphasises personalisation and efficiency. In manufacturing, collaborative robots (cobots) and advanced analytics aim to create more personalised products while maintaining cost-effectiveness and enhancing production flexibility (Adel, 2022). Many other industries, such as healthcare, electronics, and automotive, could also benefit from customisation and personalisation. Despite challenges, the benefits of increased adaptability and resilience outweigh the difficulties (Adel, 2022). Early adoption of Industry 5.0 innovations should enable organisations to stay competitive and contribute to a more sustainable future.

1.3 Context & significance

As this concept is still emerging, there is a unique opportunity to explore its key concepts and components, particularly in the South African mining industry. Due to several critical factors, the South African mining industry provides a unique context for investigating the transition towards

Industry 5.0. Historically, the mining sector has played a vital role in South Africa's economic development. In 1980, mining was the second most influential industry in South Africa, accounting for 21% of the country's GDP (Statistics South Africa, 2017). By 2023, the industry's contribution had decreased to around 6,2% of GDP, making it an ideal candidate for modernisation and technological advancement (Anon, 2024; Lumadi & Nyasha, 2024).

The industry also faces significant challenges, including high operating and labour costs and the need for modernisation and digitalisation to maintain competitiveness (Zulu *et al.*, 2021). These challenges present an opportunity to explore how Industry 5.0 can offer solutions for growth and sustainability. Although the industry has begun adopting Fourth Industrial Revolution (4IR) technologies, gaps remain in their successful implementation (Masuku, 2023).

While efforts have been made to modernise the South African mining industry, there is a notable gap in the literature regarding its overall progress towards Industry 5.0. Specifically, there is limited information on the extent of technological adoption, the industry's readiness, and the workforce's preparedness. This gap highlights the need for a comprehensive assessment of the industry's current state and future prospects.

In summary, the South African mining industry is well-suited for investigating the transition towards Industry 5.0 due to its historical significance, current challenges and technological adoption. This research will provide valuable insights into the South African mining industry's current status and future direction in the context of Industry 5.0. By identifying key challenges and opportunities, the findings will inform strategic planning and policymaking, helping to ensure the industry's sustainable growth and competitiveness in the global market.

1.4 Research problem

The global emergence of Industry 5.0 presents significant opportunities and challenges for industries worldwide. Industry 5.0 emphasises the integration of advanced technologies such as artificial intelligence, robotics, and the Internet of Things with a strong focus on human-centric, sustainable, and intelligent production systems. There is increasing recognition among mining professionals and stakeholders that Industry 5.0 technologies, such as artificial intelligence (AI), robotics, and the Internet of Things (IoT), can improve operational efficiency, reduce environmental impact, and address workforce skills gaps (Muzvondiwa, 2024). However, the mining industry has been slow to adopt this new approach, and this transition is crucial for the South African mining industry to remain relevant and competitive (PwC *et al.*, 2023).

However, the current status and maturity in the progress of the South African mining industry in adopting these Industry 5.0 principles remain unclear. Research highlights the importance of structured frameworks, such as maturity models, to assess current capabilities, identify gaps, and guide incremental progress toward Industry 5.0 adoption (Mistry, 2022). The mining sector is a vital component of South Africa's economy, and its successful transition to Industry 5.0 is essential for maintaining its competitive edge, ensuring economic growth, and achieving sustainability goals. Without a comprehensive understanding of where the industry stands in this transition, it is challenging to develop effective strategies, allocate resources appropriately, and prepare the workforce for the future demands of Industry 5.0. A maturity assessment provides a structured, measurable framework for organisations to assess their current state, identify gaps, and plan for progressive improvement, making it highly relevant for addressing the transition to Industry 5.0 in the South African mining industry (Gafner *et al.*, 2025).

1.5 Research aim, purpose and objectives

The primary aim and purpose of this research is to evaluate the progress of the South African mining industry in its transition towards Industry 5.0. This study aims to assess the current state of technological adoption, identify the challenges and opportunities the industry faces, and enable policymakers and industry leaders to provide strategic recommendations to facilitate this transition.

Overarching research question:
What are the factors influencing the state of technological adoption of the South African Mining Industry towards Industry 5.0?

Table 1.1 outlines how the chapters of this thesis are structured in alignment with the study’s research objectives and questions. Each objective supports the overall purpose and aim of the research, while the sub-research questions collectively contribute to answering the overarching research question. Each chapter contributes to addressing a specific research aim, beginning with the conceptual and theoretical foundations in the literature study, followed by the development of the Industry 5.0 framework, and concluding with the empirical assessment and practical recommendations. This structure ensures a coherent progression from theory to application, providing a clear path for evaluating the South African mining industry's transition towards Industry 5.0.

Table 1.1: Chapter division according to the research questions and objectives

Chapter	Research objectives	Research questions
Chapter 2: Literature review	To explore current Industry 5.0 research in the mining industry.	• What is Industry 5.0? • What current research exists on the transition of the mining industry towards Industry 5.0?
Chapter 2: Literature review	To explore existing Industry 5.0 frameworks and theoretical models	• What Industry 5.0 maturity assessments exist? • What is the theory underlying the study?
Chapter 4: Scoping review & Chapter 5: Industry 5.0 framework	To develop a conceptual Industry 5.0 framework	• What are the key concepts of the Industry 5.0 framework? • What are the key components of the Industry 5.0 framework? • What is the Industry 5.0 framework?
Chapter 6: Results and discussion	To assess the current level of Industry 5.0 adoption in the South African mining industry.	• What is the current state of the Industry 5.0 application in the South African mining industry? • Which concepts have been adopted? • What components (enabling technologies) have been adopted?
Chapter 6: Results & Discussion	To identify the challenges and barriers hindering the transition towards Industry 5.0 within the sector.	• What are the main challenges in adopting Industry 5.0 concepts and components?
Chapter 6: Results & Discussion	To generate strategic recommendations for industry leaders and policymakers to support and accelerate the transition to Industry 5.0.	• What recommendations can be made to support the South African mining industry in the transition?

1.6 Methodology

This study follows a structured, sequential five-phase methodological approach to evaluate the transition of the South African mining industry towards Industry 5.0. The first phase entails a literature review to identify existing Industry 5.0 maturity assessments and frameworks, establishing the foundational concepts for the study. The second phase involves a scoping review to identify and map key concepts and components, facilitating the development of a general Industry 5.0 framework.

In the third phase, these findings from the existing frameworks and the developed framework in the scoping review are combined with maturity assessment practices to construct a comprehensive Industry 5.0 framework tailored for practical application. The fourth phase focuses on the empirical investigation, applying this framework within the South African mining industry to assess the transition and challenges.

Finally, the fifth phase involves the verification and validation of the findings to ensure their credibility and relevance. This sequential phased approach provides a clear roadmap for the study, with the detailed methodology and execution of each phase captured comprehensively in Chapter 3: Methodology. Presented here in Chapter 1, this overview serves to orient the reader to the structure and flow of the thesis.

1. LITERATURE REVIEW	2. SCOPING REVIEW	3. INDUSTRY 5.0 FRAMEWORK	4. EMPERICAL INVESTIGATION	5. VERIFICATION & VALIDATION
To review existing Industry 5.0 maturity assessments and frameworks.	Develop a general Industry 5.0 framework based on key concepts and components.	Combine scoping review findings with maturity assessments to develop a comprehensive Industry 5.0 framework.	Apply the developed framework to the South African mining industry.	Verify and validate the findings from the empirical investigation.

Figure 1.1: High-level process and structure of the thesis – A five-phase approach

1.7 Limitations

1.7.1 Limitations

Given the emerging nature of Industry 5.0, there may be limited literature available that addresses this concept. The development of a general Industry 5.0 assessment framework introduces a risk, as the lack of a universally accepted definition of Industry 5.0 requires further refinement and validation of the framework beyond the scope of this study. Furthermore, the study may not fully capture the perspectives and readiness of the entire workforce, as there may be variations in awareness and understanding of Industry 5.0 concepts across different levels within the industry.

Time constraints also pose a limitation, as the rapid pace of technological advancements may render the findings quickly outdated, highlighting the need for ongoing research to maintain relevance. Finally, the scoping review conducted as part of this study may miss relevant studies due to the emerging nature of Industry 5.0, potentially introducing bias in developing the Industry 5.0 framework and its application to the mining sector. These limitations should be considered when interpreting the results and recommendations of this study, and further research is encouraged to address these constraints and expand the understanding of Industry 5.0 in various industrial contexts.

1.7.2 Delimitations

This study is confined to the South African mining industry and does not analyse the adoption of Industry 5.0 principles in other countries or regions. The research focuses solely on the mining sector and does not extend to other industries in South Africa that may also be transitioning to Industry 5.0. The study applies a specific Industry 5.0 framework, developed in Chapter 5, to evaluate progress. Other frameworks or approaches to Industry 5.0 are not considered. The findings and analysis reflect the state of the mining industry's transition toward Industry 5.0 as of the study's data collection period. It does not account for advancements made after this period. These delimitations ensure the research is focused, manageable, and aligned with the objectives. This sets the boundaries of the study and avoids overgeneralising findings beyond the defined scope.

1.8 Chapter outline

The following Table 1.2 outlines the provisional chapter division and the corresponding content description.

Table 1.2: Chapter division and description

Five Phase	Chapter	Sub-Headings (Level 2)	Content description
	Abstract	Title, Authors, Background, Purpose, Method, Findings and Conclusion	The abstract highlights the significance of the topic, emphasising the importance of the research in the context of Industry 5.0. It identifies the knowledge gap that this study aims to fill, outlining its primary aim and significance. A brief introduction to the methodology is provided, summarising the key results and contributions of the research.
	Chapter 1: Introduction	1.1 Introduction 1.2. Background 1.3. Context & significance 1.4. Research problem 1.5. Research purpose and objectives 1.6. Methodology 1.7. Limitations 1.8. Chapter outline 1.9. Conclusion	This chapter introduces the background of Industry 5.0, discussing its growing importance and how it addresses the challenges and gaps left by Industry 4.0. It presents the rationale behind the research, emphasising the study's potential impact on bridging the theoretical and practical gaps in the new industrial era. The chapter also outlines the research problem, purpose, objectives, methodology and limitations.
Phase 1	Chapter 2: Literature Review	2.1. Introduction 2.2. Industry 5.0 2.3. The South African Mining Industry transition towards Industry 5.0 2.4. Maturity level assessment 2.5. Theoretical underpinning 2.6. Conclusion	Chapter 2 reviews Industry 5.0 and its corresponding definitions. It examines the available literature regarding the global applications of Industry 5.0 and the transition within the South African mining industry towards Industry 5.0. It reviews any existing Industry 5.0 frameworks and assessments. Lastly, theoretical underpinnings supporting this transformation, such as sociotechnical systems, are discussed, providing a foundation for understanding the integration of advanced technologies with human-centric approaches.
	Chapter 3: Methodology	3.1. Introduction 3.2. Research strategy 3.3. Five-Phase approach	This chapter presents the research design and methods used in the study. Section 3.1 introduces the chapter and its context. Section 3.2 outlines the research strategy, while Section 3.3 explains the five-phase approach used to develop and apply the Industry

		3.4. Research quality 3.5. Conclusion	5.0 framework. Section 3.4 addresses research quality, including validity, reliability, and ethics.
Phase 2	Chapter 4: Scoping Review	4.1. Introduction 4.2. Method 4.3. Results 4.4. Industry 5.0 framework 4.5. Conclusion	This chapter explores the key concepts and components of Industry 5.0, providing a detailed analysis based on the scoping review.
Phase 3	Chapter 5: Industry 5.0 framework	5.1. Introduction 5.2. Overview 5.3. Interview and Analysis Guide 5.4. Conclusion	This chapter synthesises the findings from the literature and scoping review to develop a comprehensive Industry 5.0 framework.
Phase 4	Chapter 6: Results and discussion	6.1. Introduction 6.2. Method 6.3. Results 6.4. Discussion 6.5. Conclusion	This chapter presents significant and non-significant results, interprets the findings, and provides a summary. It includes an overview of the results, identifies patterns, categorises them, and concludes with a summary of the key findings as well as challenges and recommendations.
Phase 5	Chapter 7: Verification & validation	7.1. Introduction 7.2. Verification process 7.3. Validation process 7.4. Conclusion	This chapter focuses on verifying and validating the empirical investigation, ensuring the robustness and reliability of the findings and method.
	Chapter 8: Conclusion	8.1. Introduction 8.2. Research objectives and questions 8.3. Implications of the study 8.4. Limitations of the study 8.5. Recommendations for future research	The final chapter summarises the study's key results, highlighting its contributions, limitations, and implications. It discusses potential applications and suggests directions for future research.

1.9 Conclusion

Chapter 1 sets the stage for this study by establishing the historical and contextual basis for examining Industry 5.0 within South Africa's mining sector. It highlights the vital role of Industry 5.0 in addressing both the technological and social needs of the industry. The chapter’s outline of the research problem, objectives, and methodology offers a clear roadmap to explore the South African mining industry's transition to Industry 5.0. This comprehensive approach ensures a thorough understanding of the complex integration between technology and social factors in the industry’s evolution. Furthermore, the discussion of study limitations underscores the challenges inherent in assessing an emergent and rapidly evolving field while simultaneously supporting the importance of this research in addressing knowledge gaps.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This chapter explores existing Industry 5.0 literature, focusing on its core components: human-centricity, sustainability and resiliency. It examines the existing global and South African Industry 5.0 adoption trends and frameworks, identifying gaps in current literature regarding their application in mining. It also investigates existing maturity level assessment frameworks and existing underlying theories. Table 2.1 outlines the structure of the chapter according to the research questions. This alignment ensures transparency in how the literature is organised to systematically address the overarching aim of evaluating the South African mining industry's transition toward Industry 5.0. Each section in the chapter addresses a distinct area of the study. The structure ensures conceptual clarity and coherence throughout the review.

Table 2.1: Chapter 2 outline according to research questions & objectives

Research objective	Section	Research question
1. To explore current Industry 5.0 research in the mining industry	2.2 Industry 5.0	What is Industry 5.0?
	2.3 The South African Mining Industry transition towards Industry 5.0	What current research exists on the transition of the mining industry towards Industry 5.0?
2. To explore existing Industry 5.0 frameworks and theoretical models	2.4 Maturity level assessment	What Industry 5.0 maturity assessments exist?
	2.5 Theoretical underpinning	What is the theory underlying the study?

Figure 2.1 provides a stepwise overview of the study’s methodological structure. It situates the current research in Phase 1: Literature Review, which focuses on understanding existing Industry 5.0 maturity assessments and theoretical foundations. This phase is essential for identifying knowledge gaps and shaping the conceptual framework for the rest of the study.

The subsequent phases—scoping review, framework development, empirical application, and verification and validation—build sequentially on the literature insights to ensure that the proposed Industry 5.0 framework is evidence-based, contextually relevant, and practically applicable in the South African mining industry.

Figure 2.1: Overview of the study's progress: Phase 1/5

2.2 Industry 5.0

2.2.1 Definition

As Industry 5.0 is still evolving, specialists and researchers from various fields have offered multiple definitions to describe this new industrial revolution. Kovari (2024) provided a list of twelve definitions; however, on further investigation, four of the sources are no longer accessible. To ensure a comprehensive list, four additional definitions are added. Furthermore, the expanded list, as described in Table 2.2, is analysed to determine the key concepts and themes described in each definition and arranged chronologically from the oldest to the most recent. Each definition is categorised by its year, author, and key conceptual terms. This list showcases the diversity and evolving nature of Industry 5.0, highlighting the field's emphasis on cooperation between humans and machines, cognitive automation, and societal value creation. The definitions collectively frame the conceptual boundaries of the term and inform the word cloud visualisation that follows in Figure 2.2.

Table 2.2: Industry 5.0 definitions (Kovari, 2024)

Nr	Definition	Year	Author	Keywords	Source
1	"The 5th Industrial Revolution, which is still emerging, is bent on fostering cooperation between humans, machines, and technology to ensure the stability of the workforce and an understanding of worker empowerment."	n.d.	(Momenta, n.d.)	Cooperation, humans, machines, technology, workforce stability, empowerment	Kovari (2024)
2	"INDUSTRY 5.0 is future, but already penetrating trend, of change processes directing towards closer cooperation between man and machine, and systematic prevention of waste and wasting including INDUSTRIAL UPCYCLING. INDUSTRY 5.0 priority is to efficiently utilize a workforce of machines and people in a synergy environment. It goes back from virtual environment to real one."	2018	(Rada, 2020)	Cooperation, man, machine, waste prevention, upcycling, efficiency	Kovari (2024)
3	"Bringing back human workers to the factory floors, the Fifth Industrial Revolution will pair human and machine to further utilise human brainpower and creativity to increase process efficiency by combining workflows with intelligent systems. While the main concern in Industry 4.0 is about automation, Industry 5.0 will be a synergy between humans and autonomous machines."	2019	(Nahavandi, 2019)	Human, machine, creativity, intelligent systems, synergy, efficiency	Kovari (2024)
4	"The Age of Augmentation (Industry 5.0)—will be focused on the cooperation between human intelligence and cognitive computing and on treating automation as a further enhancement of the human's physical, sensorial, and cognitive capabilities. By putting humans back into the loop, Industry 5.0 profoundly restructures human tasks in the realm of manufacturing in ways that benefit the workers. They will be upskilled to shift from manual to cognitive labour, to provide value-added tasks in production and to work—with peace of mind—alongside an autonomous workforce, i.e., collaborative robots that will be perceptive and informed about human intention and desire"	2020	(Longo *et al.*, 2020)	Cooperation, cognitive computing, human intelligence, value -add, upskilling, collaborative robots	Kovari (2024)

5	"IR 5.0 is going to be distinguished by the collaboration between machines and human beings, with the ultimate objective to provide additional value to production, by creating customised products able to satisfy consumers' requirements."	2020	(George & George, 2020)	Collaboration, machine, human, customised products, value	Author
6	"This concept involves returning the human factor to industry, i.e., increasing cooperation between people and intelligent production systems and combining the best of two worlds—the speed and accuracy guaranteed by automation with humans' cognitive skills and critical thinking."	2020	(Longo *et al.*, 2020)	Human factor, cooperation, intelligent systems, automation, cognitive skills, critical thinking	Author
7	"Industry 5.0 recognises the power of industry to achieve societal goals beyond jobs and growth to become a provider of prosperity, by making production respect the boundaries of our planet and placing the wellbeing of the industry worker at the centre of the production process."	2020	(European Commission, 2020)	Societal goals, prosperity, wellbeing, environmental respect	Author
8	"The revolution of Industry 5.0 means that humans and machines are working together, improving the efficiency of industrial production. Human workers and universal robots are boosting the productivity of the manufacturing industry."	2022	(Adel, 2022)	Humans, machines, efficiency, productivity	Kovari (2024)
9	"Industry 5.0 can be considered the era of the socially intelligent factory, in which cobots converse with people. Enterprise social networks will be used by Social Smart Factory for enabling seamless communication between human and CPPS components. The overall current understanding of Industry 5.0 brings the human touch back to the industry. It also entails the incorporation of AI into human operations to enhance man's capacity. The core of Industry 5.0 is the harmony of machines, humans, values, tasks, and finally, knowledge and skills which results in personalized/individualized products as well as services."	2022	(Leng *et al.*, 2022)	Social intelligence, cobots, AI, human touch, personalised	Kovari (2024)
10	"In other words, at its heart, Industry 5.0 reflects a shift from a focus on economic value to a focus on societal value, and a shift in focus from welfare to wellbeing."	2022	(Kraaijenbrink, 2022:5)	Societal value, wellbeing	Kovari (2024)

11	"The previous tier, Industry 4.0, emerged with the arrival of automation technologies, IoT and the smart factory. Industry 5.0 takes the next step, which involves leveraging the collaboration between increasingly powerful and accurate machinery and the unique creative potential of the human being."	2022	(Nexus Integra, 2020)	Collaboration, creative potential, machinery, human	Kovari (2024)
12	"Since Industry 5.0 is a new concept there is little agreement on how it is defined. However, it is observed that the primary trend of Industry 5.0 is the introduction of human-robot co-working environment and the creation of smart society."	2022	(Akundi *et al.*, 2022)	Human-robot co-working, smart society	Author

To synthesise the definitions in Table 2.2, Table 2.3 quantifies the frequency of key themes and concepts, highlighting the most common ideas across all definitions. The top recurring themes include human/man, cooperation, machine, and efficiency.

Table 2.3: Key concepts and theme analysis

No	Key concepts and themes	Frequency of occurrence
1	Human/Man	11
2	Cooperation/ Collaboration/Co-Working/Synergy	9
3	Machine/Machinery	7
4	Efficiency/Productivity	5
5	Societal value/societal goals/Social intelligence/Smart society	4
6	Value/Value-add	3
7	Wellbeing/prosperity	3
8	Upcycling/Environmental respect/Waste prevention	3
9	Empowerment/Upskilling	2
10	Cobots/collaborative robots	2
11	Creativity/Creative	2
12	Intelligent systems	2
13	Cognitive computing/AI	2

14	Cognitive skills/Critical thinking	2
15	Personalised/Customised	2
16	Technology	1
17	Workforce	1
18	Automation	1

Figure 2.2 visualises the frequency of key terms identified in the 12 definitions of Industry 5.0. The size of each word corresponds to its relative occurrence, emphasising the importance of terms such as *human*, *cooperation*, *synergy*, *co-working*, and *machine*. This word cloud provides a visual representation of the conceptual priorities in current Industry 5.0 definitions, reinforcing the literature's focus on human-machine collaboration, wellbeing, and sustainable productivity. It supports the study's argument that Industry 5.0 represents not only a technological transition but a socio-technical approach.

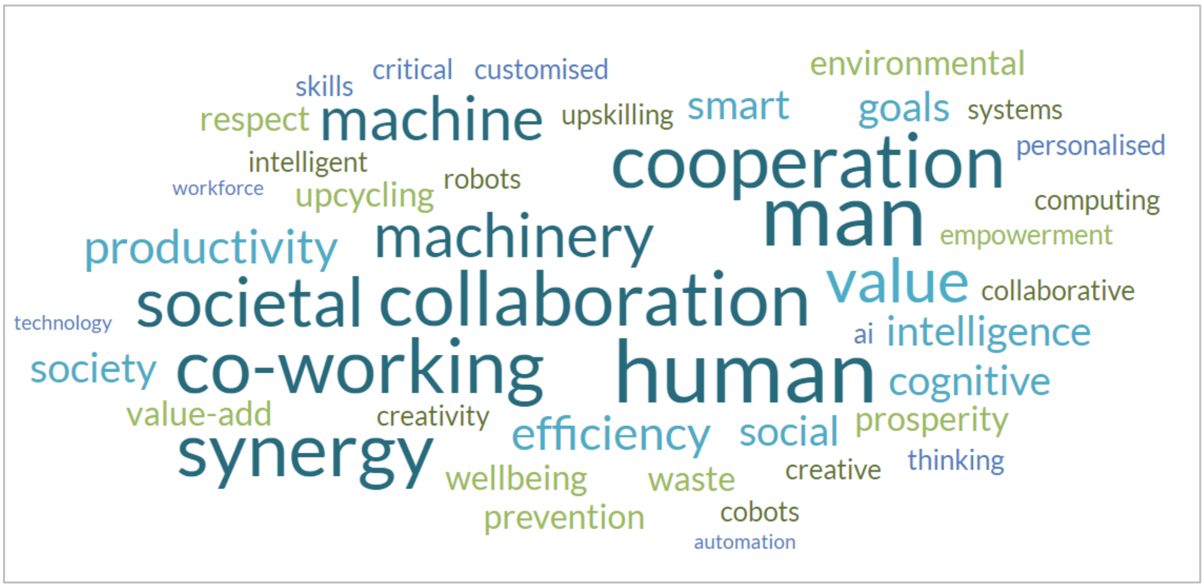

Figure 2.2: Word cloud visualisation - Highlighting key terms by frequency of occurrence to illustrate topic importance

Based on the definitions provided in Table 2.2 and the frequency and analysis of the keywords in Table 2.3 and Figure 2.2, the following definition for Industry 5.0 is used for purposes of this study. It represents a new phase of the industrial revolution, where human workers and advanced machines, such as collaborative robots (cobots) and intelligent systems, work together harmoniously to improve productivity, efficiency, and social value. This era emphasises the synergy between human creativity, cognitive skills, and the precision of automation, aiming to shift from purely automated processes to more human-centric environments whilst empowering and upskilling workers. Industry 5.0 focuses on a personalised and customised environment within environmental boundaries and placing the well-being of workers at the centre of industrial processes. Integrating human intelligence with cognitive computing improves human capabilities and ensures that the industry contributes to broader societal goals, such as sustainability and social progress.

2.2.2 Global applications of Industry 5.0

The global trend in Industry 5.0 signals a deliberate shift from efficiency-driven automation toward more human-centric, resilient, and sustainable industrial systems (Breque *et al.*, 2021). As this concept takes shape across sectors, academic literature has begun to document its varied applications in manufacturing, healthcare, and logistics. However, a critical reading of this body of work reveals that while technical progress is evident, the socio-institutional complexity of implementation often remains underexamined, particularly in sectors like mining that face entrenched operational and cultural constraints (Nahavandi, 2019; Xu *et al.*, 2021).

In advanced manufacturing, much of the literature highlights the successful integration of collaborative robots (cobots) that improve worker-machine interaction and allow for greater product customisation. For instance, Nahavandi (2019) describes cobots in Japanese assembly lines as enablers of flexible, human-supported automation (Nahavandi, 2019). Likewise, Demir et al. (2019) underscore the emerging role of human–AI collaboration in improving cognitive ergonomics (Demir *et al.*, 2019). However, these studies often assume preconditions such as digital readiness, skilled labour, and flexible organisational structures; conditions that are frequently absent in heavy industries. This limits the direct transferability of such models to mining, where legacy infrastructure and hierarchical command structures may impede adaptive implementation.

In the healthcare sector, the use of AI to support rather than replace clinicians has been framed as an example of Industry 5.0's human-centric application (Javaid *et al.*, 2020). Clinical decision-support systems now leverage machine learning to improve diagnosis, prognosis, and treatment planning while maintaining clinician oversight (Javaid *et al.*, 2020). However, this literature tends to overlook long-term implications, such as algorithmic dependence and ethical trade-offs in decision-making. While the mining sector is unlikely to mirror healthcare's service orientation, the emphasis on technology augmenting, not displacing, human expertise is highly relevant for safety-critical tasks in mines, such as ventilation management or equipment inspection.

In logistics and supply chain management, Industry 5.0 is reflected in the adoption of digital twins, blockchain, and predictive analytics, enabling responsive and decentralised operations (Nazarian & Khan, 2024). It improves productivity and product quality while simultaneously reducing production costs and optimising resource utilisation. This is achieved through the integration of automation, Artificial Intelligence (AI), and Big Data Analytics (BDA), which helps minimise waste (Lv, 2023). I5.0 can promote decentralised manufacturing with shorter supply chains, leading to decreased transportation expenses and more eco-friendly practices. The adoption of Collaborative Robots (Cobots) further reduces the overall cost of ownership (Nazarian & Khan, 2024). Blockchain-based solutions enhance dependability, quality, speed, cost, and flexibility of supply chains (Zhen & Yao, 2025). Digital twins contribute by optimising production processes, enabling predictive maintenance, and reducing operational costs in smart factories (Lv, 2023; Nazarian & Khan, 2024)

A cross-sector synthesis reveals shared patterns and tensions. First, the shift from automation for efficiency to collaboration for resilience is evident across contexts. Second, human-centered design is increasingly tied to issues of safety and ethical responsibility. Third, the emphasis on data-driven decision-making raises concerns about algorithmic governance and workforce displacement, particularly in industries with low digital (Tay *et al.*, 2019). These trends point to the need for balanced approaches that consider both technological improvements and socio-organisational dynamics.

For mining, the implications of Industry application and adoption are clear: frameworks must not only address enabling technologies (AI, IoT, digital twins) but also integrate organisational change, workforce capability, and ethical deployment. In this regard, global applications of Industry 5.0 offer valuable lessons, but also highlight the limitations of overgeneralised models. A tailored, context-sensitive framework, such as the one developed in this study, is thus necessary to guide mining's transition toward Industry 5.0.

2.3 The South African Mining Industry transition towards Industry 5.0

The transition of the South African mining industry towards Industry 5.0 is currently at a pivotal stage, characterised by both advancements and challenges (Lumadi & Nyasha, 2024). The mining sector is increasingly adopting digital technologies, which are critical for improving operational efficiency and addressing environmental, social, and governance (ESG) concerns (Zulu *et al.*, 2021).

PWC released a report (Mandela Mining Precinct, 2023) in 2023 where Roger Baxter, MCSA CEO, says: "Digital transformation is imperative for mining - a non-negotiable if you like - as it serves as the seamless thread through all the mining value chain processes, and enhances safety and health, security, production, and workforce and leadership capability. The implementation of these processes needs to be executed with care and responsibility."

The South African mining industry is facing significant challenges, including declining production and profitability, high operational costs, and outdated methods that are unsustainable at increasing depths (Minerals Council South Africa, 2018; Mishra, 2025). Harsh and deep mining conditions, such as extreme temperatures, pose particular difficulties (Minerals Council South Africa, 2018). The sector also contends with safety and health challenges, a workforce skills gap, and environmental and social concerns (Benzane, 2019). In this context, modernisation is viewed as essential to address these issues, ensure health and safety, retain and create jobs, prevent premature mine closures, and ensure the economic viability of commodity extraction (Minerals Council South Africa, 2018).

The industry is increasingly recognising the need to adapt to new technological advancements to improve operational efficiency, reduce environmental impact, and address the skills gap (Muzvondiwa, 2024). This involves undergoing a significant transformation driven by digital advancements and the concepts of Industry 5.0, which emphasises human-centricity, sustainability, and resilience (Muzvondiwa, 2024). While the sector's digital maturity still trails behind other global industries, significant progress is being made (BDO LLP, 2025). South African mining needs Industry 5.0 to improve global competitiveness on costs and environmental, social, and governance (ESG) issues (Mandela Mining Precinct, 2023).

Mining companies in South Africa are increasingly making use of innovative and cutting-edge technologies (Mandela Mining Precinct, 2023). They have begun integrating aspects of Industry 4.0, with a growing focus on digital transformation (Ndlovu *et al.*, 2022). About 40% of global mining projects now incorporate digital technology, with nearly 15% of these based in Africa (BDO LLP, 2025). Companies are making significant investments in digital technologies, although many activities remain in the planning phase (Ndlovu *et al.*, 2022). The COVID-19 pandemic further accelerated the digitisation of work processes and the adoption of automation and other innovative tools (Mandela Mining Precinct, 2023). Some companies, like Exxaro, are seen as pioneers in digitisation within the South African mining industry (Benzane, 2019).

Specific advanced technologies being adopted or explored include Artificial Intelligence (AI), automation, robotics, the Internet of Things (IoT), and data analytics/big data. Digital twins, which are virtual models of operations, are also being implemented (Benzane, 2019; Mishra, 2025). There is also a move towards remote operations, wearable technologies, and the adoption of renewable energy solutions such as solar, wind, battery storage, and potentially hydrogen. Augmented and virtual reality (AR/VR) are also being explored and process digitisation is a key area of focus (Benzane, 2019).

This uptake of technology and the push for modernisation are aimed at improving efficiency and productivity, improving health and safety standards, reducing operational costs, and developing new insights (Mandela Mining Precinct, 2023). Furthermore, these advancements contribute to sustainable development, help address the skills gap, enable the industry to remain competitive, and are seen as crucial for reducing environmental impact (Muzvondiwa, 2024). Modernisation, particularly through mechanisation and 24/7 operations, has the potential to extend the life of mines and preserve or create jobs (Minerals Council South Africa, 2018).

Despite the recognised need and the ongoing efforts, the pace of technology adoption in South African mining has generally been slower compared to other industries or global counterparts (Ndlovu *et al.*, 2022). This reluctance, along with the challenges hindering adoption, is significant. These include high capital and upfront costs, resistance to change and a lack of adequate training or skilled personnel (Muzvondiwa, 2024; Pelders & Schutte, 2021). Inadequate or outdated infrastructure, such as IT systems and connectivity in remote areas, also poses a barrier (Mishra, 2025). Difficulties in quantifying the return on investment, cultural reluctance towards innovation, and the complexities of legacy systems are also impediments (Mandela Mining Precinct, 2023; Mishra, 2025). Furthermore, regulatory uncertainty and complexity, and social concerns, particularly the fear of job displacement among workers and union resistance, are significant challenges that affect the speed and extent of adoption (Pelders & Schutte, 2021). The lack of leadership buy-in and support, as well as a risk-averse mentality, further contribute to the challenges.

The need for modernisation is clear and driven by the need for survival and competitiveness. The uptake of advanced technologies is occurring, albeit with significant challenges, as the industry attempts to leverage digital solutions to improve efficiency, safety, and sustainability in a unique and complex operating environment. A report released from the Mandela Mining Precinct in 2023 (Mandela Mining Precinct, 2023) highlights that mining CEOs are now prioritising innovation and digitalisation as integral to their strategies, moving beyond traditional top-down approaches. The report also states, “the mining industry’s commitment to using digitalisation and technology for the ultimate creation of business value in the mining sector”. This highlights the gap in focus on creating societal value as well.

Key insights included in the report are as follows (Mandela Mining Precinct, 2023):

- Mining CEOs prioritise innovation and digitalisation, viewing 4IR as essential to modern mining, with all respondents integrating technology into their ESG programs.

- Technology is being used where it offers the most significant measurable benefits, improving business visibility and decision-making. Data-driven platforms are expected to mature by 2027.

- Labour unions recognise the value of digital technology in improving health, safety, and worker support, highlighting its role in enabling daily tasks.

- South African mining CEOs acknowledge progress in digitalisation since 2019 but believe more could have been achieved.

- Attracting and retaining talent is crucial. Success stories show that digital transformation can occur internally without needing new external skills.

- ESG is increasingly critical for mining companies, requiring a rethink of risks and opportunities, moving beyond mere compliance to creating long-term value.

Several of these insights also align with Industry 5.0. The shift in focus from a top-down approach to one that prioritises innovation and digitalisation aligns with Industry 5.0's emphasis on integrating advanced technologies with human-centric approaches (Innopharma Education, 2024). This reflects the move towards more personalised, efficient, and sustainable production processes that Industry 5.0 advocates (Leng *et al.*, 2022). The application of technology, which provides the most significant measurable benefits, ties into Industry 5.0's goal of improving decision-making and efficiency through advanced digital tools (European Commission, 2021). Developing data-driven decision-making platforms aligns with Industry 5.0’s emphasis on cognitive computing and real-time data analytics to optimise operations (Pujala *et al.*, 2025).

The role of digital tools in improving health and safety and enabling workers to perform their daily duties is closely linked to Industry 5.0's focus on human-machine collaboration. Industry 5.0 aims to develop human capabilities and well-being by integrating digital technologies that support and supplement the workforce (European Commission, 2020). The emphasis on data as central to business success and sustainability reflects Industry 5.0’s principle of using digital technologies to achieve broader societal goals, such as sustainability. The shift towards proactive management with real-time data is a key characteristic of Industry 5.0's innovative, responsive systems (Rijwani *et al.*, 2025).

The focus on creating an environment that attracts young talent and digitally transforming the existing workforce aligns with Industry 5.0's emphasis on upskilling and integrating human creativity with advanced technologies. Industry 5.0 supports a culture of continuous learning and adaptation, which is vital for navigating the digital era (Ambhore, 2024). Lastly, recognising that digital tools are necessary for achieving ESG goals ties directly into Industry 5.0's focus on sustainability and social value. Industry 5.0 promotes the use of technology to meet environmental, social, and governance objectives, ensuring that industrial practices are aligned with long-term sustainability goals (Asif *et al.*, 2023).

These insights collectively demonstrate how the principles of Industry 5.0 are increasingly being recognised and integrated within the mining industry, particularly in innovation, digital transformation, sustainability, and workforce engagement. Current literature depicts that despite the progress, the sector faces significant hurdles (Lumadi & Nyasha, 2024). However, little to no literature is available on the adoption of Industry 5.0 in the South African mining industry. The slow uptake of advanced technologies and the need for modernisation are critical issues. While there is a drive towards adopting Industry 5.0 principles, the mining sector must overcome barriers related to technology acceptance and integrating new practices into existing operations (Lumadi & Nyasha, 2024). The transition is expected to mature over the next few years, with significant advancements in data-driven decision-making and operational transparency anticipated between 2025 and 2027 (Mandela Mining Precinct, 2023). The focus on creating business value through digitalisation will likely continue, with a strong emphasis on safety and efficiency improvements.

The South African mining industry plays a critical role in the nation's economy, and its transition towards Industry 5.0 is essential for maintaining competitiveness. Current literature highlights a growing awareness of Industry 5.0 concepts within the industry, with some companies beginning to experiment with human-machine collaboration and smart technologies. However, these efforts are still in their early stages, and significant challenges remain, such as the high costs of implementation, the need for upskilling the workforce, and infrastructural limitations. Nonetheless, the existing literature reveals a notable gap in comprehensive studies on the transition, indicating a need for further research to provide more detailed insights.

2.4 Maturity level assessment

Maturity levels are frequently used to evaluate the current state, identify and prioritise areas for improvement, and monitor progress. (Pöppelbuß & Röglinger, 2011). Measuring the maturity and transition of industries towards Industry 5.0 is essential for understanding progress and identifying areas for improvement. Various maturity assessments, such as the Industry 4.0 maturity index, exist to measure Industry 4.0 maturity. These assessments typically evaluate technological integration, workforce readiness, and innovation capacity. In the context of the South African mining industry, the application of these assessments is still limited, with most companies relying on traditional productivity and efficiency metrics. However, as the industry seeks to embrace Industry 5.0, more sophisticated measurement tools will be needed to assess the different pillars of Industry 5.0.

A review has been conducted to evaluate current maturity assessments in the context of Industry 5.0. The study highlights the lack of human-centered maturity assessments and proposes adaptions to existing frameworks to fit the Industry 5.0 paradigm better. The study by Mikhael Chandra Arta et al. (2024) develops a maturity assessment specifically for assessing the readiness of Indonesian companies for Industry 5.0. The methodology involves a three-stage process: (1) understanding Industry 5.0 and reviewing existing maturity assessments, (2) creating a new assessment tailored to Industry 5.0, and (3) applying this assessment through online surveys and interviews. The assessment focuses on three core pillars: Human-Centered Design, Resiliency, and Sustainability, and it has a total of 11 maturity elements. The responses are measured on a Likert scale, and the results are visualised through radar charts and maturity reports. The study also employs the Kruskal-Wallis Test to compare readiness levels across different sectors (Arta *et al.*, 2024).

The assessment covers key aspects of Industry 5.0, including human-centered design, resiliency, and sustainability, which are critical for assessing readiness. The study also uses a straightforward, step-by-step approach to apply the assessment, making it accessible for real-world use. However, the study is focused on Indonesian companies, which may limit the generalisability of the findings to other regions or industries. As Industry 5.0 is still evolving, the assessments may require future updates to remain relevant and comprehensive as the concept develops. The authors of the evaluations also state that “The authors picked a company that is already involved in Industry 4.0 and has the necessary fundamental knowledge and comprehension of its core ideas of Industry 5.0 to assure the correctness of the results” (Arta *et al.*, 2024).

To evaluate existing Industry 5.0 maturity frameworks, five criteria were established based on theoretical grounding, practical applicability, and alignment with the foundational principles of Industry 5.0. These include: contextual relevance, comprehensiveness, scalability and flexibility, stakeholder inclusivity, and methodological transparency. *Contextual relevance* ensures that the framework is applicable across diverse industrial and regional settings, particularly in sectors such as mining in developing economies. *Comprehensiveness* reflects the extent to which a model captures the three core pillars of Industry 5.0 - human-centricity, sustainability, and resilience - as defined by the European Commission (2021). *Scalability and flexibility* were adapted from maturity model design literature (Becker *et al.*, 2009) to ensure the framework accommodates organisations at varying levels of digital readiness. *Stakeholder inclusivity* is grounded in sociotechnical systems theory, which highlights the role of diverse human actors in systemic transformation. Finally, *methodological transparency* reflects the need for clear, validated, and replicable assessment methods. Together, these criteria provide a rigorous and context-sensitive basis for assessing the suitability of existing frameworks and justifying the development of a new, generalised Industry 5.0 maturity model.

a. Criteria for evaluating Industry 5.0 maturity frameworks:

1. **Contextual Relevance**: Applicability across various industries and geographies, particularly resource-intensive sectors such as mining.
2. **Comprehensiveness**: Coverage of all Industry 5.0 pillars; human-centricity, sustainability, and resilience, along with enabling technologies and organisational alignment.
3. **Scalability and Flexibility**: Ability to assess different levels of organisational maturity, from low-tech to high-tech environments.
4. **Stakeholder Inclusivity**: Incorporation of multiple perspectives (e.g., workers, managers, system architects, customers).
5. **Methodological Transparency**: Clearly defined measurement mechanisms and validation procedures.

Based on these criteria, a review of available Industry 5.0 maturity frameworks was conducted and the results are shown in Table 2.4.

Table 2.4: Assessment of Indonesian Industry 5.0 Readiness Framework (Arta et al., 2024)

Evaluation Criteria	Assessment
Summary	Developed through literature review, expert input, and field testing with Indonesian firms. Focuses on Human-Centred Design, Resiliency, and Sustainability. Uses a Likert scale and radar chart for visualisation.

Contextual Relevance	Limited – Framework was designed for companies already engaged in Industry 4.0 and is tailored to the Indonesian industrial landscape.
Comprehensiveness	Captures the three core pillars of Industry 5.0 but lacks depth in enabling technologies and socio-technical system integration.
Scalability and Flexibility	Limited – Assumes a high level of digital maturity and prior Industry 4.0 exposure, making it less suitable for early-stage sectors like mining.
Stakeholder Inclusivity	Partially inclusive – Focuses on organisational-level inputs with limited attention to diverse stakeholder groups such as workers or communities.
Methodological Transparency	High – The framework is well-documented, featuring clear statistical methods and visual representation tools.

The Industry 5.0 readiness framework developed by Arta et al. (2024) was constructed through an extensive literature review, expert consultations, and empirical testing with Indonesian firms. The model is structured around three core pillars - human-centred design, resiliency, and sustainability - which are assessed using a Likert-scale-based instrument, with results visualised through radar charts and maturity reports. While the framework successfully captures the principal dimensions of Industry 5.0 and demonstrates a methodologically transparent design supported by statistical analysis, it presents several limitations when evaluated against the criteria defined in this study. In terms of contextual relevance, the framework was developed for application within Indonesian industrial sectors, specifically targeting firms that have already adopted Industry 4.0 technologies. As such, it lacks generalisability to other contexts, particularly resource-based industries with low digital maturity such as South African mining. Although the framework is comprehensive in addressing the three pillars of Industry 5.0, it does not explicitly incorporate enabling technologies or broader socio-technical system interactions. Its scalability and flexibility are constrained by the assumption of a high baseline level of Industry 4.0 literacy, limiting its applicability to organisations at earlier stages of digital transformation. From a stakeholder inclusivity perspective, the framework primarily reflects organisational-level insights and does not account for multi-level perspectives, such as those of frontline workers or local communities. Despite its structured design and methodological rigour, these contextual and conceptual limitations reduce the framework's suitability for evaluating Industry 5.0 readiness within the South African mining sector.

Therefore, a general Industry 5.0 framework will be developed (in Chapter 4) and compared to the existing Industry 5.0 maturity assessment to ensure that a comprehensive and relevant framework is used to evaluate the South African Mining industry's progress towards Industry 5.0. The existing Industry 5.0 maturity assessment is shown in Figure 2.3.

Measurement	Categories	Level 0	Level 1	Level 2	Level 3
Human centered Design	Main driver and innovative factor for I5.0	No collaboration between employees and new technology.	The company is trying to make collaboration between employees and new technology	The employees can collaborate with the new technology or robots	Collaboration between employees and new technology is already running well
	Focus on employees	No improvement in technology and study the needs of employees.	The company has started to improve to maximise technology and study the needs of employees	The company has developed technology enhancements to understand the needs of employees	The company have been able to recognise what technology can do for the people and focus on how technology can adjust to the requirements of the worker instead of the other way
	Holistic Adaptation of the processes and system to employees	No study about relation between employees and new technology	Trying to study the skill gap between each employee to build a good adaptation between employees and new technology	Have been able determine the skills gap between employees and new technology, so the company able to make forecast the skills needs	Provide training for every skill requirement to build good collaboration between employees and new technologies in the future
	Basic requirement for achieving maturity levels for digitalisation and AI	No supporting technology.	The company has started build some supporting technology, such as big data, network coverage and specialist skills for use new technology in the future	The company has developed build some supporting technology, such as big data, network coverage and specialist skills for use new technology in the future	The company already have the supporting technology, such as big data, network coverage and specialist skills for use new technology in the future
Resiliency	Stabilisation Policy	No policy.	Policy is taken randomly and reacts to market conditions.	The stabilisation policy has been well formulated and structured but is still focused on reacting to market conditions. There is no clear long-term strategy.	The stabilisation policy has been well integrated into overall economic policy and has been carried out in a proactive and effective manner. There is a continuous evaluation and improvement mechanism to increase the effectiveness of the stabilisation policy.
	Creation of Competitiveness	The company is not aware of the Industry 5.0.	The company start to aware of the definition and concept of Industry 5.0.	The company has developed a strategy to leverage Industry 5.0 for competitiveness, but it is not yet fully integrated into its operations.	The company has fully integrated Industry 5.0 into its strategy and operations, and it regularly measures and manages its performance in this area.
	Use of Modern Technologies and Approaches	No modern technologies or approaches are used in manufacturing processes.	The company start to study modern technologies or approaches to be used in manufacturing processes.	A few modern technologies and approaches are used, and their integration into the manufacturing process is improving. However, they are still used in isolation from each other.	Most modern technologies and approaches are used in the manufacturing process, and their integration is highly cohesive and optimised. However, there is still room for improvement and refinement.
Sustainability	Implementation of environmental solution	Organisation has no awareness of environmental and society issue.	Organisation only give donation as a philanthropy	Organisation makes activity based on their stakeholder demand (CSR) Several programs are done to solve the sustainable issue to society	Organisation integrates all of their activities and culture to achieve business goals and sustainability goals
	Business model with sustainable aspects	No sustainability goals.	Company has bad image to society Employee does not know about the company sustainability goals	The organisation feels it has tried to give the best benefit to employees, but the employees do not feel any benefit from conducting sustainability Some of employee know the company sustainability goals	Organisation has a good image in society Organisation has made a work life balance working style and the employees are loyal All of the employee knows the company sustainability goals and make it as a culture
	Involvement in strategy planning	No regulations are met	Fulfilment of regulations is done by reactive There are no top management commitment to achieve sustainability goals	All of regulations are identified and fulfilled Company has PIC to make a relation with government to update the regulations The Organisation has the commitment to achieve sustainability goals, but there is no review to the achievement	The Organisation is an active member of association to develop regulation The Organisation goals has been synchronized with government goals about sustainability The Organisation report its achievement of their sustainability goals to all stakeholder annually

Figure 2.3: Existing Industry 5.0 maturity assessment (Arta *et al.*, 2024)

2.5 Theoretical underpinning

2.5.1 Introduction

A theoretical underpinning is a critical element in research, providing a structured approach that guides the design and execution of a study (PhD Assistance Editors, 2019). It shapes the research by formulating questions, hypotheses, and methodologies, ensuring coherence and relevance. By situating the study within the broader context of existing literature, the framework allows researchers to build on or challenge established theories, thereby contributing to the academic area (Pretorius, 2024). It also clarifies key concepts and variables, helping to focus the research and guide data analysis. This improves the rigour and relevance of the study, making the findings more applicable to real-world situations. Additionally, the theory addresses critical "how" and "why" questions, offering insights into the underlying mechanisms of the phenomenon under investigation (Sacred Heart University, 2020). Theoretical underpinnings provide essential lenses through which the transition towards Industry 5.0 can be understood and analysed. The following two relevant theories are discussed, and the most appropriate one is chosen.

2.5.2 Technology Organisation Environment (TOE) Theory

The TOE theory, developed by Tornatzky, Fleischer and Chakrabarti in 1990, emphasises three contexts that influence technology adoption: technological context, organisational context and environmental context (Baker, 2012). The technological context refers to the technology's availability, suitability, and perceived benefits. The organisational context involves its internal characteristics, such as its structure, resources, and culture, which can impact its capacity to adopt new technologies. Finally, the environmental context includes external factors, including market conditions, competition, regulatory frameworks, and other external pressures that influence an organisation’s decision to adopt new technologies (Baker, 2012). The theory primarily focuses on assessing an organisation's readiness and capability to implement new technologies and predicting the organisation’s intentions during this transition (Jere & Ngidi, 2020).

2.5.3 Sociotechnical Systems (STS) Theory

Sociotechnical Systems (STS) theory, developed in the 1950s, emphasises the interaction between people (social aspects) and technology within an organisational system (Gumede & Tladi, 2023). This theory has been widely applied in studies examining the integration of new technologies into existing industrial processes (Walker *et al.*, 2008). The theory states that for successful organisational change, both the social system and the technical system must be aligned and mutually supportive. The social system consists of human elements such as culture, behaviour, work practices, and interactions, while the technical system includes the tools, machines, and processes used to accomplish tasks (Walker *et al.*, 2008). STS theory is applied in contexts where understanding the integration of technology and human factors is crucial. It is often used to design or analyse systems to improve both productivity and human well-being by balancing technological and social considerations (Gumede & Tladi, 2023).

2.5.4 Summary

Sociotechnical Systems (STS) Theory is more appropriate for evaluating the mining industry's transition towards Industry 5.0. This is because Industry 5.0 places a strong emphasis on human-centricity, the integration of human skills with advanced technologies, and the optimisation of both social and technical systems within industrial environments. STS theory's focus on the interaction between social and technical elements aligns closely with the goals of Industry 5.0, which seeks to harmonise human and machine collaboration, improve worker well-being, and foster sustainable practices.

On the other hand, while TOE theory could provide insights into the factors influencing technology adoption in the mining industry, it does not fully address the critical human-centric and sociotechnical integration aspects that are central to Industry 5.0. Therefore, STS theory provides a more comprehensive theory for evaluating the complexities involved in the mining industry's transition towards Industry 5.0, making it a more suitable choice for this study.

2.6 Conclusion

In conclusion, this chapter has outlined the core components of Industry 5.0, with a particular emphasis on human-centricity, sustainability, and resiliency, which are essential to the framework’s application within industrial sectors. By analysing both global and South African trends in Industry 5.0 adoption, significant insights have been gathered, including a gap in the literature concerning the unique requirements and challenges faced by the mining industry. Existing frameworks and maturity assessments were reviewed, providing insight into how these frameworks measure technological readiness and workforce adaptability. However, the limitations of these frameworks highlight the need for a more tailored approach that addresses the specific environmental, economic, and operational constraints of mining. This chapter has laid the groundwork for the development of an Industry 5.0 framework specifically suited to the South African mining sector, which is expanded upon in subsequent chapters.

CHAPTER 3 METHODOLOGY

3.1 Introduction

The following chapter outlines the research methodology, detailing the study's design, data collection techniques, and analytical approach. It discusses how the research design is well-suited to address the study's objectives in evaluating the adoption of Industry 5.0 within the mining industry.

3.2 Research strategy

The research strategy includes key factors: research paradigm, approach, design, and time horizon. This study draws on socio-technical systems (STS) theory and a structured maturity model to guide its research design, data collection, and analysis. The STS framework provides the conceptual foundation for exploring the relationship between human and technological elements in the mining industry. At the same time, the maturity model operationalises these dimensions into measurable indicators of Industry 5.0 transition.

3.2.1 Research paradigm

Research paradigms are the different lenses that shape how people see and study the world. Positivism views reality as objective and quantifiable, often using experiments and statistical analysis (Rehman & Alharthi, 2016). In contrast, interpretivism sees reality as subjective and formed by personal experiences. Critical theory acknowledges both the objective truth and the role of human perception and experiences. Pragmatism is a practical approach that emphasises solving real-world problems. Lastly, postmodernism advocates that different perspectives shape more than one reality. (Rehman & Alharthi, 2016). Each paradigm guides how researchers choose methods and influences how findings are interpreted.

Pragmatism is a suitable philosophical approach for this research because it focuses on practical solutions to real-world problems and values objective and subjective knowledge. Given the practical and applied nature of assessing the South African mining industry's transition to Industry 5.0, pragmatism allows for the effective use of multiple methods and perspectives to address the research questions.

3.2.2 Research approach

Different approaches to generating conclusions depend on the research context and available data. Deductive reasoning starts with a general theory or hypothesis and tests it with specific cases, aiming to confirm or disprove the theory. Inductive reasoning begins with specific observations and builds up to a general conclusion or theory, often used to identify patterns and relationships. Abductive reasoning starts with incomplete information and seeks the most likely explanation, a process commonly employed in diagnostic processes (Nathaniel, 2023).

This study employed both inductive and deductive reasoning at different phases to suit the evolving nature of the research. An inductive approach was applied during the scoping review to identify patterns and recurring concepts in the literature, which were then used to develop the Industry 5.0 framework presented in Chapter 5. This ensured that the framework was grounded in empirical and conceptual evidence from existing studies. Subsequently, a deductive approach was adopted during the analysis of interview transcripts of the empirical investigation phase. The themes and codes established in Chapter 5 served as a priori categories, guiding the coding of qualitative data. This allowed for a structured assessment of how well real-world responses aligned with the conceptual framework, thereby supporting the evaluation of Industry 5.0 adoption within the South African mining sector.

3.2.3 Research design

Sue & Ritter (2007) state that the purpose of research can be classified into three categories: exploratory, descriptive, and explanatory research. Exploratory research is used to clarify concepts, identify problems, and generate hypotheses, typically through qualitative methods such as expert interviews or literature reviews with non-random sampling (Sheppard, 2020). Descriptive research focuses on systematically describing characteristics of people or phenomena, often using probability sampling and summary statistics, while explanatory research aims to test hypotheses, explain relationships between variables, and predict outcomes, relying on quantitative data and statistical analysis (Sue & Ritter, 2007). This study adopts an exploratory research design, as it seeks to clarify emerging concepts, identify patterns of Industry 5.0 adoption, and develop a context-specific framework within a largely under-researched domain.

Vogt (2012) defines research design as 'the master category' of collecting evidence through different methods or combinations of techniques such as surveys, interviews, experiments or observations (Vogt *et al.*, 2012). The selection of an appropriate research design is therefore critical to ensure that the research objectives are achieved and the findings are reliable and accurate, specifically when the research seeks to explore complex, real-world systems involving both human and technological components (Gangadhar & Seethi, 2023). Research design acts as a link between the formulated research questions and the practical application of the chosen research strategy (Mafuwane, 2011).

Research designs can be broadly categorised into quantitative, qualitative, and mixed-methods approaches (Creswell & Creswell, 2017). Qualitative and quantitative research designs have different purposes and are suited to varying types of research questions and objectives (Bisht, 2024). Qualitative research provides rich, contextual insights into human behaviour and experiences, while quantitative research offers numerical and measurable data to test hypotheses and identify patterns (Bisht, 2024).

The Sociotechnical Systems (STS) theory provides a foundational theoretical lens for this study. STS emphasises the interdependence between social (e.g., people, roles, and organisational culture) and technical (e.g., tools, infrastructure, digital systems) subsystems in achieving effective and sustainable organisational change (Gumede & Tladi, 2023). This system's view directly influenced the framing of the research design by highlighting the need to examine Industry 5.0 readiness not only through technological adoption but also through human-centric adaptation and organisational learning. Complementing the STS foundation is the use of a maturity model, which provides a structured way to assess the level of progression across defined socio-technical dimensions. Maturity models have proven effective in guiding both descriptive assessments and strategic improvements in complex systems (Pöppelbuß & Röglinger, 2011).

In the context of this study and considering the underlying theory (STS) and maturity model, a purely quantitative design would have been insufficient to capture the complex, socially embedded factors influencing adoption. On the contrary, while a strictly qualitative approach offers the necessary depth and flexibility to explore diverse contexts, it also poses challenges for structured evaluation and comparison. To reconcile these needs, the study adopts a qualitative research design with a quantitising strategy; a form of qualitatively-driven investigation in which qualitative data is converted into numerical form to support structured analysis and cross-case comparison (Sandelowski *et al.*, 2009). Onwuegbuzie and Combs (2010) coined the term "crossover mixed analysis", where an analysis technique usually associated with one design (quantitative) is used in another design (qualitative) (Onwuegbuzie & Combs, 2010).This method supports a more holistic interpretation of data by leveraging the complementary strengths of both qualitative and quantitative approaches, thereby enriching the overall scope and insight of the research findings (Onwuegbuzie, 2025).

Quantitising has several benefits. It acts as a bridge between qualitative and quantitative findings, improving the recognition of patterns, contradictions, and nuances. This supports a more precise meaning and a deeper understanding of the research problem (Cao, 2007). Quantitising improves methodological strength by enabling empirical integration across data types. It supports richer analyses and helps clarify ambiguous qualitative meanings, leading to more generalisable conclusions (Driscoll *et al.*, 2007; Morse, 2009). Lastly, quantitising promotes transparency, serves as a reliability or triangulation check, and supports deeper, multivariate interpretation (Tufte, 2006). In summary, quantitising is more than a data transformation technique; it is a powerful strategy to improve integration, understanding, and rigour in research.

In summary, the qualitative component enables an in-depth examination of stakeholders' experiences, perceptions, and contextual challenges. This is crucial for understanding the current state of readiness and adoption of Industry 5.0 concepts and components. It provides rich, descriptive insights into how Industry 5.0 is interpreted and implemented across various organisational settings. The quantitising component, specifically the use of Likert-scale items, is employed to operationalise maturity dimensions identified through the literature and scoping review. These structured assessments enable comparability, tracking, and pattern recognition across respondents, allowing the research to quantify levels of readiness, adoption, and alignment with core Industry 5.0 principles. While Likert scales are typically associated with quantitative methods, in this study, they are integrated as part of a structured framework that translates qualitative insights into measurable indicators, bridging the exploratory and evaluative objectives of the research. Figure 3.1 illustrates the overarching research design adopted in this study, which follows a qualitative approach with quantitising.

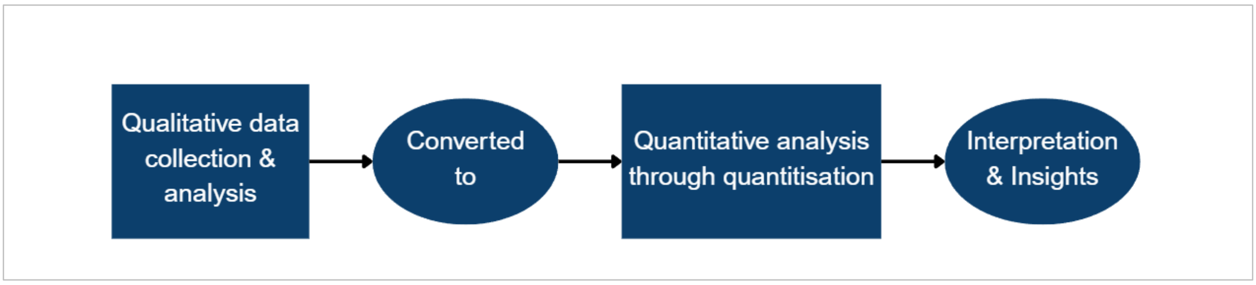

Figure 3.1: Qualitative research with a quantitising research design

Source: Adapted from Webber et. al. (2024).

By combining these two approaches, the study ensures both depth and generalisability, generating actionable insights for both policy and practice. The use of qualitative research with quantitising research design is central to answering the multifaceted research question.

3.2.4 Research time horizon

The concept of a research time horizon refers to the period within which data is collected and analysed, influencing how the phenomena under study are interpreted over time. Saunders, Lewis, and Thornhill (2019) distinguish between two primary types of time horizons: cross-sectional and longitudinal. A cross-sectional study examines data at a single point in time and is typically used to capture a snapshot of a particular phenomenon, such as attitudes, behaviours, or conditions (Saunders *et al.*, 2009). This approach is common in survey-based research, where the aim is to explore relationships or test hypotheses without tracking changes over time (Bryman & Bell, 2011). In contrast, a longitudinal time horizon involves collecting data over an extended period, allowing researchers to observe developments, causal relationships, or patterns as they unfold. This design is particularly valuable in studying organisational change, behavioural adaptation, or policy impact (Ritchie *et al.*, 2013).

A cross-sectional time horizon is chosen for this research because it involves collecting data at a single point in time. This approach is suitable for assessing the current state of Industry 5.0 adoption, challenges, and opportunities within the South African mining industry. Given the scope and resources of a master's thesis, a cross-sectional study allows for a snapshot view of the industry's transition status without the extended time commitment required for a longitudinal study.

3.3 Five-Phase Approach

Figure 3.2 illustrates the high-level process and structure followed to achieve the overall aim and purpose of the thesis. This structured 5-phase approach ensures the study is presented in a clear, logical, and easily understandable manner, simplifying and improving readability and coherence.

1. LITERATURE REVIEW	2. SCOPING REVIEW	3. INDUSTRY 5.0 FRAMEWORK	4. EMPERICAL INVESTIGATION	5. VERIFICATION & VALIDATION
To review existing Industry 5.0 maturity assessments and frameworks.	Develop a general Industry 5.0 framework based on key concepts and components.	Combine scoping review findings with maturity assessments to develop a comprehensive Industry 5.0 framework.	Apply the developed framework to the South African mining industry.	Verify and validate the findings from the empirical investigation.

Figure 3.2 Sequential Five-Phase Methodological Approach for Evaluating Industry 5.0 Transition in the South African Mining Industry

Each phase, with the corresponding research details and design, is discussed in the following sections.

3.3.1 Phase 1: Literature review

The first phase of the study consisted of a structured literature review aimed at identifying and evaluating existing Industry 5.0 maturity assessments and theoretical frameworks. This phase established the conceptual foundation of the study by critically analysing global developments in Industry 5.0, with particular focus on its defining pillars: human-centricity, sustainability, and resilience. Emphasis was placed on understanding how these pillars have been incorporated into maturity models and transition frameworks across various industrial contexts. The review also examined relevant applications within the mining sector, highlighting gaps in current knowledge, particularly regarding their applicability to developing regions such as South Africa. The insights gained from this phase were instrumental in shaping the scope and direction of the subsequent scoping review and framework development phases.

All sources were selected based on academic rigour and relevance, ensuring that the theoretical base of the study is grounded in current, credible research. Different sources are included, such as scholarly journals, industry reports, conference papers, e-books, blog posts and governmental publications. Online search engines such as ScienceDirect, Scopus, IEEE Xplore, Web of Science, and Google Scholar were used.

3.3.2 Phase 2: Scoping review

Phase 2 plays a critical role in identifying the key concepts and components of Industry 5.0 and in formulating an initial general framework to evaluate the transition toward Industry 5.0. This preliminary framework will subsequently be aligned with the maturity model discussed in the literature review to develop a more comprehensive and integrated assessment tool. A summary of the approach followed is provided below; however, a detailed discussion of the methodology, including data collection procedures and analytical strategies, is presented in 4.2 Method.

a. Research method

A scoping review will be conducted in accordance with the Preferred Reporting Items for Scoping Reviews and Meta-Analyses (PRISMA-ScR) guidelines.

b. Data collection

- Sources: Academic journals, industry reports, conference papers, and governmental publications.

- Keywords: Industry 5.0, Fifth Industrial Revolution, 5IR, 5th Industrial Revolution, Framework

- Databases: ScienceDirect, Scopus, IEEE Xplore, Web of Science, and Google Scholar.

c. Data analysis

- Thematic Analysis: Identify recurring themes, concepts, and gaps in the literature.

- Framework Development: Synthesis of themes in a structured Industry 5.0 framework.

3.3.3 Phase 3: Industry 5.0 Framework

This section outlines the methodological approach used to develop an integrated Industry 5.0 framework suitable for assessing the transition towards Industry 5.0 within the South African mining industry. Building on the scoping review and the existing maturity assessment framework identified by Arta (2024), this phase synthesised findings to create a comprehensive framework that captures the technological, human, and environmental dimensions central to Industry 5.0.

The objective of this phase is to develop a comprehensive Industry 5.0 framework to assess readiness and maturity within the South African mining industry. This framework is designed to capture the technological, human-centric, environmental, and customer-focused dimensions central to the adoption of Industry 5.0. This section outlines the systematic methodological steps taken to develop this framework. To develop the Industry 5.0 framework, a comparative synthesis method will be employed, integrating key concepts and components identified through the scoping review (Phase 2) and the structure and assessment criteria from an existing Industry 5.0 maturity and readiness assessment (Arta, 2024).

This process involves:

- Step 1: Scoping Review - A comprehensive scoping review is conducted to identify key Industry 5.0 concepts, such as human-centricity, resilience and sustainability. These recurring themes from academic and grey literature are grouped into thematic categories to form a preliminary Industry 5.0 framework. This is completed in phase 2 of the study.

- Step 2: Selection of Comparison Maturity Model - An existing Industry 5.0 maturity model, Arta et al. (2024), is selected for comparison due to its structured assessment of human, technological, and organisational readiness. This model serves as a benchmark for alignment and identifying gaps and is completed in phase 1 of the study.

- Step 3: Comparative Mapping and Analysis - The scoping review framework is compared against the maturity model using a comparative matrix to assess alignment, highlight omissions, and guide refinement. This analysis ensures the framework is both comprehensive and contextually relevant.

- Step 4: Integration and Framework Synthesis - Aligned elements from both models are synthesised into a single, comprehensive Industry 5.0 framework

- Step 5: Operationalisation of Framework - The final framework is operationalised through a semi-structured interview guide. Each category is linked to specific questions and rated using Likert-type scales (four levels) for maturity and importance. This allows for structured qualitative analysis and comparison across cases.

To operationalise the framework for empirical data collection, the following steps will be taken:

- An interview guide will be constructed, aligning each of the framework's categories and indicators with targeted, open-ended questions designed to elicit detailed insights from industry participants.

- Follow-up probes will be designed to ensure depth and consistency in data collection while allowing flexibility for contextual explanations.

- Maturity Level Descriptions: For each framework indicator, a four-level maturity scale (Levels 1–4) will be established, providing explicit descriptors to enable consistent coding and interpretation of responses during analysis.

This phase will result in the development of a structured Industry 5.0 framework prepared for implementation in the empirical investigation phase. The framework will serve as a comprehensive, multidimensional tool for assessing the adoption of Industry 5.0 within the South African mining industry. Additionally, it will offer a systematic means of evaluating readiness levels and provide a clear structure for analysing and interpreting findings, directly aligning with the study's research questions.

3.3.4 Phase 4: Empirical investigation

a. Research method

Qualitative research encompasses a variety of methods designed to explore complex phenomena in depth and within context. Common qualitative methods include case studies, ethnography, grounded theory, phenomenology, and narrative research (Creswell & Poth, 2016). A case study involves an in-depth, contextual investigation of a bounded system, such as an organisation or event, within its real-life setting (Yin, 2018). Ethnography focuses on understanding cultural practices and social behaviours through immersive observation in natural environments (Hammersley & Atkinson, 2019). Grounded theory aims to develop a new theory directly from data by employing iterative coding and constant comparison (White & Cooper, 2022). Phenomenology explores individuals' lived experiences to reveal how they perceive and make sense of specific phenomena (Moran, 2000). Lastly, narrative research examines personal stories and how individuals use narratives to construct meaning and identity in their lives (Riessman, 2008).

The case study research method involves a detailed investigation of a specific entity, such as a person, group, organisation, event, or phenomenon, in its real-life context (Priya, 2021). A case study method was chosen for this research since it focuses on a specific industry, shares common characteristics among the participants and companies, and aims to provide a holistic understanding of the industry's practices (Serfontein-Jordaan & Dlungwane, 2022). Studying multiple companies within the same industry enables a deep dive into the specifics of how the South African mining industry is transitioning towards Industry 5.0. This approach captures the detailed interactions between technology and people by focusing on real-world examples, providing practical and detailed insights into the transition process.

b. Data collection

Data collection methods

There are several different data collection types within a qualitative research design. Common methods include interviews, which allow for in-depth exploration of individual perspectives; focus groups, used to capture group dynamics and shared understandings; and observations, which provide insights into behaviours and interactions within natural settings. Researchers may also analyse documents and artefacts, use diaries or journals for longitudinal reflections, or examine audio-visual materials and online content to understand cultural or digital narratives. Field notes often supplement these methods by capturing contextual and reflective insights (Creswell & Creswell, 2017; Merriam *et al.*, 2025).

Interviews were chosen as the primary data collection method for this study due to their ability to capture in-depth insights into participants' experiences, perceptions, and contextual realities. There are several types of qualitative interviews, each offering varying levels of structure and flexibility. Structured interviews follow a fixed set of questions to ensure consistency across participants (Bryman, 2016). Semi-structured interviews, the most commonly used in qualitative research, combine predetermined questions with flexibility to probe deeper based on participant responses (Kallio *et al.*, 2016). Unstructured interviews are open-ended and conversational, allowing participants to lead the discussion and reveal nuanced experiences (Alsaawi, 2014). Lastly, focused interviews centre on a specific event or stimulus and are designed to explore participants' responses in a targeted manner (Alsaawi, 2014).

Since participants may not fully align on the Industry 5.0 concept, semi-structured interviews with key stakeholders will be used to gather in-depth insights on the adoption and impact of Industry 5.0 technologies. This will be analysed and categorised according to the Industry 5.0 framework. The respective categories of Industry 5.0 carry varying significance when measuring the transition towards this new industrial paradigm; hence, the relative importance of each factor is also considered.

Sampling

In terms of selection of participants, qualitative design usually relies on non-probability sampling. There are four standard non-probability sampling techniques in qualitative research namely purposive, convenience, snowball, and theoretical sampling (Sooleen, 2023). Purposive sampling, where participants are deliberately chosen based on their experience, role, or relevance to the study objectives (Palinkas *et al.*, 2015). In some cases, snowball sampling is used, particularly when accessing hard-to-reach groups, by asking initial participants to refer others who meet the criteria (Simkus, 2023). Theoretical sampling, commonly used in grounded theory, involves selecting participants iteratively as concepts emerge from the data to refine the developing theory (Delve *et al.*, 2020). Convenience sampling selects participants based on their availability and ease of access, although this may limit the depth or transferability of findings (TGM Research, s.a.). Based

The selection of participants began with convenience sampling from a pre-identified list of individuals across various mining companies who were known to have relevant experience or insight into the study topic. Following this, snowball sampling was employed to identify additional participants, either within the same organisations or across other companies, based on referrals from the initial interviewees. Initial contact was made via phone, using references provided through professional networks, after which a detailed email was sent outlining the purpose of the study, the interview process, and ethical considerations, allowing potential participants to make an informed decision about their involvement.

In terms of saturation, a sample size of 8 to 10 participants is targeted, which is appropriate for an exploratory qualitative design aimed at gaining in-depth insights rather than statistical generalisation. This range is commonly sufficient to identify recurring themes, particularly when participants are knowledgeable and share contextual similarities (Guest *et al.*, 2006; Marshall *et al.*, 2013). Semi-structured interview studies in engineering and organisational fields often reach thematic saturation within this range (Creswell & Poth, 2016).

Interview Guide

An interview guide is developed to ensure consistency in the structure, content, and approach of all interviews conducted during the empirical phase of the study. The guide serves as a flexible framework that aligns with the study's research objectives while allowing for open-ended responses and follow-up questions where necessary. It ensures that all participants are asked comparable questions, facilitating analysis and cross-case comparison. The interview questions are directly informed by the conceptual Industry 5.0 framework developed in Chapter 5. This framework identifies the core dimensions and maturity components relevant to the transition towards Industry 5.0 within the mining sector. These dimensions form the basis for the interview categories.

Each question in the guide is designed to probe how these concepts are interpreted, implemented, or challenged within the organisational context of the participants. The interview guide includes both primary and secondary prompts to encourage elaboration and clarification, while maintaining a coherent line of inquiry across all sessions.

Conducting interviews

The empirical phase of the study involves conducting semi-structured interviews using virtual platforms, specifically Microsoft Teams. This format is chosen to accommodate participants from different geographic locations, allowing for flexible scheduling while maintaining direct, real-time interaction. At the beginning of each interview, the informed consent process is revisited to ensure participants understand the purpose of the research, the voluntary nature of their involvement, and how their data will be used and protected. The researcher reads through a summary of the informed consent document and explicitly asks the participant for verbal confirmation, which is recorded as a 'yes' or 'no' response. No interview proceeds without an explicit verbal agreement.

All interviews are conducted in English and are recorded using the Microsoft Teams recording feature, with prior permission from the participant. The automatic transcription function within Microsoft Teams is enabled to generate an initial transcript of the conversation. After the interview, the researcher reviews and manually edits the transcript for accuracy, ensuring that all relevant content is correctly captured and that any identifying information is removed during the anonymisation process. These transcripts serve as the primary data for analysis and are securely stored on a password-protected device accessible only to the research team. This process ensures data integrity, ethical compliance, and a reliable basis for qualitative interpretation.

Informed Consent

In alignment with ethical research standards, this study followed a rigorous informed consent process approved by the North-West University Engineering Research Ethics Committee. Prior to data collection, participants were provided with a comprehensive information sheet detailing the nature and purpose of the study, the procedures involved, potential risks and benefits, and the voluntary nature of participation. The informed consent process was designed to ensure that participants clearly understood their role in the study and the use of the information they would provide.

The consent document outlined the study’s primary aim: to evaluate the South African mining industry’s progress in transitioning towards Industry 5.0, with particular focus on technological adoption, human-centric integration, and strategic readiness. Participants were informed of their importance in contributing expert insights relevant to the research objectives. Participants were invited to partake in a 60-minute semi-structured interview, with the interview guide provided in advance to allow for preparation. The document emphasised that participation was entirely voluntary and that individuals could withdraw at any stage without any negative consequences. It also highlighted the right to skip any question that may cause discomfort or concern.

To address ethical concerns regarding privacy and confidentiality, participants were assured that no identifying personal or organisational information would be collected or disclosed. Data confidentiality was ensured through the secure storage of digital transcripts on a password-protected device. Only anonymised data were used for analysis and reporting. Furthermore, the informed consent statement explicitly granted permission to use anonymised quotations from the interviews in the final dissertation, academic presentations, and potential publications.

Participants confirmed their consent either in writing or through a recorded verbal agreement prior to the interview, ensuring compliance with ethical protocols.

c. Data analysis

The data is analysed using the maturity framework developed in Chapter 5. A deductive analysis approach is employed, utilising predefined themes (categories such as human centricity and sustainability) and associated codes (specific items within each category) established during the framework development phase. By integrating STS theory into both the logic and coding structure, this study ensures that the analysis reflects not only the presence of technology, but also the interaction with human and organisational systems.

Following initial coding, the data undergoes quantitising, whereby qualitative responses are systematically transformed into numerical representations. This process enables statistical summarisation and pattern identification, thereby enhancing the analytical depth. The approach is adapted from the method outlined by Miles, Huberman, and Saldaña (2014) and Onwuegbuzie & Combs (2010). , where data coded under a priori categories is entered into matrices, enabling cross-case analysis and quantification. The overall data analysis process thus supports both thematic interpretation and structured evaluation aligned to the maturity assessment model. Key steps include (Miles *et al.*, 2014; Onwuegbuzie & Combs, 2010):

- Step 1: Define a priori themes - Based on theoretical frameworks, research questions, or literature review, establish a set of initial codes before data collection or analysis begins.
- Step 2: Data Collection – Conduct semi-structured interviews.
- Step 3: Coding the data - Apply the a priori codes to the qualitative data.
- Step 4: Quantitising for maturity assessment – apply the defined four-level maturity scale to the coded responses, assigning numerical values (Levels 1-4) based on the alignment of participant responses with the maturity descriptions provided in the framework – interview and analysis guide.
- Step 5: Data display via matrices - Use matrices or tables to display coded data by case or theme, with occurrences and intensities noted.
- Step 6: Pattern Detection- Identify patterns or trends across cases/themes and prepare the quantitised data for analysis.

- Step 7: Visual Analysis - Apply basic statistics (e.g., boxplots, radar charts, bar charts, etc.).
- Step 8: Interpretation - Combine the numeric findings with qualitative insights to develop richer conclusions.

This structured approach ensures that the analysis directly aligns with the framework developed in Phase 3, allowing for a consistent, rigorous assessment of the transition towards Industry 5.0 while maintaining the ability to capture participant perspectives systematically.

- Themes refer to the framework's main categories (e.g., Human Centricity, Sustainability, Resilience, etc).
- Codes refer to the specific items under each theme (e.g., human-machine collaboration, training and development, personalisation and customisation).

This structured approach ensures that the analysis directly aligns with the framework developed in Phase 3, allowing for a consistent, rigorous assessment of Industry 5.0 readiness while maintaining the ability to capture participant perspectives systematically. Table 3.1 illustrates how qualitative interview data were translated into quantitative maturity scores as part of the analysis process. Each response was coded according to a predefined framework (themes and items), and then evaluated against a four-level maturity scale. The assigned maturity level reflects the alignment between participant responses and the established descriptors for each level. This process enabled the systematic conversion of qualitative insights into structured, comparable data across cases.

Table 3.1: Example of theme-to-maturity quantitising process

Theme	Code	Example Quote	Assigned Maturity Level	Justification
Human-Centricity	Human-Machine Collaboration	"We use AI only for basic analytics..."	Level 2	Limited interaction, no adaptive interface
Sustainability	Emission Monitoring	"We occasionally report emissions manually."	Level 1	Ad hoc, no formalised system

Once the data is categorised, it is presented visually in three ways: an average maturity and importance matrix for each measurement item, as shown in Figure 3.3, a radar chart summarising the average maturity and importance levels across each category as depicted in Figure 3.4, and lastly, a boxplot showing the variation and distribution across each category, as shown in Figure 3.5.

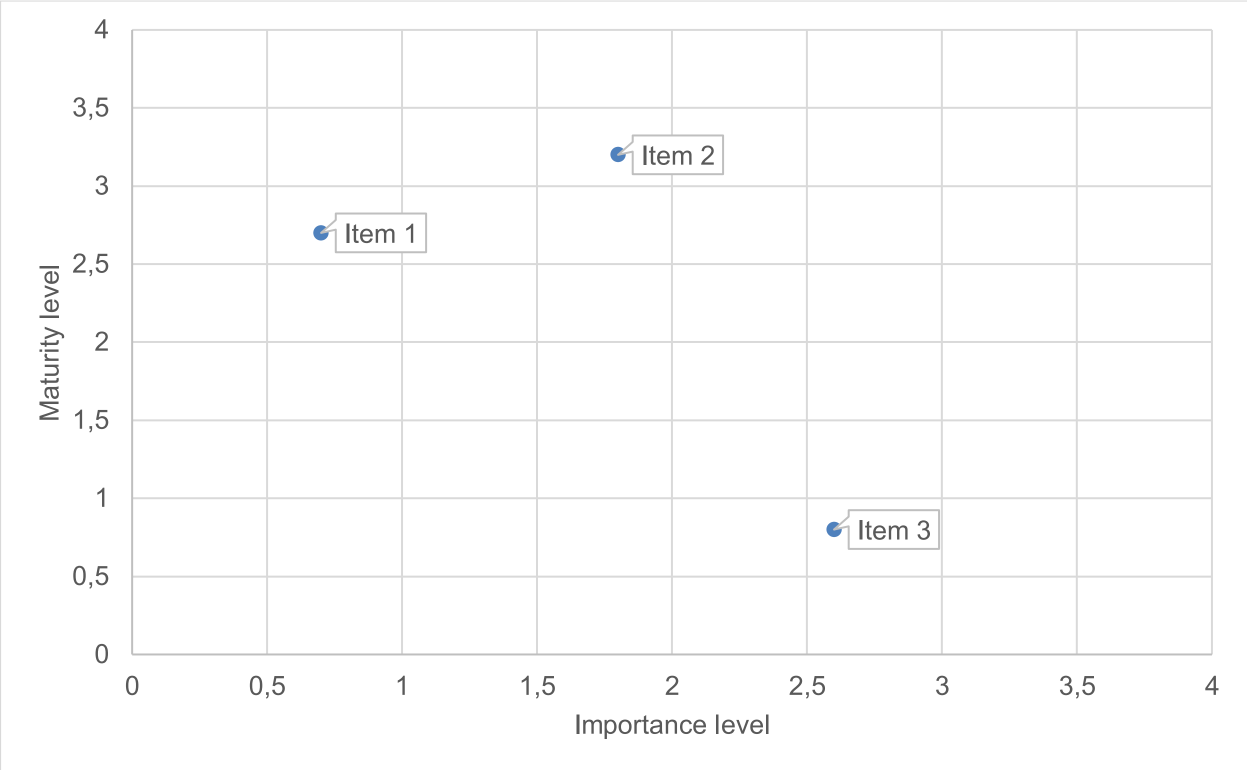

Figure 3.3: Average maturity vs importance level for each item

A radar chart is generated for each category to depict the average maturity and importance level of all items within that category based on responses from all interviewed participants.

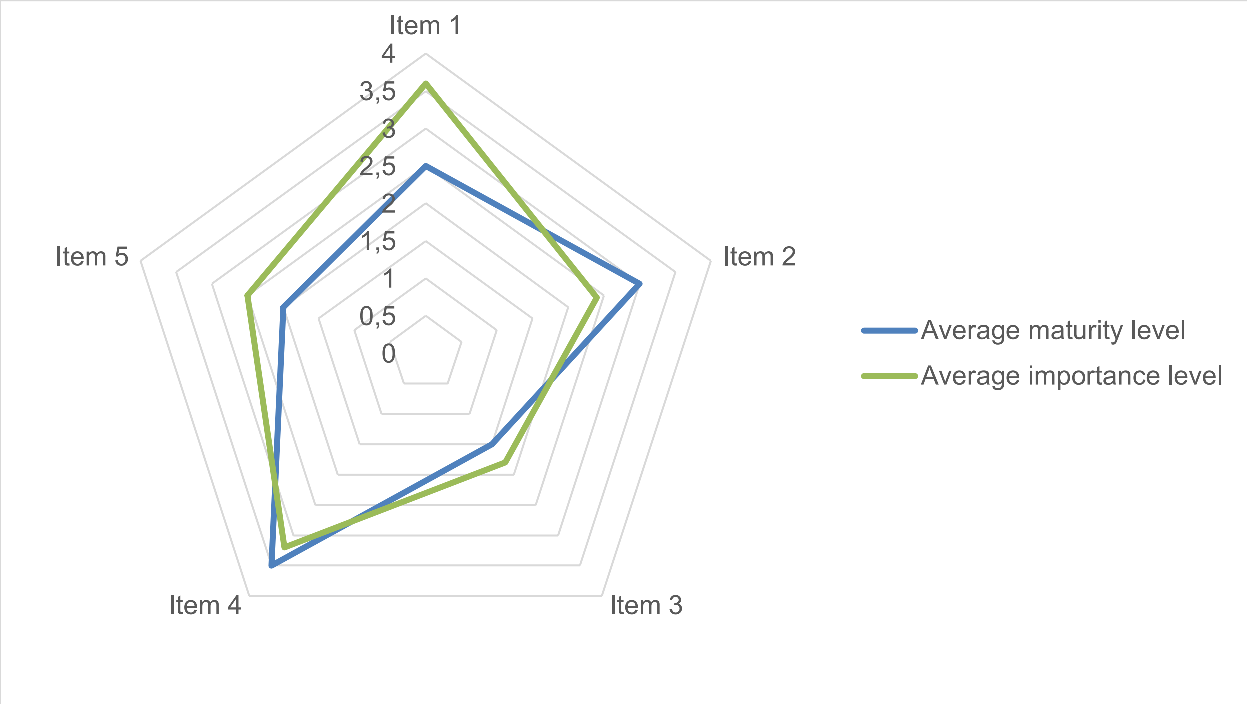

Figure 3.4: Example average maturity and importance level for category 1

When assessing the Industry 5.0 framework, it is crucial to evaluate the balance between the perceived importance and the current maturity levels of various elements within the framework, as not all elements will have equal significance. This ensures a priority-driven approach to understanding progress and identifying areas for improvement. The maturity and importance levels are combined to obtain a weighted maturity level for each item. The calculation adapted from Arta (2024) is used to complete the maturity evaluation.

- Y: Weighted maturity level
- M: Maturity level
- C: Category
- I: Item
- Z = Importance level
- N: Number of Maturity Item

$$Y_C = \frac{\sum_{i=1}^{n} M_{CIi} \times Z_{CIi}}{\sum_{i=1}^{n} Z_{CIi}} \quad \textbf{(1)}$$

Maturity level (M)

The maturity level represents the current state of development or implementation of a particular item within the Industry 5.0 framework. It is measured on a defined scale (e.g., 1-4), with higher values indicating a more advanced or complete implementation. The maturity level provides a benchmark for evaluating progress and identifying gaps that need to be addressed to achieve strategic objectives.

Category (C)

A category groups related items within the framework into thematic areas, such as human-centric design, sustainability, or resiliency. Each category reflects a critical dimension of Industry 5.0 and helps organise the analysis into manageable segments. Evaluating categories individually ensures that specific areas of focus are given adequate attention, facilitating targeted improvements across the framework.

Item (I)

An item is an individual component or element within a category. Each item represents a specific factor or attribute contributing to the maturity of the category. For example, items under the category of "Sustainability" might include "Implementation of environmental solutions" or "Monitoring of sustainability indicators." Analysing items individually ensures a deeper understanding of strengths and weaknesses, enabling organisations to make precise and informed decisions.

Importance level (Z)

The importance level reflects the perceived significance of an individual item within the broader Industry 5.0 framework. It is determined based on its relevance to achieving the objectives of Industry 5.0, such as enhancing human-centricity, sustainability, and resilience. Higher importance factors indicate items that are deemed critical to the success of the framework. Incorporating the importance factor into the maturity evaluation ensures that the weighted maturity score not only reflects progress but also aligns with organisational priorities.

Weighted maturity calculation (Y)

The weighted maturity calculation combines the importance factor **(Z)** and the maturity level **(M)** for each item **(I)** within a category **(C)** to produce a composite maturity score. This score **(Y)** provides a holistic view of how well a category performs relative to its strategic importance. This calculation enables a more targeted and meaningful analysis of maturity, helping organisations identify the most critical areas for improvement and prioritise interventions accordingly.

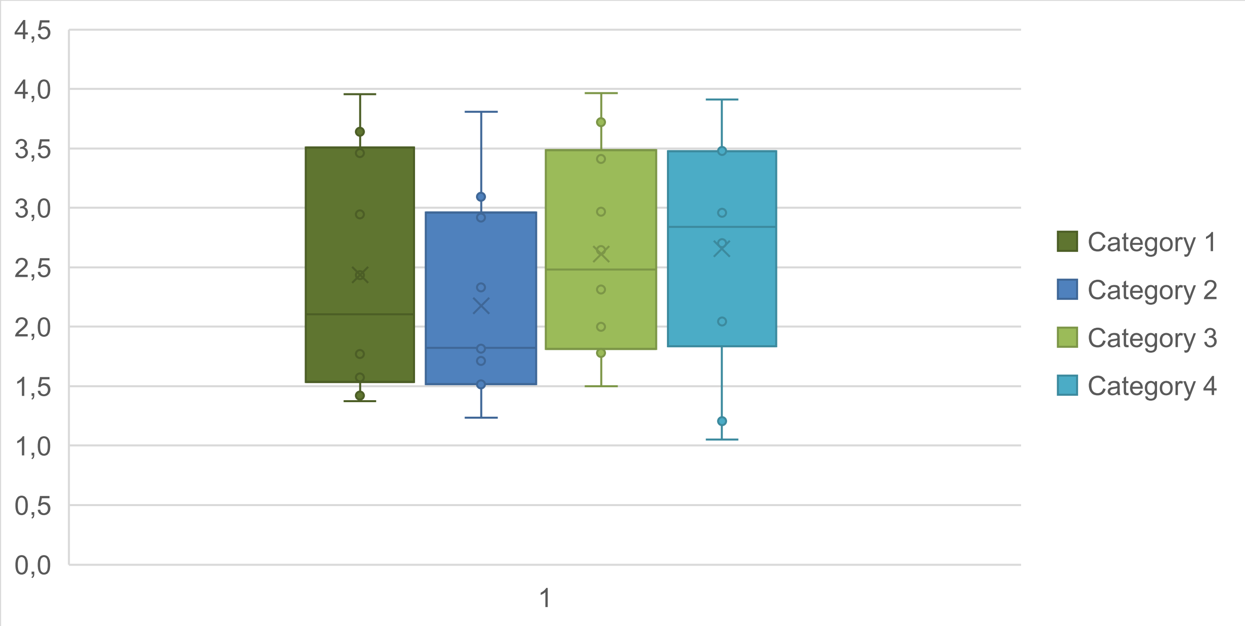

Figure 3.5: Weighted maturity levels for each category

The data is analysed, and the most critical areas for improvement, as well as common challenges and trends, are identified.

3.3.5 Phase 5: Verification & Validation

The final phase of the research methodology focuses on verifying and validating the findings to ensure their credibility, accuracy, and trustworthiness. In qualitative research, establishing rigour is essential to demonstrate that the results are dependable and reflect the perspectives of participants as well as the broader research context (Nowell *et al.*, 2017). Verification in research is the process of checking, confirming, and ensuring that the research process and findings are accurate, reliable, and valid (Lee, 2025). Whereas validation in qualitative research is an attempt to assess the 'correctness' or 'credibility' of a description, explanation or interpretation (Maxwell, 2013). The following verification and validation methodologies are evaluated to conduct the verification process: triangulation, member checking and audit trail.

a. Triangulation

Triangulation utilises multiple data sources, methods, or investigators to verify findings (Campbell *et al.*, 2020). This method verifies whether data gathered from interviews aligns with other data sources (e.g., document reviews, focus groups) or if multiple researchers reach consistent conclusions. Strengths include the improved credibility and trustworthiness of the results, as well as a more comprehensive understanding of the research issue. However, this method may require significant time, resources, and access to various data sources or additional researchers (Creswell & Poth, 2016).

b. Member checking

Member checking involves presenting the findings to participants to confirm accuracy and alignment with their experiences. This method ensures that the interview conclusions reflect participants' perspectives accurately (Shenton, 2004). Collecting feedback from participants improves the credibility and precision of the findings and helps uncover and correct any misunderstandings or inaccuracies. Weaknesses of this method include that participants may not always respond or provide feedback, and potential bias may arise if participants alter their views based on the findings (Birt *et al.*, 2016).

c. Audit trail

An audit trail consists of keeping detailed records of all research steps, decisions, and changes made throughout the study (Merriam & Tisdell, 2015). This ensures transparency and reproducibility, typically following a systematic approach. One of the key strengths of an audit trail is that it improves the transparency and accountability of the research process, making it easier for other researchers to replicate and validate the findings. However, it requires thorough documentation, which can be time-consuming, and the level of detail needed may be overwhelming for some researchers (Patton, 2014).

d. Peer review

Peer review involves colleagues or industry experts evaluating the research design, methodology, and findings to provide feedback. This approach is relevant as it ensures that the research design is scientifically robust and that the findings are both credible and applicable to the research problem (Creswell & Poth, 2016). One of its main strengths is that it provides expert validation, which improves the reliability of the research while also identifying potential weaknesses or areas that may require improvement. However, organising a peer review process can be time-consuming, and the feedback received may sometimes be conflicting or subjective, which could pose challenges in determining the best course of action (Shenton, 2004).

e. Summary

The research method relies on interviews; therefore, member checking is the most suitable approach for verification, as it involves the interviewees' participation in confirming the accuracy, completeness, and interpretation of the data. This method ensures that the findings reflect the participants' perspectives and experiences. To address the validity of the research design and whether the output addresses the research problem, a peer review strategy is utilised. It allows experts to provide feedback and evaluate the research design's scientific foundation and the research findings' relevance. Additionally, it provides an external perspective, which is vital for assessing the overall quality and validity of the study.

3.3.6 Summary

Figure 3.6 describes the research methodology and is adapted from Research Methods for Business Students (Saunders *et al.*, 2009).

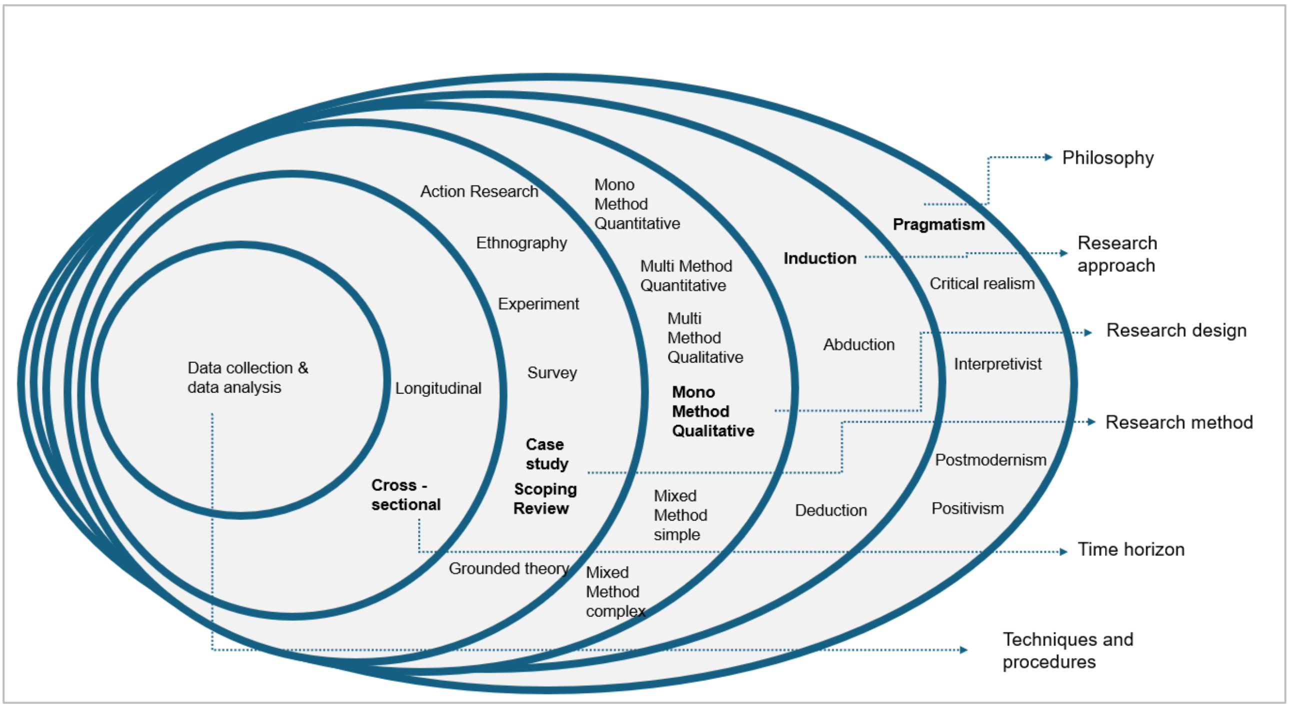

Figure 3.6: The 'research onion' is adapted from 'Research methods for business students' (Saunders *et al.*, 2009)

Figure 3.7 illustrates the high-level process and structure followed to achieve the overall aim and purpose of the thesis. This structured 5-phase approach ensures the study is presented in a clear, logical, and easily understandable manner, enhancing readability and coherence.

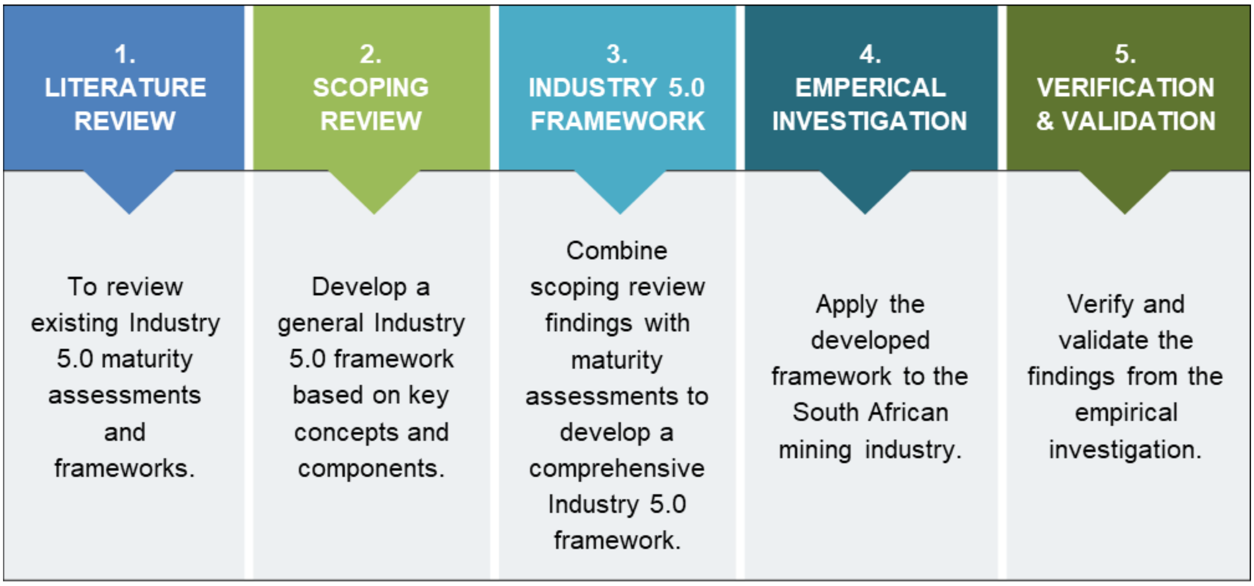

Figure 3.7: High-level process and structure of the dissertation – a phased approach

3.4 Research quality

Research quality is an important aspect of any research, ensuring the findings and results are trustworthy and ethically sound. The following key components of research quality are discussed: reliability, replicability, and ethics. Validity and verification are discussed in Chapter 7.

3.4.1 Reliability

Reliability refers to the consistency of the research findings. It ensures that if the study is repeated under similar conditions, it will yield the same results. Reliable research should produce consistent outcomes across time, different observers, and various parts of the test itself (Middleton, 2019). In qualitative research, reliability is achieved through consistency in data collection and analysis, with researchers providing detailed descriptions of their methods and procedures (Leung, 2015).

3.4.2 Replicability

Replicability is closely related to reliability and refers to the ability of other researchers to reproduce a study's findings by following the same methods and procedures. Replicable research allows for the verification of results and builds confidence in the findings (National Academies of Sciences *et al.*, 2019). In qualitative research, replicability is less emphasised due to the contextual nature of the data and the difference in interpretation and perception.

3.4.3 Ethics

Research ethics refers to the moral principles and guidelines that govern the conduct of research, ensuring that studies are carried out in a responsible, respectful, and legally compliant manner. Ethical research should protect the rights, dignity, and well-being of research participants, as well as maintain the integrity of the research process (University of Stirling, s.a.). Key ethical considerations include:

- Obtaining informed consent from participants.
- Voluntary participation.
- Ensuring confidentiality and anonymity.
- Minimising potential harm or risks.
- Adhering to relevant laws and regulations.

In terms of data handling and storage, the following principles apply (Minion, 2023):

- Establish a clear and consistent folder structure for storing data. Organise files by type and research question or theme to facilitate easy retrieval and analysis.
- Use descriptive and consistent naming conventions for files to improve clarity.
- Attach relevant metadata to qualitative data to provide context without compromising confidentiality.
- Only the author and the relevant supervisor have access to the database with any confidential information.
- Store data in secure locations to prevent unauthorised access.
- Implement a regular backup system to protect against data loss.

This study complied with the Protection of Personal Information Act (POPIA), Act No. 4 of 2013, which governs the lawful processing of personal data in South Africa. All personal and identifying information collected during the research process was anonymised, securely stored, and used solely for academic purposes. Participants were informed of their data protection rights, including access, correction, and withdrawal. Access to research data was restricted to the researcher and managed in accordance with institutional protocols and national data protection principles (Department of Justice and Constitutional Development (South Africa), 2021).

This research study followed all required ethical procedures as prescribed by the North-West University. The researcher formally signed the NWU Code of Conduct for Researchers and adhered to all institutional and national ethical standards. Ethics clearance was granted by the North-West University Engineering Research Ethics Committee (NWU-ENG-REC) under ethics number NWU-00495-24-A3. Approval was issued on 2 September 2024, authorising the commencement of the study, provided all general and specific conditions are met and pending any other necessary authorisations.

3.4.4 Trustworthiness

In qualitative research, trustworthiness refers to the confidence that readers and stakeholders can have in the quality, credibility, and ethical conduct of a study. Trustworthiness includes four interrelated components: credibility, transferability, dependability, and confirmability (Williams & Morrow, 2009):

- Credibility refers to the confidence in the accuracy of the findings (Amin *et al.*, 2020). It was ensured through the triangulation of data sources (interviews, member checks, and framework literature), as well as prolonged engagement with participants during interviews to establish rapport and gather in-depth insights.

- Transferability involves the extent to which findings can be applied to other contexts (Amin *et al.*, 2020). This was supported by providing detailed descriptions of the study context, participant roles (see anonymised profile), and mining sector characteristics, allowing readers to judge relevance to their own contexts.

- Dependability demonstrates that the research process is logical, traceable, and documented (Morrow, 2005). This was addressed through a transparent documentation of the research process, including the scoping review protocol, interview guides, and data analysis procedures.

- Confirmability refers to the neutrality of findings (Morrow, 2005). This was addressed through member checks, where the findings were shared with participants to ensure they were correctly captured.

3.4.5 Researcher Positionality and Bias

Positionality refers to the “individual's worldview and the position they adopt about a research task” (Holmes, 2020). Addressing researcher positionality and bias is essential for ensuring rigour, transparency, and ethical integrity in research, especially in qualitative and participatory fields, as it can influence the research outcomes and results (Holmes, 2020). Given the researcher’s professional background in engineering and innovation within the mining industry, there exists both an advantage of insider insight and a risk of interpretive bias.

Researcher positionality is acknowledged as an integral element of the study. Self-reflection and reflexivity involve both a foundational commitment and a continuous process through which researchers examine and articulate their own positionality. It requires ongoing critical self-awareness, allowing the researcher to recognise how their background, assumptions, and interactions shape the research process. At its core, reflexivity calls for researchers to acknowledge their presence within the study and to consider how their perspectives may influence the generation and interpretation of knowledge (Cohen *et al.*, 2013). Malterud (2001) states that “Reflexivity starts by identifying preconceptions brought into the project by the researcher, representing previous personal and professional experiences, pre-study beliefs about how things are and what is to be investigated, motivation and qualifications for exploration of the field, and perspectives and theoretical foundations related to education and interests” (Malterud, 2001).

Savin-Baden & Major (2013 identified a three-step process to create a researcher positionality statement (Savin-Baden & Major, 2023):

- Identifying your personal and professional beliefs and values: Reflect on your worldview, assumptions, life experiences, and cultural background that shape how you see the world.
- Locating yourself within the research: Consider how your identity (e.g. race, gender, class, discipline, role) and relationship to the research topic and participants may influence the research process and findings.
- Considering the influence of your positionality on the research, acknowledge how your position may affect data collection, interpretation, power dynamics, and interactions with participants, and how you will manage or account for this influence.

Researcher Positionality Statement

As a professionally trained industrial engineer currently working in a senior role focused on innovation and value realisation within the mining sector, I occupy a dual position as both a researcher and an industry practitioner. My career has involved direct engagement with digital transformation initiatives, operational optimisation, and the integration of emerging technologies in mining operations. This background provides me with a strong understanding of the organisational structures, technical systems, and stakeholder dynamics that underpin the themes explored in this research.

I hold a strong personal belief that humans should be at the centre of all transformation efforts, and that technology should serve to support and improve both society and the environment. My values have been shaped by growing up as a white woman in a small community, where I was closely connected to nature and actively involved in outreach and community upliftment initiatives. These formative experiences have shaped my conviction that technology, when applied responsibly and ethically, can significantly enhance the quality of life.

While my professional proximity to the industry provides valuable insider insight and strengthens my ability to interpret both technological readiness and human-centred challenges, I acknowledge that it also introduces potential subjectivity. My belief in the value of digitalisation and innovation may influence how I interpret participant responses, particularly those reflecting resistance, uncertainty, or scepticism towards Industry 5.0. To address this, I have approached the research with reflexivity, remaining critically aware of my assumptions and continuously reflecting on how they may shape the research process and interpretation of findings. To ensure trustworthiness and reflexivity, I employed several strategies throughout the research process:

- Throughout the analysis process, I engaged in ongoing critical reflection on my assumptions, perspectives, and evolving interpretations.
- Positionality statements are used to disclose and manage bias.
- Self-reflection and reflexivity approach.
- Participants were offered the opportunity to review the interpretations of their responses to confirm accuracy and authenticity

By explicitly acknowledging my positionality and taking steps to manage its influence, this research aims to strike a balance between insider understanding and critical objectivity, thereby enhancing the credibility and integrity of the findings. By recognising and transparently addressing researcher influence, this study improves its integrity, reflexivity, and interpretive authenticity, key principles in high-quality qualitative inquiry (Berger, 2015).

Reflexivity Statement

Throughout this research, I engaged in a process of continual reflexivity to critically examine how my background, professional experiences, and assumptions may have influenced the research process. Recognising that the qualitative approach is inherently interpretive, I consistently reflected on my role in shaping the research questions, interactions with participants, and the analysis of data.

Given my professional engagement in the mining sector and my orientation towards innovation and digital transformation, I remained aware of the potential for these perspectives to influence how I understood and interpreted participant responses, particularly those that challenged or diverged from dominant narratives of progress and technological advancement. I approached the data with a commitment to exploring all viewpoints, even those that presented discomfort or contradiction to my prior beliefs.

This ongoing self-awareness allowed me to question initial assumptions, remain open to alternative meanings, and ensure that participants' voices were represented authentically and respectfully. By embracing reflexivity as an integral part of the research process, I aimed to uphold transparency and enhance the credibility and trustworthiness of the study.

3.5 Conclusion

This chapter presented the research methodology adopted to investigate the adoption of Industry 5.0 within the South African mining sector. It outlined the research strategy, justified the use of a qualitative approach, and detailed the five-phase methodological framework used to structure the study. The chapter also discussed the criteria used to ensure research quality, including trustworthiness, reflexivity, and ethical rigour.

By systematically aligning data collection and analysis methods with the research objectives, this methodology provides a coherent and credible foundation for exploring the factors influencing the state of technological adoption of the South African Mining Industry towards Industry 5.0. The next chapter presents the findings that emerged from the scoping review used to define key concepts and components of Industry 5.0.

CHAPTER 4 SCOPING REVIEW

4.1 Introduction

Chapter 4 presents a comprehensive scoping review designed to explore and synthesise existing Industry 5.0 frameworks, models, and thematic concepts relevant to industrial transformation. This review directly supports the overarching research question: What are the factors influencing the state of technological adoption in the South African Mining Industry towards Industry 5.0? By systematically mapping the key concepts, enabling technologies, and human-centric principles embedded in Industry 5.0 frameworks, the review provides the conceptual foundation needed to assess the maturity and applicability of these frameworks within the South African mining context.

The primary objective of this chapter is to examine the core components and key concepts of Industry 5.0 frameworks, addressing the evolving needs of industrial sectors. A scoping review methodology is chosen as it allows for a broad investigation of relevant sources to map out existing knowledge, identify themes, and highlight research gaps. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) guidelines are followed to ensure a structured and unbiased approach to the review process. By clarifying the conceptual boundaries and structure of Industry 5.0, this chapter informs both the framework development and the empirical investigation that follows. Table 4.1 outlines the chapter's structure in relation to the research questions.

Table 4.1: Chapter 4 outline according to research questions & objectives

Research objective	Section	Research question
3. To develop a conceptual Industry 5.0 framework	4.3.1 Key concepts	What are the key concepts of the Industry 5.0 framework?
	4.3.2 Key components	What are the key components of the Industry 5.0 framework?
	4.4 Initial Industry 5.0 framework	What is the Industry 5.0 framework?

Figure 4.1 illustrates the study's progress, indicating that it is currently in Phase 2 of the 5-phase approach, which consists of developing a general Industry 5.0 framework based on the key concepts and components identified.

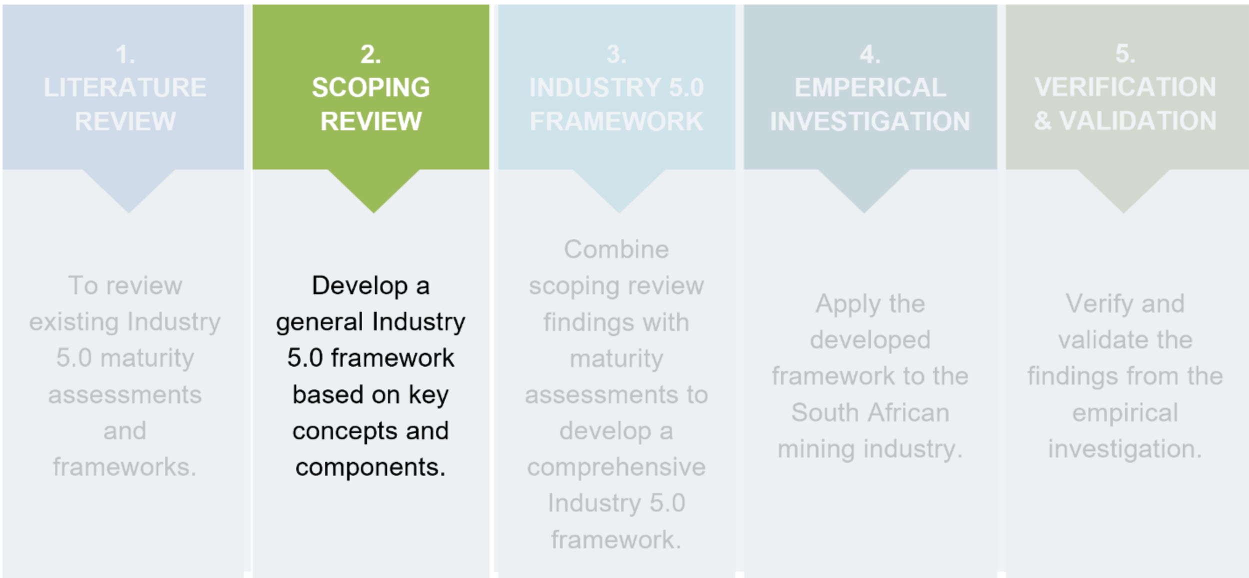

Figure 4.1: Overview of the study's progress: Phase 2/5

4.2 Method

A scoping review is the optimal methodology for this investigation due to the broad nature of the research questions (Tricco *et al.*, 2018). It excels at mapping existing frameworks, clarifying key concepts, and identifying knowledge gaps – ideal for exploring Industry 5.0 frameworks.

The review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) guidelines and protocol. The protocol provides the plan for the scoping review and is important in limiting the occurrence of reporting bias. After creating the detailed protocol, the eligibility criteria for selecting studies or evidence sources are clearly defined. The review identifies and searches relevant databases and search engines to retrieve studies or evidence.

A search strategy is formulated to identify relevant studies, and a systematic process is used to select sources based on eligibility criteria. Data from the selected sources is extracted and organised through a charting process. The findings of individual sources are synthesised to identify common themes, patterns, or gaps in the literature. The general results of the findings, common themes, and trends are discussed. The review concludes with a summary of the evidence, a discussion of limitations and implications for practice, policy, or future research, along with any recommendations. Industry 5.0, the next iteration of industrial automation, emphasises a human-centred approach alongside the technological advances of Industry 4.0. The objective is to identify key elements in the new industrial revolution through the following research questions.

- **RQ 1: What are the key concepts in the Industry 5.0 frameworks?**

  Concepts are the higher-level ideas and theories that underpin the Industry 5.0 paradigm.

- **RQ 2: What are the key components of the Industry 5.0 frameworks?**

  The components comprise the specific technologies, systems, and approaches that make up the Industry 5.0 framework.

This investigation lays the groundwork for future Industry 5.0 frameworks, ensuring it provides all the necessary guidance for successful industry-wide adoption. The following inclusion and exclusion criteria are established as part of the protocol.

Table 4.2: Inclusion & exclusion criteria

PRISMA Phase	Type of the criteria	Description of the criteria
Identification	Inclusion	Publication year > 2016
		Title, abstracts, or keywords containing terms: ("Industry 5.0" or "Fifth industrial revolution" or "5th industrial revolution") and "Framework"
	Exclusion	Duplicated Articles
		Articles not published in English
Screening	Inclusion	Industry 5.0 concepts or components are among the main or several topics that are reviewed, surveyed, or discussed.
	Exclusion	Articles out of the scope based on titles and abstract assessment
		Studies solely focused on Industry 4.0 or earlier industrial revolutions (unless explicitly compared to Industry 5.0)
		Full text not available

The following engineering-related databases are used: ScienceDirect, Scopus, IEEE Xplore, Web of Science, and Google Scholar. The keywords used in the search strategy are shown in Table 4.3. No synonyms for 'Framework' are used in the search strategy to limit the number of studies relevant to the study topic.

Table 4.3: Keywords for search strategy

Keywords	Synonyms
Industry 5.0	'Fifth Industrial Revolution', '5IR', '5th Industrial Revolution'
Framework	n/a

4.3 Results

The final search strategy and results, conducted on 18 May 2024, are found in the Table 4.4 .

Table 4.4: Search terms and results

Search terms and database	Science Direct	Scopus	IEEE Xplore	Web of Science	Google Scholar	Total
("industry 5.0" OR "fifth industrial revolution" OR "5^{th} industrial revolution" OR 5IR) AND (framework)	96	447	174	216	71	1004

Search terms were used to search the title, abstract and keywords. However, since Google Scholar is a search engine, not a database, only keywords were searched to limit the number of articles. Other sources include publications by the European Commission, as it is a key driver and initiator of this transition.

The final search results were exported to Rayyan, a web application designed to organise, manage and facilitate the screening process. Based on the search, 1008 resources were gathered from 5 databases. After the duplicates were removed, a total of 612 citations were identified from searches of electronic databases and review article references. Based on the research protocol used to perform an initial screening, 560 were excluded, with 52 full-text articles to be retrieved and evaluated for eligibility and to ensure they directly address the research questions and objectives and provide relevant information about the Industry 5.0 frameworks.

Of these, 22 were excluded for the following reasons:

- Unable to retrieve the full article.
- Focus on a very specific application of a technology.

- Industry 5.0 is only used as a reference and is not discussed in the paper.
- Focus only on challenges, opportunities, advantages, disadvantages or risks.
- Focus only on industry 4.0 technology frameworks.
- The remaining 30 studies were considered eligible for this review.

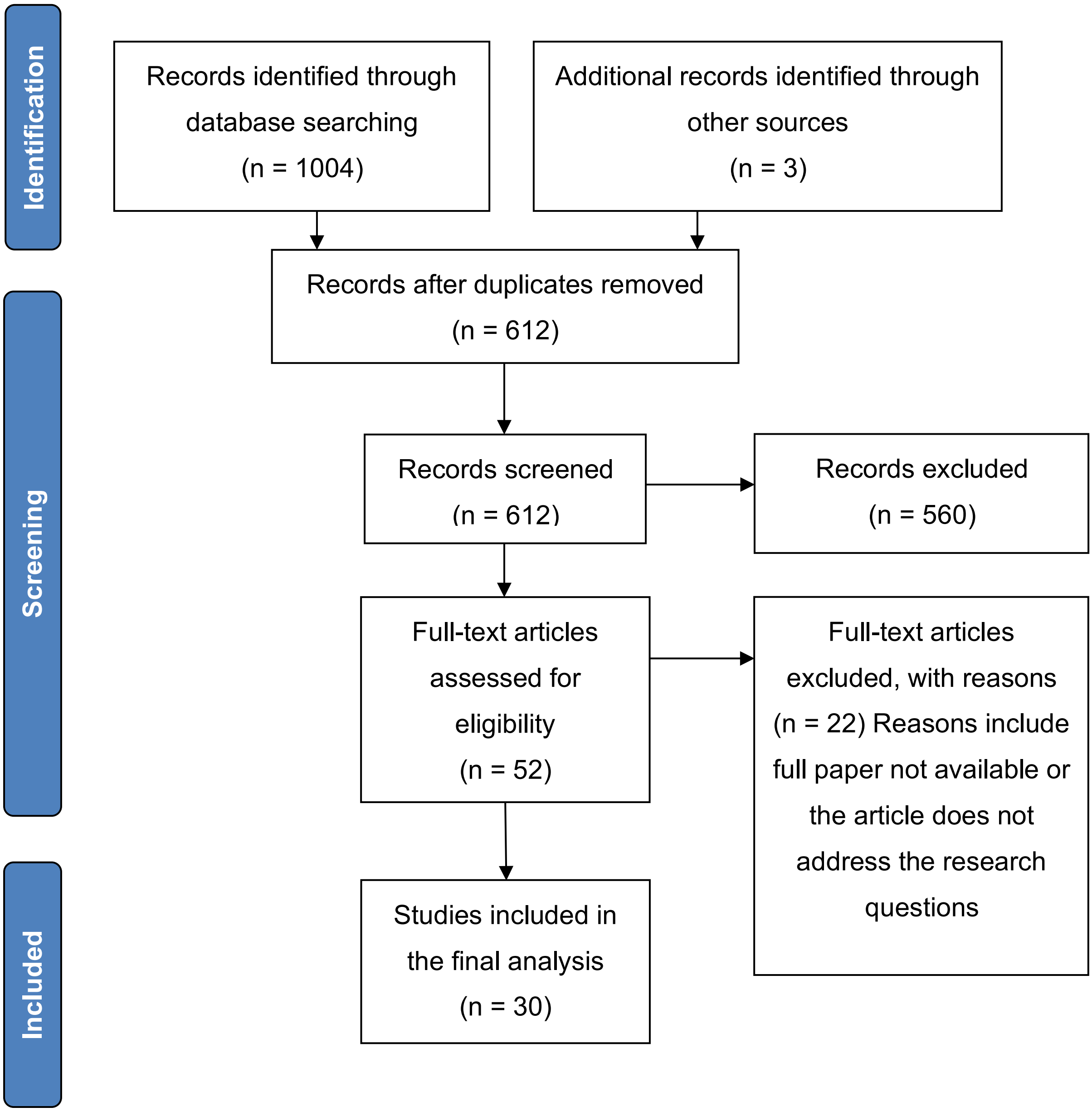

Figure 4.2: PRISMA-ScR flow diagram

4.3.1 Key concepts

Figure 4.3 shows the most common to the least discussed concepts in the 30 included articles. Each of these concepts is discussed individually to gain a deeper understanding of its definition and application.

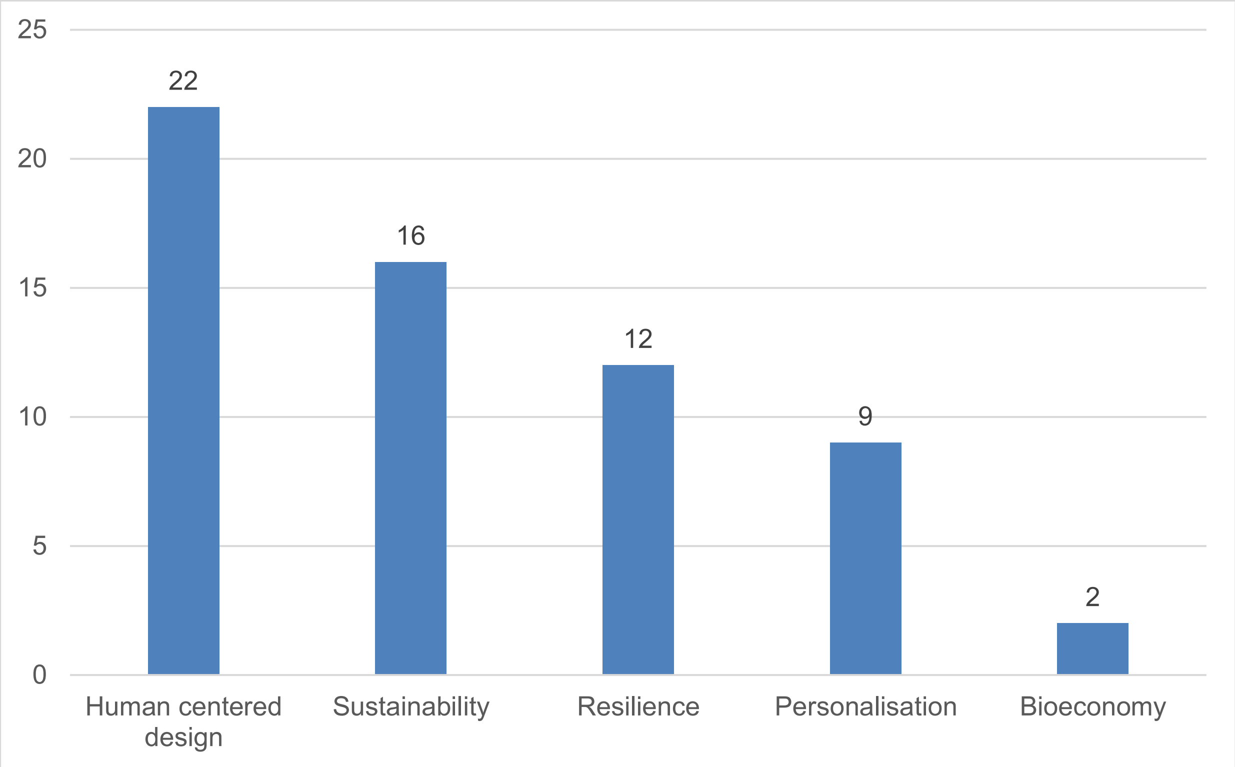

Figure 4.3: Number of articles discussing Industry 5.0 concepts

a. Human centered design

The authors emphasise that technology is not a replacement for humans but a collaboration between people and machines to create more value-added for customers (George & George, 2020; Grabowska *et al.*, 2022). It improves their role in manufacturing by placing more importance on human intelligence and the improvement of quality (Tallat *et al.*, 2023). Industry 5.0 will eliminate monotonous and tedious tasks and pave the way for curiosity, empathy, creativity, and judgment (Ahamed *et al.*, 2022; George & George, 2020). Humans will take on greater responsibility and increased supervision of systems (Ahamed *et al.*, 2022). Therefore, it is imperative to hire the right people with the right skills to work safely alongside machines (Iqbal *et al.*, 2022).The goal is to improve workplace safety, minimise errors, and increase productivity through human-machine interaction (Kovari, 2024).

Human centricity focuses on improving physical and mental well-being and viewing humans as assets. This includes incorporating principles such as autonomy, development, and psychological safety (Asif *et al.*, 2023). The 5C human-machine relations framework is introduced to implement the principles of coexistence, cooperation, collaboration, compassion, and coevolution (Lu *et al.*, 2022). A human-centric interaction model is created that consists of three elements: 1) human-machine understanding, (2) human-machine collaborative intelligence, and (3) human-machine communication (Lu *et al.*, 2022).

Technology will be used to benefit humanity, generate new employment opportunities, and increase productivity. This will lead to the upgrading and reskilling of workers (Nair *et al.*, 2024). Somroo (Soomro *et al.*, 2022) also states that modern automated industries are considering adding the human element back into their technological systems and strategies to get the most value from automation. It combines the best of both worlds: the speed and precision of automation with the cognitive abilities and critical thinking of humans (Grabowska *et al.*, 2022). Machines and humans should work as collaborators and not as competitors (Grabowska *et al.*, 2022).

b. Sustainability

Organisations concentrating only on profit are finding it increasingly challenging to succeed in a global, unpredictable, and competitive environment. For companies to be sustainable, they need to achieve a symbiosis between economic, technological, social, and ecological aspects (Ahamed *et al.*, 2022; Grabowska *et al.*, 2022). Ahamed (Ahamed *et al.*, 2022) states that Industry 5.0 emphasises sustainable supply chain management, incorporating elements such as 'employee education and training, working conditions, the balance between productivity and wages, technology versus human redundancy, optimal product quality, sustainable governance, and a business ethics code'. Sustainability is also argued to be driven by the implementation of digital transformation and pro-social and pro-environmental solutions in organisations (Mesjasz-Lech, 2023). There is a shift in typical economic models to circular economy models to improve overall sustainability, considering social and environmental needs and challenges (Mesjasz-Lech, 2023).

There is also a rise in environmental policies aimed at reducing waste materials and improving waste management. More companies are prioritising environmental sustainability, aligning with the growing demands of international organisations, government regulations, and customer expectations (George & George, 2020). The 6R principles of upcycling are introduced to accompany Industry 5.0, namely, recognising, reconsidering, realising, reducing, reusing and recycling (Chabane *et al.*, 2023; Mesjasz-Lech, 2023; Soomro *et al.*, 2022). Akundi (Akundi *et al.*, 2022) also mentions the 6R principles as a means to promote human values and needs.

c. Resilience

Resilience is the organisation's ability to return to a stable state after expected and unexpected conditions, such as geopolitical shifts and global crises, ensuring that critical infrastructure remains operational during challenges (Górny, 2023; Mouhib *et al.*, 2023). It involves building robust supply chains, systems, networks, and societies capable of responding quickly to threats and recovering efficiently from failures (Asif *et al.*, 2023). Industry 5.0 improves resilience in manufacturing by using flexible, agile, and adaptable technologies (Mesjasz-Lech, 2023).

There are two types of resilience, "self-resilience" for employees and "system resilience" for human-machine systems; this encourages collaboration to reach goals that neither could reach independently (Mouhib *et al.*, 2023). This allows for a robust system that can adapt to changes (Martin-Gomez *et al.*, 2024). The European Commission found that enforcing environmental and social governance criteria leads to better resilience (European Commission, 2021). Resilience in organisations is critical where they provide vital services such as healthcare or security (European Commission, 2021).

d. Personalisation and Customisation

A key concept in Industry 5.0 is moving from mass production to mass personalisation and customisation (George & George, 2020). This can be achieved through the collaboration between humans and advanced, intelligent, high-speed, and precise machines (Soomro *et al.*, 2022). By including critical thinking within processes, mass personalisation can be achieved based on customer needs and expectations. The demand for human touch is expected to increase as customers increasingly seek to express their individuality through their purchasing decisions. This trend reflects a new level of personalisation and a sense of luxury that businesses must address (Ahamed *et al.*, 2022). Kovari states that the combination of human skills and smart factories will enable companies to respond quickly to market changes and demands (Kovari, 2024).

e. Bioeconomy

The bioeconomy is described as one of the visions for Industry 5.0, focusing on breakthroughs in agriculture, healthcare, and biosciences (Sindhwani *et al.*, 2022). Sindhwani (Sindhwani *et al.*, 2022) defines a bioeconomy as ‘the conversion and production of renewable biological sources into value-added products such as food, bioenergy and biobased products'. This includes a wide variety of industries, such as agriculture, forestry, fisheries, technology, energy, and manufacturing industries. Bioeconomy will act as an enabler for the symbioses between ecology, industry, and economy through the use of bioinspired technologies (Asif *et al.*, 2023; Mouhib *et* *al.*, 2023). The demand for bioinspired technologies is expected to rise due to the growing need for clean, affordable, and sustainable energy sources. These technologies will be part of bioinspired systems (Narkhede *et al.*, 2024).

4.3.2 Key components

A recent report by the European Commission outlines six desired characteristics of technologies that support the concept of Industry 5.0 (European Commission, 2020):

- Human-Centric Solutions
- Bio-Inspired Technologies
- Real-Time Digital Twins
- Cyber-Safe Data Transmission
- Artificial intelligence
- Technologies for Energy Efficiency and Trustworthy Autonomy

Figure 4.4 shows the components discussed from most to least commonly in the 30 articles included. To understand their definitions and applications, each component is discussed individually.

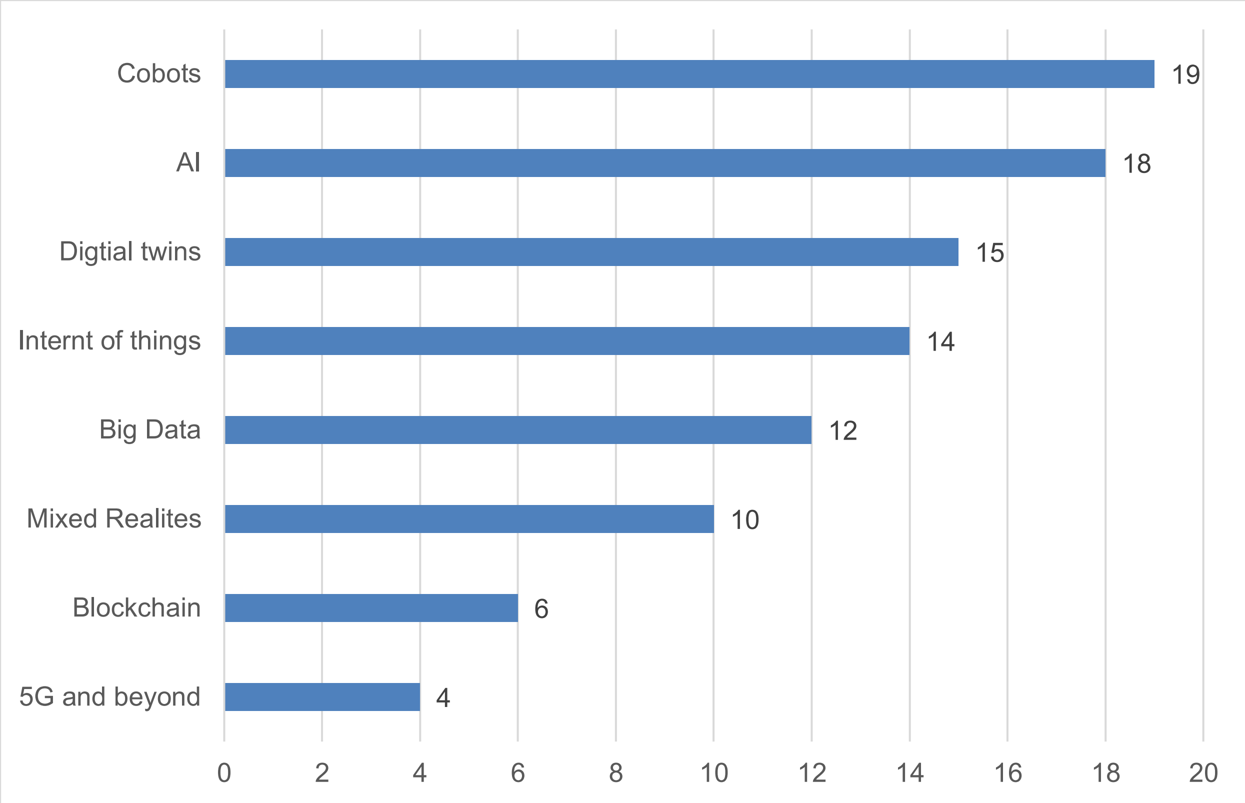

Figure 4.4: Number of articles discussing Industry 5.0 components

a. Collaborative Robots (Cobots)

According to George (George & George, 2020), the definition of a cobot is a robot designed to physically interact with people in a shared workplace where safety is prioritised. These robots collaborate with humans on the production line and learn from them. Cobots can recognise and adapt to the activities of their colleagues, creating a safer and more efficient work environment (Kovari, 2024).

Specifically, in a manufacturing setup, there are two concepts: a) Allowing humans to work on customised, personalised and creative tasks. b) Utilising robots for repetitive and labour-intensive tasks. This can help mitigate risks on the job (Akundi *et al.*, 2022). By integrating human intelligence and cognitive processes into computers through cognitive computing, they can create more value. Cobots are also discussed when describing smart factories and improved communication between components and humans (Soomro *et al.*, 2022). Humans are connected to smart factories through intelligent devices (Grabowska *et al.*, 2022).

Another author discussed the role of cobots in intelligent healthcare, where cobots can monitor patients' conditions and assist doctors in performing surgeries and handling routine medical tasks, allowing doctors to focus on more complex tasks (Kovari, 2024). In manufacturing, consider an example where a technician is performing maintenance on a piece of machinery. The cobot, equipped with a camera, observes the technician's actions, analyses the images using machine learning, and predicts the technician's next steps using fNIRS (functional Near-Infrared Spectroscopy) and deep learning. The cobot then provides the necessary tools and parts to assist the technician when needed (Mouhib *et al.*, 2023).

b. Artificial Intelligence (AI)

AI is a collection of technologies based on AI models and techniques, including machine learning and natural language generation. It is designed to provide services or insights that are challenging or impossible to attain solely through human effort or conventional technologies (Andres *et al.*, 2024). By leveraging AI technology in conjunction with human-centred digitalisation, organisations can increase their productivity and sustainability. It is the responsibility of organisations to realise the benefits of AI by adopting, extending, and implementing AI tools (Dimirakopoulos *et al.*, 2023). For example, artificial intelligence is used to improve predictive forecasts and, therefore, reduce excess manufacturing (Mesjasz-Lech, 2023). According to Akundi (Akundi *et al.*, 2022), AI can meet the personalisation needs of customers in the manufacturing industry and provide faster feedback (Voulgaridis *et al.*, 2022).

c. Digital Twins

Digital twins are virtual replicas of physical devices or systems that collect real-time data and are used to gather insights and analytics (Andres *et al.*, 2024). These twins assist organisations in developing and optimising production processes and can improve predictive maintenance in the manufacturing industry (Kovari, 2024). In the banking sector, Digital Twins can customise products and services, improve the accuracy of automated financial statements, quickly identify technical issues, improve risk management, and avoid investments in high-risk projects (Soomro *et al.*, 2022).

d. Internet of Things (IoT)

It refers to the network of interconnected software, sensors, and devices that communicate data with other devices, systems, applications, and users to create a comprehensive network infrastructure (Andres *et al.*, 2024). It connects different people, systems, data, devices and processes (Voulgaridis *et al.*, 2022). With the use of smart sensors, IoT devices, and human insights, organisations can gather and analyse data to gain insight into processes (Kovari, 2024) (Asif *et al.*, 2023). IoT data gathering and analysis are useful when monitoring products and machinery to achieve predictive maintenance (Voulgaridis *et al.*, 2022). In the banking sector, IoT is used to address challenges related to customer retention and satisfaction (Soomro *et al.*, 2022).

e. Mixed Realities (Augmented Reality and Virtual Reality)

Augmented reality (AR) integrates digital information with the physical world through computer-generated content such as text, video, or animated 3D models (Andres *et al.*, 2024). Virtual reality (VR) provides a fully virtual experience that completely isolates the user from the real world, utilising advanced user-computer interfaces for simulation and real-time interaction (Andres *et al.*, 2024). This type of technology allows workers to interact and engage with processes and equipment in virtual environments (Kovari, 2024). Since the operator is in a safe environment, this makes it an excellent tool for training and education and is cost-effective and time-saving (Mourtzis, 2021; Mourtzis *et al.*, 2022).

f. Big Data Analytics

Big data is large volumes and a variety of data sets that need to be handled and processed accordingly (Andres *et al.*, 2024; Asif *et al.*, 2023). Using big data can support decision-making strategies and automation (Voulgaridis *et al.*, 2022). Big data analytics helps to understand customer behaviour, product promotions, and process customisation, thus improving production efficiency and reducing costs (Soomro *et al.*, 2022). It enables organisations to develop successful business strategies and maintain their competitive edge. The use of human creativity and data insights is vital for optimising the value derived from big data (Tallat *et al.*, 2023).

g. Blockchain

Blockchain creates transparency and provides secure storage for encrypted data (Voulgaridis *et al.*, 2022). Blockchain technology is used to improve energy efficiency and resource use through process management (Mesjasz-Lech, 2023:5). It is used to create secure and transparent transactions when improving ESG reporting (Asif *et al.*, 2023). Blockchain also has significant potential to improve supply chains by increasing transaction efficiency, reducing costs, and improving security (Tallat *et al.*, 2023).

h. Other technologies

Other technologies mentioned or briefly discussed in the articles include exoskeletons, drones, additive technology, edge computing, cloud computing, cyber security, multilingual speech and gesture recognition, tracking technologies, bioinspired safety and support equipment, decision support systems, smart grids, machine learning, federated learning, internet of intelligence, quantum computing, cognitive robotics, bioinspired technology, smart cities, holography, bionics, hybrid intelligence, radio frequency identification (RFID), cognitive cyber-physical systems, human interaction and recognition technologies, intelligent energy management system (IEMS), industrial smart wearable (ISW), horizontal and vertical system integration, and 5G and beyond.

4.4 Initial Industry 5.0 framework development

While Industry 4.0 is focused on technology, Industry 5.0 is focused on value. Industry 4.0 provides the tools and technologies, and Industry 5.0 uses them to create a positive impact on societal and environmental levels. This scoping review has identified key concepts and components essential for the successful implementation of Industry 5.0 frameworks, offering valuable insights into the future of industrial practices. Based on the results above an Industry 5.0 framework is created and visualised in Figure 4.5. The concepts identified in the scoping review are categorised into three concepts and three different perspectives. Corresponding information, discussed for each pillar and perspective, is also included in the framework. For example, multiple sources mention the 6R principle when talking about the Sustainability pillar. This is included in the graphic to create a comprehensive view. The creation of the Industry 5.0 framework in Figure 4.5 is guided by a systematic integration of key principles, concepts, and technological enablers. The reasoning behind the design and structure of the framework is further discussed:

4.4.1 Core structure

At the centre are critical enabling technologies (the top 8 most discussed industry 5.0 components) like Cobots, AI, Digital Twins, IoT, Big Data, Mixed Realities, Blockchain and 5G & Beyond, which serve as the foundational enablers for Industry 5.0. These technologies bridge the gap between human and machine capabilities, facilitating collaboration, decision-making, and automation while improving human-centred processes. These components are selected because they represent the cutting-edge tools necessary to implement the principles of Industry 5.0 across various industries.

4.4.2 Surrounding layers – Key concepts

- Human-centricity: Representing the core shift of Industry 5.0, this pillar places human skills, creativity, and well-being at the forefront. The 5C Principles (Coexistence, Cooperation, Collaboration, Compassion, Coevolution) emphasise how humans and machines must work together seamlessly. Subcategories such as Human-Machine Understanding, Human-Machine Collaboration, and Human-Machine Communication capture the multi-dimensional interaction between humans and machines.

- Sustainability: This pillar incorporates the 6R principles (Recognising, Reconsidering, Realising, Reducing, Reusing, Recycling), reflecting the ecological and social importance of Industry 5.0. The four aspects: Ecological, Social, Economic, and Technological are included to ensure a comprehensive balance between environmental and business objectives when discussing sustainability.

- Resilience: Addressing the need for adaptability and robustness in dynamic environments, this pillar highlights self-resilience (at the employee level) and system resilience (at the organisational level). It also focuses on creating a robust system, network, and society that can withstand external disruptions while maintaining operational stability.

4.4.3 Outer ring – Perspectives

The outer layer addresses stakeholder-specific perspectives, ensuring the framework's inclusivity:

- Customer Perspective: Focuses on Personalisation and Customisation to meet individual customer demands through advanced technologies.

- System Perspective: Integrates the Bioeconomy, emphasising sustainable and renewable resource utilisation, reflecting the growing importance of eco-friendly practices.

- Worker Perspective: Highlights training, quality, working conditions, governance, and ethics to improve employee well-being and engagement in Industry 5.0 environments.

4.4.4 Rationale behind the integration

- Balance between technology and humanity: The framework recognises the limitations of Industry 4.0, which primarily focuses on automation and efficiency, by incorporating a stronger emphasis on human-machine collaboration and sustainability. Technologies are not viewed as replacements for humans, but rather as enablers to enhance their roles, creativity, and decision-making.

- Comprehensive approach: By combining the three core pillars (key concepts), Human-centricity, Sustainability, and Resilience, the framework addresses the key challenges faced by industries, including the workforce's well-being, environmental concerns, and the ability to adapt to unforeseen disruptions.

- Actionable and scalable framework: The inclusion of specific principles (5C, 6R) and categories ensures the framework's practical applicability. It provides actionable guidance for industries to adopt the Industry 5.0 framework incrementally while customising approaches to specific contexts

- Holistic approach: The three different perspectives (customer, system & worker) are integrated across all three pillars and core enabling technologies as the other elements work together to promote Industry 5.0 principles.

This framework aims to provide a holistic, actionable general roadmap for organisations transitioning to Industry 5.0, ensuring alignment between technological developments and societal well-being.

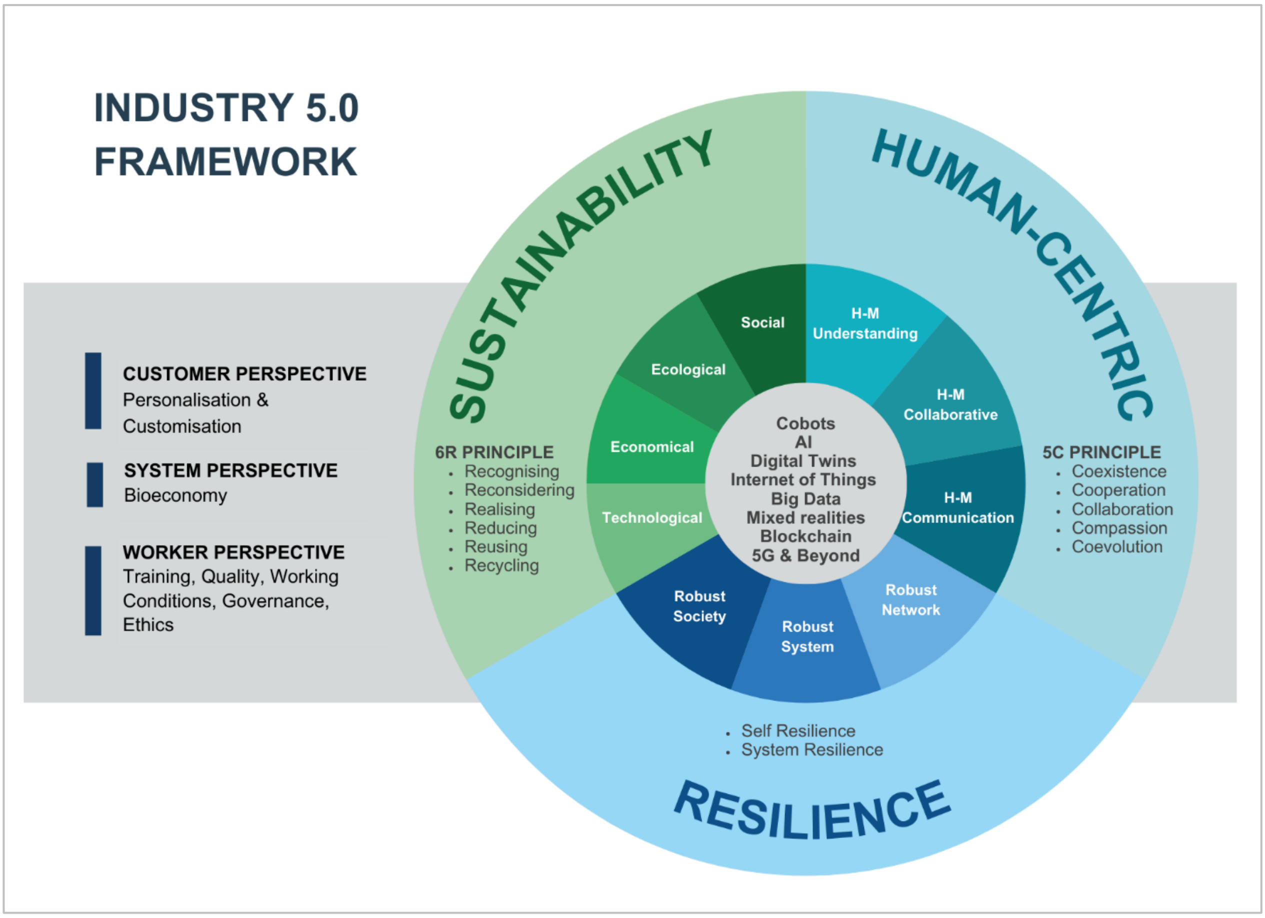

Figure 4.5: Industry 5.0 Framework: Key concepts & components

4.4.5 Discussion

Industry 5.0 places human well-being at its core, emphasising the collaboration between humans and machines using the 5C principles (Coexistence, Cooperation, Collaboration, Compassion, Coevolution). Integrating human skills such as creativity, decision-making, and problem-solving with advanced technologies like collaborative robots (cobots) improves workplace safety, reduces errors, and leads to the reskilling and upskilling of the workforce. Humans still need to make certain immediate or unscheduled decisions that robots cannot.

Sustainability in Industry 5.0 consists of economic, technological, ecological and social dimensions. It involves sustainable supply chain management practices, circular economy models, and the application of the 6R principles (recognising, reconsidering, realising, reducing, reusing, and recycling). Organisations need to work within the limits of our planet. Companies must strike a balance between profit and social and environmental responsibilities to succeed in a global, unpredictable environment. Resilience is critical for organisations to withstand and recover from disruptions. Industry 5.0 strengthens resilience through flexible, agile, and adaptable technologies. Building robust supply chains and systems capable of quick response and recovery is essential. Enforcing Environmental, Social, and Governance (ESG) criteria further strengthens organisational resilience.

Resilience is the ability of an organisation to maintain stability during crises, ensuring critical infrastructure remains operational. It involves building robust supply chains, systems, and networks that respond quickly and recover efficiently. Industry 5.0 strengthens resilience through flexible, agile, and adaptable technologies. The two types of resilience are "self-resilience" for employees and "system resilience" for human-machine systems, promoting collaboration for achieving shared goals.

From a customer perspective, moving from mass production to mass personalisation and customisation is key to Industry 5.0. Advanced technologies, such as AI and digital twins, enable companies to tailor products and services to individual customer needs, thereby enhancing satisfaction and loyalty. From a system perspective, the bioeconomy focuses on the sustainable production and conversion of renewable biological resources. Bioinspired technologies, driven by the need for clean, affordable, and sustainable energy, promote the symbiosis between ecology, industry, and the economy.

Lastly, Industry 5.0 will positively impact employees by exploring different and alternative job roles and training through reskilling and upskilling. It will improve the quality and health of their working environment through innovative solutions and better organisational governance and ethics. The review identified several critical components supporting the Industry 5.0 framework, including collaborative robots, artificial intelligence, digital twins, the Internet of Things, mixed realities (AR and VR), big data analytics, blockchain, and other emerging technologies. These components collectively advance human-machine interaction, improve operational efficiency, and drive innovation.

The transition to Industry 5.0 presents several challenges, including legal, psychological, regulatory, and social issues. The evolving roles of HR and IT departments will need to address these challenges by fostering a culture that supports human-machine collaboration and continuous learning. Additionally, integration and technological challenges, such as ensuring interoperability between systems and maintaining data security, require robust leadership and strategic planning to address effectively. Industry 5.0 represents a transformative phase in industrialisation, focusing on human-centric, sustainable, and resilient practices. By integrating advanced technologies with human skills, organisations can achieve greater productivity, customisation, and sustainability. The concepts and components identified in this review provide a foundational framework for the successful implementation of Industry 5.0, guiding organisations towards a future where technological developments and human well-being are balanced.

4.5 Conclusion

Industry 5.0 represents a transformative phase in industrialisation, focusing on human-centric, sustainable, and resilient practices. By integrating advanced technologies with human skills, organisations can achieve greater productivity, customisation, and sustainability. The concepts and components identified in this review provide a foundational framework for the successful implementation of Industry 5.0, guiding organisations towards a future where technological advancements and human well-being are harmoniously balanced.

CHAPTER 5 INDUSTRY 5.0 FRAMEWORK

5.1 Introduction

Chapter 5 investigates how the existing maturity assessment identified in Chapter 2 align with the broader Industry 5.0 framework developed in Chapter 4, identifying their strengths and limitations. To improve the comprehensiveness of the Industry 5.0 maturity framework, additional dimensions such as worker perspectives (training, quality, and ethical considerations), system perspectives (bioeconomy), and customer perspectives (personalisation and customisation) are introduced. By synthesising the findings from the scoping review and existing frameworks, this integrated framework captures the technological, human and environmental dimensions necessary for assessing Industry 5.0 adoption. It also provides a basis for evaluating Industry 5.0 maturity in the South African mining industry, ensuring that all relevant aspects are fully considered in the assessment process. Table 5.1 outlines the chapter's structure in relation to the research questions.

Table 5.1: Chapter 5 outline according to research questions & objectives

Research objective	Section	Research question
3. To develop a conceptual Industry 5.0 framework	**Error! Reference source n ot found. Error! Reference source not found.** 5.3 Interview & Analysis Guide	• What is the Industry 5.0 framework?

Figure 5.1 illustrates the study's progress, indicating that it is currently in phase 3 of the 5-phase approach.

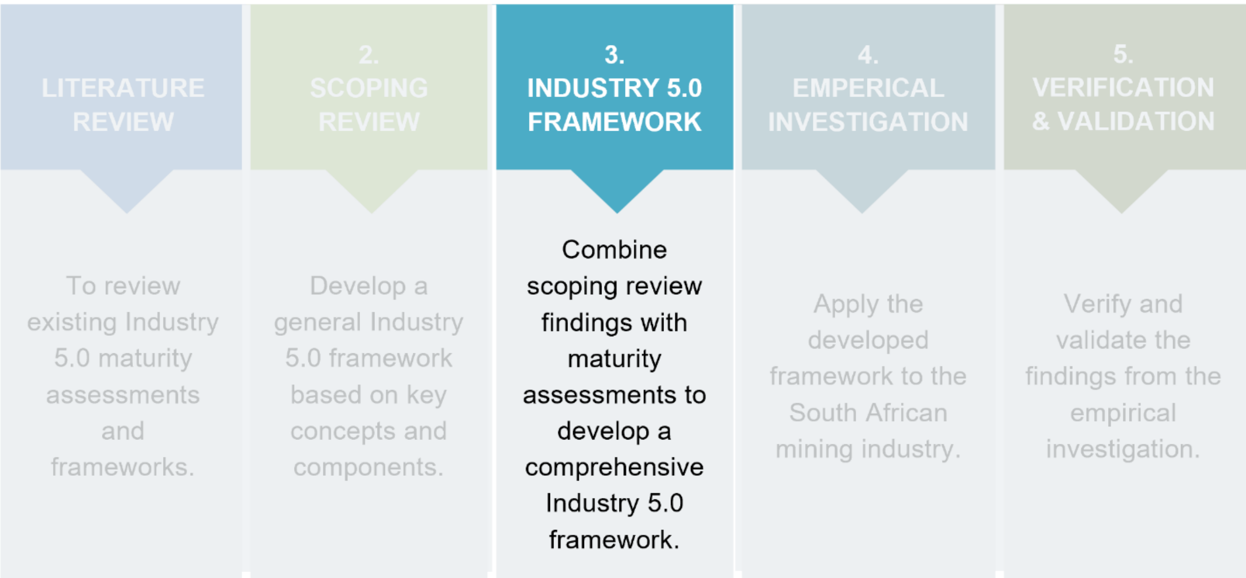

Figure 5.1: Overview of the study's progress: Phase 3/5

5.2 Results

The framework is constructed through a structured five-step process. First, a scoping review is conducted (Phase 2) to extract key Industry 5.0 concepts - such as human-centricity, resilience, and sustainability - which are thematically organised into an initial framework. Second, the maturity model developed by Arta et al. (2024) is selected as a comparison benchmark based on its clarity, dimensional breadth, and relevance to human, technological, and organisational aspects of Industry 5.0. Third, a comparative table maps and analyses the alignment between the scoping review and the maturity model, highlighting conceptual gaps and informing refinements. Fourth, a synthesis step integrates shared and additional elements into a unified framework. Finally, the framework is operationalised through a semi-structured interview guide with linked maturity and importance rating scales, enabling systematic qualitative analysis and cross-case comparison.

Step 1 is addressed in Chapter 4 and visually presented in Figure 4.5. Step 2 is completed in Chapter 2, where the selected maturity model by Arta et al. (2024) is illustrated in Figure 2.3. Step 3, involving the comparative mapping and analysis, is presented in Table 5.2, which aligns each thematic category from the scoping review with the corresponding measurement areas from the maturity model.

Table 5.2: Industry 5.0 framework comparison mapping

Measurement	Categories	
	I5.0 existing maturity assessment	**I5.0 general framework from scoping review**
Human-Centered Design	Main driver and innovative factor for I5.0	Human-Machine Understanding
	Focus on employees	Human-Machine Collaboration
	Holistic Adaptation of the processes and systems to employees	Human-Machine Communication
	Basic requirement for achieving maturity levels for digitalisation and AI	
Resiliency	Stabilisation Policy	Self-Resilience
	Creation of Competitiveness	System Resilience
	Use of Modern Technologies and Approaches	
Sustainability	Implementation of environmental solutions	Ecological
	Business model with sustainable aspects	Economic
	Involvement in strategy planning	Social
	Monitoring of sustainability indicators	Technological
Other		Worker Perspective
		System Perspective
		Customer Perspective

- **Human-Centric**: The general Industry 5.0 framework consists of elements such as Human-Machine Understanding, Collaboration, and Communication, which align closely with the specific assessment areas of Human-Centered Design. The maturity assessment's focus on the role of employees and the holistic adaptation of systems complements the broader understanding of human-machine interactions in the general framework. This alignment indicates a shared emphasis on integrating technology while considering human needs.
- **Resilience**: The general framework's emphasis on Self-Resilience and System Resilience aligns with the specific assessment categories of Stabilisation Policies, Competitiveness, and the application of modern technologies. The inclusion of resilience as both a technological and strategic aspect in the general framework ensures that the focus on stability and

adaptability is well covered, reflecting the need for industries to manage external shocks and maintain continuity.

- **Sustainability**: The general framework integrates economic, social, ecological, and technological aspects of sustainability, corresponding closely to the maturity assessment’s categories, such as environmental solutions, sustainable business models, strategic involvement, and monitoring of sustainability indicators. This alignment highlights a balanced approach, covering both the practical implementation of sustainability initiatives and their broader impacts on society and the environment.

- **Worker Perspective**: The general framework's emphasis on worker-centric aspects, including training, working conditions, and ethics, offers a more comprehensive view of employee well-being and engagement. Integrating these elements into the assessment model ensures that the human dimension of Industry 5.0, particularly related to skills development and quality of work life, is fully considered.

- **System Perspective (Bioeconomy):** Incorporating bioeconomy considerations into the sustainability dimension could strengthen the framework's focus on circular economy principles and environmentally sustainable practices. This would provide a more in-depth evaluation of how organisations are adapting to eco-friendly innovations and resource management.

- **Customer Perspective (Personalisation & Customisation):** While the current maturity assessment does not explicitly address customer-driven customisation, incorporating this element aligns with Industry 5.0's emphasis on personalised products and services. This would enable a better understanding of how organisations are adapting their offerings to meet individual customer needs, thereby improving their competitiveness.

Next, the framework is synthesised and integrated. In this fourth step, aligned categories from the scoping review (Chapter 4) and the Arta et al. (2024) maturity model (Chapter 2) were synthesised into a single, unified Industry 5.0 framework. New dimensions such as worker perspective (training, working conditions, ethics), system perspective (bioeconomy), and customer perspective (personalisation and customisation) were added to strengthen the framework’s scope and contextual relevance to the mining industry.

The outcome of this step is a more comprehensive and multidimensional Industry 5.0 framework that incorporates human-centricity, resilience, sustainability, and emerging perspectives not present in the original model. This integrated framework serves as the theoretical foundation for assessing Industry 5.0 maturity in the empirical phase and is structured to reflect both socio-technical balance and practical applicability.

5.3 Interview & Analysis Guide

For the final and fifth step: operationalisation of the framework, an integrated interview guide was developed, incorporating input from the maturity assessment by Arta (2024) and additional elements identified through the scoping review. This is based on the synthesised framework discussed in section 5.2 Results. This guide aligns each framework category and item with targeted, open-ended questions aimed at eliciting detailed insights from participants across the South African mining sector. Optional follow-up prompts accompany each question to support depth and consistency while allowing for contextual elaboration, as exhibited in Table 5.3.

Table 5.3: Developed interview guide

Measurement Categories		Question	Item
General		What is your role? How long have you been in the mining industry?	
Human centered Design	1	Can you describe how collaboration between employees and new technology currently happens in your organisation? What efforts have been made to improve this collaboration? Follow-up: What challenges have you faced in integrating new technology with employee roles? How important is this item?	Main driver and innovative factor for I5.0
	2	How does your organisation consider and respond to the needs of employees when implementing new technologies? Follow-up: How do you ensure that technology is adapted to suit the workers' needs rather than the other way around? How important is this item?	Focus on employees
	3	Can you describe how your organisation assesses the relationship between employees and new technologies? Follow-up: What steps have been taken to identify skill gaps and adapt systems or processes to support employees in collaborating effectively with new technologies? How important is this item?	Holistic adaptation of the processes and systems to employees
	4	What supporting technologies (such as big data, AI) has your organisation implemented to facilitate digitalisation? Follow-up: How have these technologies impacted your organisation's readiness for Industry 5.0? How important is this item?	Basic requirement for achieving maturity levels for digitalisation and AI

Resiliency	5	Does your organisation have a stabilisation policy to manage market fluctuations? How is it structured? Follow-up: How does this policy contribute to the resilience of your organisation in the context of Industry 5.0? How important is this item?	Stabilisation policy
	6	How aware is your organisation of Industry 5.0 concepts, and how are they integrated into your strategy? Follow-up: What steps are you taking to leverage Industry 5.0 for maintaining or improving competitiveness? How important is this item?	Creation of competitiveness
	7	Can you share examples of modern technologies or approaches your organisation is using in its manufacturing processes? Follow-up: How well integrated are these technologies, and what benefits or challenges have you experienced? How important is this item?	Use of modern technologies and approaches
Sustainability	8	How does your organisation address environmental and societal issues in its operations? Follow-up: What specific initiatives have been taken to align with sustainability goals, and how successful have they been? How important is this item?	Implementation of environmental solution
	9	Question: What sustainability goals does your organisation have, and how do they influence your business model? How do your employees and stakeholders perceive the effectiveness of these sustainability efforts? How important is this item?	Business model with sustainable aspects
	10	How is your organisation involved in strategy planning related to sustainability, and how does it ensure compliance with regulations? Follow-up: How do you review and measure the success of your sustainability strategies? How important is this item?	Involvement in strategy planning
	11	What indicators does your organisation use to monitor sustainability, and how are they reviewed? Follow-up: How do you ensure that these indicators align with your long-term sustainability goals? How important is this item?	Monitoring of sustainability indicators
Worker Perspective	12	What training programs does your organisation offer to employees, particularly concerning Industry 5.0 skills? Follow-up: How are these programs integrated into your operations, and how do they impact employee adaptability? How important is this item?	Training & development
	13	How does your organisation approach improving working conditions and maintaining ethical standards? Follow-up: How are these efforts aligned with the principles of Industry 5.0, and what results have you observed? How important is this item?	Working conditions and ethical standards

System Perspective	14	How aware is your organisation of bioeconomy principles, and how have they been applied in your operations? Follow-up: What impact has the integration of these principles had on your sustainability practices and innovation? How important is this item?	Bioeconomy principles
Customer Perspective	15	How does your organisation approach personalisation and customisation in its products or services? Follow-up: How do you leverage Industry 5.0 technologies to meet customer-specific needs, and what challenges have you encountered? How important is this item?	Personalisation & customisation

To enable structured qualitative analysis and cross-case comparison, a four-level Likert-type scale is applied to each framework item, capturing both maturity and perceived importance. The maturity scale descriptors, adapted from Arta et al. (2024), are refined and extended to fit the expanded framework, ensuring that each dimension, including newly added categories on worker, system, and customer perspectives, can be assessed with clarity and consistency. This process results in a detailed interview and analysis guide, presented in the next section. Responses are categorised into predefined levels of the Likert scale (e.g., "Strongly Disagree" to "Strongly Agree") with a corresponding numerical value to provide measurable data. For example, a theme might indicate a respondent's overall satisfaction, which could be rated on a Likert scale, as shown in Figure 5.2 and Figure 5.3.The scale is specific to each item in the framework.

To comprehensively capture the socio-technical dimensions of Industry 5.0 beyond those assessed in existing models, three new measurement categories, Worker Perspective, System Perspective, and Customer Perspective, are added to the framework. As no pre-existing maturity descriptors were available for these categories in Arta et al. (2024), the author developed four-level maturity scales for each based on the general maturity modelling principles established in Figure 5.2.

1. Awareness but no implementation
2. Initial adoption in isolated areas
3. Significant integration with room for further optimisation
4. Full integration and continuous improvement

Figure 5.2: Example maturity level Likert scale

The following scale is used to determine the importance of each factor.

1. **Not Important:** The factor has little to no significance in achieving Industry 5.0 goals
2. **Somewhat Important:** The factor plays a minor role in supporting Industry 5.0, but is not critical
3. **Important**: The factor is significant and contributes to the successful implementation of Industry 5.0
4. **Very Important:** The factor is essential and crucial for the full realisation of Industry 5.0

Figure 5.3: Importance level Likert scale

The interview maturity analysis guide is presented in Table 5.4.

Table 5.4: Maturity level analysis guide (Arta *et al.*, 2024)

Measurement Categories	Nr	Item	Level 1	Level 2	Level 3	Level 4
Human centered Design	1	Main driver and innovative factor for I5.0	No collaboration between employees and new technology.	The company is trying to make collaboration between employees and new technology	The employees can collaborate with the new technology or robots	Collaboration between employees and new technology is already running well
	2	Focus on employees	No improvement in technology and study the needs of employees.	The company has started to improve to maximise technology and study the needs of employees	The company has developed technology enhancements to understand the needs of employees	The company has been able to recognise what technology can do for the people and focus on how technology can adjust to the requirements of the worker instead of the other way
	3	Holistic adaptation of the processes and systems to employees	No study about relation between employees and new technology	Trying to study the skill gap between each employee to build a good adaptation between employees and new technology	Have been able determine the skills gap between employees and new technology, so the company able to make forecast the skills needs	Provide training for every skill requirement to build good collaboration between employees and new technologies in the future
	4	Basic requirement for achieving maturity levels for digitalisation and AI	No supporting technology.	The company has started build some supporting technology, such as big data, network coverage and specialist skills for	The company has developed build some supporting technology, such as big data, network coverage and specialist skills for	The company already have the supporting technology, such as big data, network coverage and specialist skills for

				use new technology in the future	use new technology in the future	use new technology in the future
Resiliency	5	Stabilisation policy	No policy	Policy is taken randomly and reacts to market conditions.	The stabilisation policy has been well-formulated and structured, but it is still focused on reacting to market conditions. There is no clear long-term strategy.	The stabilisation policy has been well integrated into the overall economic policy and has been carried out in a proactive and effective manner. There is a continuous evaluation and improvement mechanism to increase the effectiveness of the stabilisation policy.
	6	Creation of competitiveness	The company is not aware of the Industry 5.0.	The company start to aware of the definition and concept of Industry 5.0.	The company has developed a strategy to leverage Industry 5.0 for competitiveness, but it is not yet fully integrated into its operations.	The company has fully integrated Industry 5.0 into its strategy and operations, and it regularly measures and manages its performance in this area.
	7	Use of modern technologies and approaches	No modern technologies or approaches are used in manufacturing processes.	The company start to study modern technologies or approaches to be used in manufacturing processes.	A few modern technologies and approaches are used, and their integration into the manufacturing process is improving.	Most modern technologies and approaches are used in the manufacturing process, and their integration is highly

					However, they are still used in isolation from each other.	cohesive and optimised. However, there is still room for improvement and refinement.
Sustainability	8	Implementation of environmental solution	The organisation has no awareness of environmental and society issue.	Organisation only give donations as a philanthropy	The organisation makes activities based on their stakeholder demand (CSR) Several programs are done to solve the sustainability issue in society	The organisation integrates all of their activities and culture to achieve business goals and sustainability goals
	9	Business model with sustainable aspects	No sustainability goals.	Company has a bad image in society. Employees do not know about the company's sustainability goals	The organisation feels it has tried to give the best benefit to the employee, but the employee does not feel any benefit from conducting sustainability. Some of the employees know the company's sustainability goals	The organisation has a good image in society The organisation has made a work-life balance working style, and the employees are loyal. All of the employee knows the company's sustainability goals and Make it a culture

	10	Involvement in strategy planning	No regulations are met	Fulfilment of regulations is done by reactive There are no top management commitments to achieve sustainability goals	All of the regulations are identified and fulfilled. The company has a PIC to form a relationship with the government to update the regulations. The Organisation has a commitment to achieve sustainability goals, but there is no review of the achievement	The Organisation is an active member of the association to develop regulations. The Organisation's goals have been synchronised with the government's goals regarding sustainability. The Organisation reports the achievement of its sustainability goals to all stakeholders annually.
	11	Monitoring of sustainability indicators	No perspective on sustainability indicators.	The organisation only has economic perspective indicators to review their achievement. Organisations are not conducting regular reviews of their indicators	The organisation has two perspective indicators: economic and social/environment The organisation is already defined and can be calculated, but it is still not synchronised with its sustainable goals.	All of the indicators meet triple bottom-line perspectives. An indicator review is conducted regularly, and a corrective action report is generated when the achievement falls below the targeted level to ensure it remains aligned with company goals.
Worker Perspective	12	Training & Development	No training programs or development plans are in place for employees.	Basic training programs are available, but not aligned with Industry 5.0 requirements.	Training programs are regularly updated to include Industry 5.0 skills, but are not fully integrated into the company's operation.	Comprehensive training programs are fully integrated, regularly updated, and aligned with Industry 5.0, focusing on enhancing

						employee skills and adaptability.
	13	Working conditions and ethical standards	No initiatives to improve working conditions and ethics	Some initiatives have been made to improve working conditions and ethics, but they are not systematic or aligned with Industry 5.0.	Working conditions and ethical standards are improved through focused initiatives, but there is still room for them to be aligned with Industry 5.0 requirements.	Working conditions and ethical standards are fully integrated into the company's culture, with continuous improvements in line with Industry 5.0 principles.
System Perspective	14	Bioeconomy principles	No awareness and minor applications of bioeconomy principles	Initial awareness and minor applications of bioeconomy principles, but not systematically integrated.	Bioeconomy principles are applied in some areas of operation, but integration into the overall system is partial	Bioeconomy principles are fully integrated into the company's operations, driving sustainable practices and innovation.
Customer Perspective	15	Personalisation & Customisation	No attempts at personalisation or customisation.	Basic attempts at personalisation or customisation, but not effectively integrated or aligned with Industry 5.0 capabilities.	Products and services are partially personalised or customised, with ongoing efforts to align with Industry 5.0	Full integration of personalisation and customisation into the company's offerings, leveraging Industry 5.0 technologies to meet customer-specific needs.

5.4 Conclusion

In conclusion, Chapter 5 provides a structured synthesis of Industry 5.0 frameworks and assessments, identifying the key components and concepts critical to the new industrial paradigm. The analysis reveals that the existing maturity assessment aligns well with the broader Industry 5.0 framework, providing a foundation for evaluating readiness. However, to ensure a more comprehensive evaluation, additional categories such as worker perspectives (training, quality, and ethical considerations), system perspectives (bioeconomy), and customer perspectives (personalisation and customisation) are incorporated. These concepts were further examined with enabling technologies like collaborative robots, AI, digital twins, IoT, big data, mixed realities, blockchain and 5G & beyond. The synthesis of the scoping review findings, combined with existing frameworks, informs the development of an Industry 5.0 framework that provides a holistic approach to assessing the progress of Industry 5.0 adoption. This framework will serve as a basis for evaluating Industry 5.0 maturity in the South African Mining Industry.

CHAPTER 6 RESULTS AND DISCUSSION

6.1 Introduction

The results and discussion chapter presents a comprehensive evaluation of the Industry 5.0 framework within the South African mining sector, focusing on maturity and importance levels across various dimensions, including human-centered design, resiliency, sustainability, and worker, system, and customer perspectives. In section 6.3, an analysis of the Maturity vs. Importance matrix and weighted calculations is used to identify gaps between the perceived significance of Industry 5.0 principles and their implementation maturity. Then, in section 6.4 based on the empirical results, conclusions are made regarding challenges and opportunities that the sector is facing while offering critical insights into how technologies, strategies, and organisational structures align with the goals of Industry 5.0. The discussion further contextualises the findings, offering targeted recommendations to bridge identified gaps and promote sustainable, human-centric growth. Table 6.1 outlines the structure of the chapter according to the research questions.

Table 6.1: Chapter 6 outline according to research questions & objectives

Research objective	Section	Research question
4. To assess the current level of Industry 5.0 adoption in the South African mining industry.	6.3 Results	What is the current state of the Industry 5.0 application in the South African mining industry? Which concepts have been adopted? What components (enabling technologies) have been adopted?
5. To identify the challenges and barriers hindering the transition towards Industry 5.0 within the sector.	6.4 Discussion	What are the main challenges in adopting Industry 5.0 concepts and components?
6. To generate strategic recommendations for industry leaders and policymakers to support and accelerate the transition to Industry 5.0.	6.4 Discussion	What recommendations can be made to support the South African mining industry?

Figure 6.1 illustrates the study's progress, indicating that it is currently in phase 4 of the 5-phase approach.

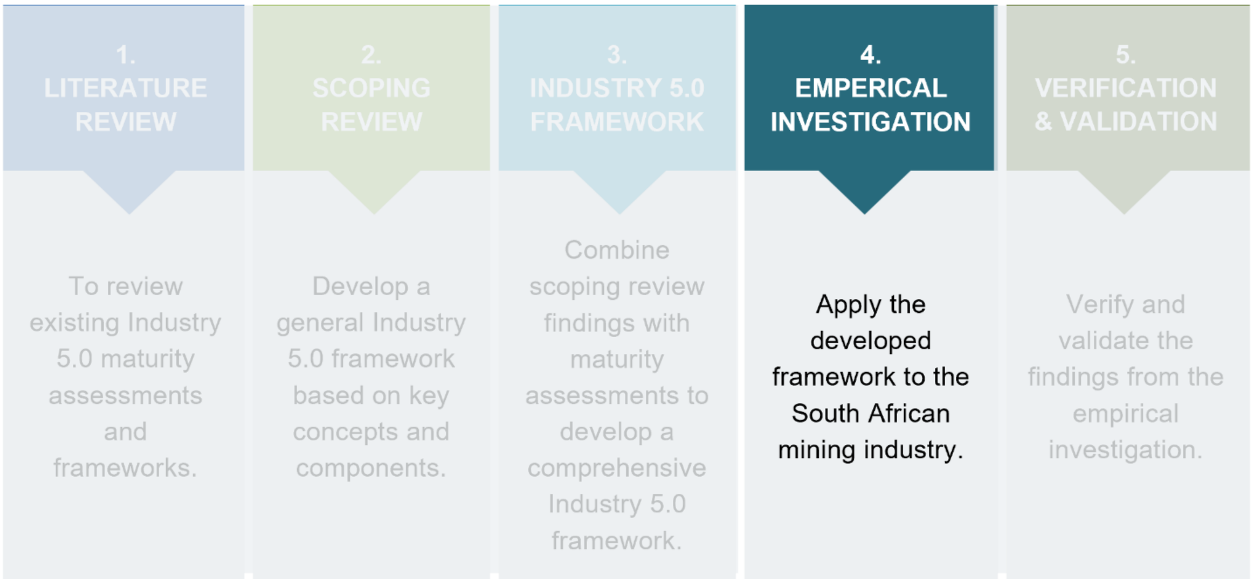

Figure 6.1: Overview of the study's progress: Phase 4/5

6.2 Method

The results presented in this chapter were generated through a structured analysis process adapted from Miles et al. (2014) and Onwuegbuzie & Combs (2010) and described in the methodology outlined in Chapter 3. The process began with the definition of a priori themes, which were developed from existing maturity assessments and findings from the scoping review. These themes formed the initial coding structure for the study. This was followed by qualitative data collection, primarily through semi-structured interviews. The third step involved coding the data using the predefined themes.

In the fourth step, the coded responses underwent quantitising using a four-level maturity scale. This involved assigning numerical values (Levels 1 – 4) to responses based on how well they aligned with the maturity descriptions established in the framework and interview guide. Once coded and converted to numerical data, the data were then organised into matrices, enabling systematic display by case and theme and allowing occurrences and intensities to be easily examined.

In the sixth step, patterns and trends were identified across cases and themes. This was followed by a visual analysis, which involved the use of descriptive statistical tools, such as radar diagrams and box plots, to present and compare the results. Finally, in the interpretation phase, the quantitative patterns were combined with qualitative insights, allowing for an understanding that reflects both the depth of individual responses and the structure provided by the maturity framework. This approach ensures that the results are both credible and analytically robust.

6.3 Results

Step 1: Define a priori themes

The themes (categories) and codes (items) were established in Chapter 5 and are listed in Table 6.2. The maturity descriptors used to determine the Likert scale are shown in Table 5.4.

Table 6.2: List of themes and codes used in interview analysis

Theme (Category)	Code (Item)
Human-Centered Design	Main driver and innovative factor for I5.0 Focus on employees Holistic Adaptation of the processes and systems to employees Basic requirement for achieving maturity levels for digitalisation and AI
Resiliency	Stabilisation Policy Creation of Competitiveness Use of Modern Technologies and Approaches
Sustainability	Implementation of environmental solutions Business model with sustainable aspects Involvement in strategy planning Monitoring of sustainability indicators
Worker Perspective	Training & development Working conditions and ethical standards
System Perspective	Bioeconomy principles
Customer Perspective	Personalisation & customisation

Step 2: Data collection

To address the research aim of evaluating the South African mining industry's transition toward Industry 5.0, the study engaged with a strategically selected group of industry professionals using a convenience and snowball sampling strategy. A total of 10 participants contributed to the study, each bringing extensive experience and insight from their roles in large mining operations, technology innovation divisions, and contract mining services.

All participants hold senior-level or executive positions within their organisations and have direct involvement in technology adoption, innovation strategy, or workforce digitalisation, making them highly relevant to the research objectives. The cohort includes individuals responsible for digital strategy development, Information and Communication Technology (ICT) infrastructure, innovation leadership, and technical systems integration. Notably, participants had between 10 and 40 years of industry experience, with the majority exceeding 20 years, underscoring the depth of expertise represented among them.

To maintain confidentiality and uphold ethical standards, specific identifiers, such as names, exact job titles, and company names, have been anonymised. Roles have been generalised by function and level of responsibility. This approach ensures participant anonymity while still demonstrating the credibility, seniority, and strategic alignment. Table 6.3 summarises the thresholds for each size category in the mining and quarrying sector, as per the National Small Business Act and related guidelines (Zulu, 2019):

Table 6.3: Extraction of "The new National Small Enterprise Act thresholds or defining enterprise size classes by sector using two proxies" (Zulu, 2019)

Sector	Category	Employees (max)	Turnover (max)	Asset Value (max)
Mining and Quarrying	Micro	5	R0.20m	R0.10m
	Very Small	20	R4m	R2m
	Small	50	R10m	R6m
	Medium	200	R39m	R23m
	Large	Above 200		

Organisational size in this study was classified primarily based on the number of employees, in alignment with the thresholds outlined by the South African National Small Enterprise Act (Act No. 102 of 1996, as amended) (Zulu, 2019). The following categories were applied:

- Micro: 0–10 employees
- Small: 11–50 employees
- Medium: 51–250 employees
- Large: More than 250 employees.

An overview of the participant characteristics is provided in Table 6.4, the Anonymised Participant Profile.

Ownership was categorised as either local or multinational, depending on the location of company headquarters. Local companies are those founded and primarily controlled within South Africa, whereas multinational companies operate across borders and are controlled from outside the country. Furthermore, the relevance of each participant to the study objectives is briefly described.

Table 6.4: Anonymised Participant Profile Table

Participant number	Role level (Generalised)	Years of experience	Relevance to study objectives	Company size	Type of company ownership
1	Executive – Digital Strategy	10	Leads digital transformation strategy	Large	Multinational
2	Senior Project Leader	26	Oversees operational project execution	Large	Local
3	External Industry Consultant	40	Provides cross-sector insights on technology adoption	Large	Multinational
4	Managing Director	28	Drives innovation in mining systems	Medium	Local
5	Systems & Engineering Lead	27	Manages engineering and maintenance technologies	Large	Multinational
6	Executive – Information and Communication Technology	23	Guides Information and Communication Technology integration across the group	Large	Local
7	Executive – Innovation	12	Leads the adoption of Industry 5.0 technologies	Large	Local
8	Department Head – Innovation	11	Responsible for systems innovation implementation	Medium	Local
9	Senior Industrial Engineer	15	Involved in process optimisation projects	Large	Multinational
10	Training & Human Resource Systems Lead	27	Leads workforce training in digital systems	Large	Multinational

Step 3: Coding the data & Step 4: Quantitising

Each participant's response was evaluated against a predefined maturity scale (ranging from Level 1 to Level 4), based on how effectively the organisation addressed both social and technical aspects of Industry 5.0 readiness. This approach enabled the creation of a structured and quantifiable dataset from qualitative input, allowing the use of statistics to identify patterns, maturity gaps, and imbalances between technical progress and social capability. These insights, grounded in the STS framework, were essential for evaluating the integrated readiness of organisations transitioning towards Industry 5.0.

Each transcript was read in full to familiarise oneself with the data before systematically applying the codes to segments of text relevant to each item under the six main themes (Human-Centric Design, Resilience, Sustainability, Worker Perspective, System Perspective, Customer Perspective) and their respective items in each theme. The qualitative insights were then evaluated against the four-level maturity descriptors for each code, enabling the assignment of Likert-type ratings (1 = Low Maturity to 4 = High Maturity). This structured transformation of qualitative data into quantitative maturity scores ensured comparability while retaining alignment with the framework. Table 6.5 demonstrates how qualitative interview data were systematically analysed using the predefined Industry 5.0 framework. Similarly, the same process was followed to evaluate the importance of the item within the framework, as shown in Table 6.6.

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Table 6.5 Coding and Theme Maturity Analysis Excerpt

Nr	Question	Quote/Excerpt	Code Assigned	Theme	Maturity Level Assigned (1–4)	Maturity Level Nr Description
P3	How does your organisation consider and respond to the needs of employees when implementing new technologies? Follow-up: How do you ensure that technology is adapted to suit the workers' needs rather than the other way around? How important is this item?	"Need starts with the question, how do we increase production? There are pockets of excellence within the company, but it starts with technological needs and not the needs of the workers."	Focus on employees	Human-Centric Design	2	The company has started to improve to maximise technology and study the needs of employees
P6	Can you share examples of modern technologies or approaches your organisation is using in its manufacturing processes? Follow-up: How well integrated are these technologies, and what benefits or challenges have you experienced?	Technologies such as AI, big data, IoT sensors, and digital twins are actively used. AI is applied to equipment monitoring and predictive maintenance, allowing faster decision-making. However, challenges remain in terms of managing data influx, integrating systems, and fully leveraging advanced technologies such as blockchain. In the traditional method of underground monitoring, you would have your PLC and SCADA networks installed underground for ventilation and pumping purposes. That info would be collected on the surface, where someone would analyse it at the end of every shift and provide feedback. Now, through big data, AI, and digitalisation, it enables management to make faster decisions. Another use case: an engineer would conduct daily inspections; however, now we have real-time data in control rooms, allowing us to perform behavioural analysis and predictive analysis.	Use of modern technologies and approaches	Resiliency	3	A few modern technologies and approaches are used, and their integration into the manufacturing process is improving.

Table 6.6: Coding and Theme Importance Analysis Excerpt

Nr	Question	Quote/Excerpt	Code Assigned	Theme	Importance Level Assigned (1–4)	Importance Level Nr Description
P3	How does your organisation consider and respond to the needs of employees when implementing new technologies? Follow-up: How do you ensure that technology is adapted to suit the workers' needs rather than the other way around? How important is this item?	"Need starts with the question, how do we increase production? There are pockets of excellence within the company, but it starts with technological needs and not the needs of the workers."	Focus on employees	Human-Centric Design	4	Very important: The factor is essential and crucial for the full realisation of Industry 5.0
P6	Can you share examples of modern technologies or approaches your organisation is using in its manufacturing processes? Follow-up: How well integrated are these technologies, and what benefits or challenges have you experienced?	Technologies such as AI, big data, IoT sensors, and digital twins are actively used. AI is applied to equipment monitoring and predictive maintenance, allowing faster decision-making. However, challenges remain in terms of managing data influx, integrating systems, and fully leveraging advanced technologies such as blockchain. In the traditional way of monitoring underground, you would have your PLC and SCADA networks for ventilation and pumping underground. That info would be collected on the surface, where someone would analyse it at the end of every shift and provide feedback. Now, through big data, AI, and digitalisation, it enables management to make faster decisions. Another use case: an engineer would conduct daily inspections; however, now we have real-time data in control rooms, allowing us to perform behavioural analysis and predictive analysis.	Use of modern technologies and approaches	Resiliency	3	Important: The factor is significant and contributes to the successful implementation of Industry 5.0

Step 5: Data display, Step 6: Pattern recognition and Step 7: Visual analysis

This section focuses on three distinct sections of analysis, which are structured as follows in Table 6.7. The results are divided into three sections: analysis of each individual item, analysis of each category, and, lastly, analysis of each weighted category.

Table 6.7: Empirical results structure and outline

Section			
6.3.1 Analysis of each individual item		**6.3.2 Analysis of each category**	**6.3.3 Analysis of weighted category**
Item		**Category**	**Weighted category**
1	Main driver and innovative factor for I5.0	a. Human centered design	$Y_{Human\ centered\ design}$
2	Focus on employees		
3	Holistic adaptation of the processes and systems		
4	Basic requirement for achieving maturity levels for digitalisation and AI		
5	Stabilisation policy	b. Resiliency	$Y_{Resiliency}$
6	Creation of competitiveness		
7	Use of modern technologies and approaches		
8	Implementation of environmental solution	c. Sustainability	$Y_{Sustainability}$
9	Business model with sustainable aspects		
10	Involvement in strategy planning		
11	Monitoring of sustainability indicators		
12	Training & development	d. Worker perspective	$Y_{Worker\ perspective}$

13	Working conditions and ethical standards		
14	Bioeconomy principles	e. System Perspective	$Y_{System\ perspective}$
15	Personalisation & customisation	f. Customer Perspective	$Y_{Customer\ perspective}$

6.3.1 Analysis of each individual item

The ratings presented in Table 6.8 are derived from systematically coded interview transcripts, where each participant's response was assessed against the predefined codes and aligned with the maturity descriptors and importance levels. These ratings represent a quantification of qualitative data, ensuring consistency with the framework that has been developed. Table 6.8 presents the importance and maturity scores assigned to each item by individual participants. This data is further analysed by calculating the average maturity and importance levels for each item.

Table 6.8: Importance & maturity level assigned to each item

Item		Importance /Maturity Level	Participant										
			1	2	3	4	5	6	7	8	9	10	Ave
1	Main driver and innovative factor for I5.0	Importance	4	4	3	3	3	3	4	4	4	4	3,6
		Maturity	4	1	2	2	2	2	2	2	2	3	2,2
2	Focus on employees	Importance	4	3	4	4	3	4	4	4	4	4	3,8
		Maturity	2	1	1	3	1	2	2	2	1	3	1,8
3	Holistic adaptation of the processes and systems	Importance	4	4	3	4	2	3	3	4	3	4	3,4
		Maturity	2	1	2	2	1	2	1	2	1	2	1,6
4	Basic requirement for achieving maturity levels for digitalisation and AI	Importance	3	4	4	4	4	3	2	4	4	4	3,6
		Maturity	3	2	2	3	2	3	2	3	3	3	2,6
5	Stabilisation policy	Importance	3	3	3	3	2	3	3	4	2	3	2,9
		Maturity	1	2	2	3	2	3	4	2	2	3	2,4

6	Creation of competitiveness	Importance	4	4	4	4	3	4	4	3	1	2	3,3
		Maturity	3	3	2	2	3	3	3	2	2	2	2,5
7	Use of modern technologies and approaches	Importance	3	3	3	3	2	3	2	4	4	4	3,1
		Maturity	3	3	3	3	2	3	3	4	3	3	3
8	Implementation of environmental solution	Importance	4	3	4	4	4	4	4	3	2	4	3,6
		Maturity	3	1	2	3	3	3	3	3	3	3	2,7
9	Business model with sustainable aspects	Importance	4	3	3	4	3	4	3	3	3	3	3,3
		Maturity	3	2	2	3	2	3	3	2	2	3	2,5
10	Involvement in strategy planning	Importance	4	4	3	3	4	4	3	4	4	4	3,7
		Maturity	3	3	3	3	3	3	3	3	3	3	3
11	Monitoring of sustainability indicators	Importance	4	4	4	3	3	3	2	4	3	4	3,4
		Maturity	3	3	3	2	2	3	3	3	3	3	2,8
12	Training & development	Importance	4	4	4	4	3	3	4	3	3	3	3,5
		Maturity	2	4	2	3	2	3	2	4	2	4	2,8
13	Working conditions and ethical standards	Importance	4	3	3	4	3	3	4	4	4	3	3,5
		Maturity	3	3	3	3	3	2	3	3	2	3	2,8
14	Bioeconomy principles	Importance	3	4	3	4	3	3	3	3	3	3	3,2
		Maturity	3	3	2	2	3	2	3	2	1	1	2,2
15	Personalisation & customisation	Importance	4	4	2	3	2	3	3	4	1	4	3
		Maturity	2	2	1	2	2	2	2	2	1	1	1,7

The graph in Figure 6.2 visualises the relationship between the average maturity and importance of various items within the Industry 5.0 framework. Each coloured point represents an individual item, with the x-axis denoting "Importance" and the y-axis denoting "Maturity" on a scale from 1-4 as defined:

- Maturity level analysis guide: Table 5.4: Maturity level analysis guide (Arta *et al.*, 2024)

- Importance Likert scale: Figure 5.3: Importance level Likert scale

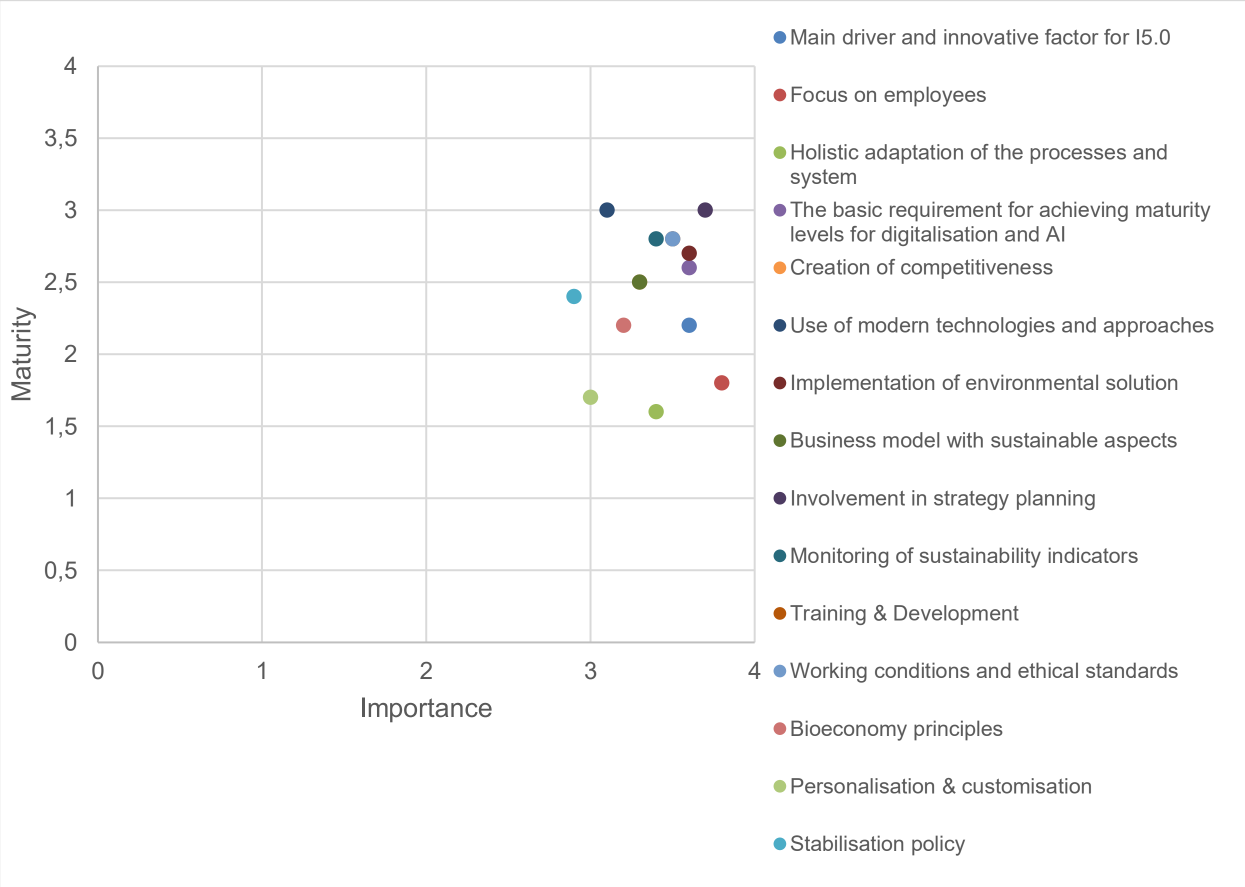

Figure 6.2: Average maturity vs importance for each item

Items such as "Use of modern technologies and approaches" and "Monitoring of sustainability indicators" are rated highly on both maturity and importance, indicating that organisations have recognised their critical role in Industry 5.0 and made significant progress in implementing these areas effectively. Categories such as "Creation of competitiveness" and "Focus on employees" demonstrate high importance but moderate maturity. This suggests that while organisations value these areas, they have yet to fully mature in their execution, indicating the need for further development and investment.

"Holistic adaptation of processes and systems" and "Personalisation & Customisation" are placed lower in terms of maturity and are moderately important, indicating that these areas are still underdeveloped and have not yet reached their full potential in driving Industry 5.0. "Focus on employees" and "Business models with sustainable aspects" are highly important to organisations but exhibit relatively lower maturity, suggesting that despite their importance, there is still room for considerable improvement in how these initiatives are integrated.

Overall, the graph indicates that while many organisations have made strides in adopting modern technologies and sustainability measures, other crucial elements, such as employee focus, system adaptation, and competitive creation, still require more attention to reach optimal maturity. The findings suggest that organisations should prioritise developing these areas to align with their perceived importance and advance their Industry 5.0 maturity.

6.3.2 Analysis of each category

The following analysis looks at the average results for each item grouped according to category and discussed:

Table 6.9: Analysis of categories, outline, and structure

Category	Paragraph	Figure
Human centered design	a	Figure 6.3
Resilience	b	Figure 6.4
Sustainability	c	Figure 6.5
Worker, System & Customer Perspective	d	Figure 6.6

a. Human centered design

Figure 6.3 evaluates the four items within the context of human-centered design. Each axis represents a different aspect of human centred design, scored on a scale from 1.0 to 4.0, where higher values indicate higher maturity.

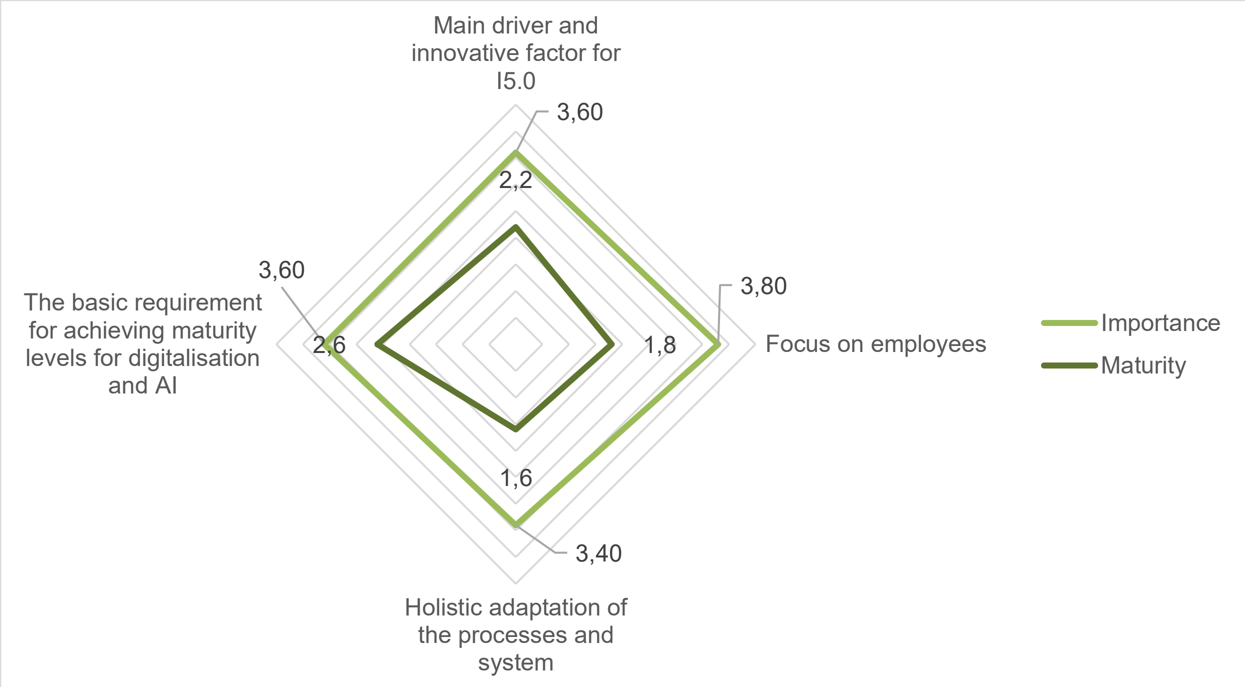

Figure 6.3: Human centered design average maturity & importance level

- **The Main driver and innovative factor for I5.0** reflects how human-centered design is seen as a primary enabler or innovator within Industry 5.0. This aspect is considered highly important (3.6) as a driving factor for Industry 5.0 initiatives. The current maturity level is lower (2.2), indicating that while it is recognised as a key driver, implementation is lagging behind its perceived significance.

- **Focus on employees** has the highest importance rating (3.8), which strongly emphasises prioritising employees' needs and engagement. The maturity level is notably lower (1.8), reflecting a significant gap between its recognised importance and the extent to which these practices have been effectively implemented.

- **The Basic requirement for achieving maturity levels for digitalisation and AI** is considered foundational (3.6) for advancing Industry 5.0. The maturity level of 2.6 shows better progress than other factors, but still indicates room for further development to align with its importance.

- **Holistic adaptation of the processes and system** has a rating (3.4) that suggests integrating a holistic approach into processes is important for improving human-centered design. With a maturity level of 1.6, there is a significant difference, highlighting challenges in fully adapting systems and processes in line with human-centered principles.

Across all factors, the perceived importance exceeds the current maturity levels. This may suggest that while the industry acknowledges the critical role of human-centered design, there are significant challenges or delays in achieving corresponding maturity levels. The most significant gaps are observed in areas such as employee focus and the holistic adaptation of processes, underscoring the need for targeted strategies to enhance employee engagement and better align systems with human-centric goals.

b. Resiliency

Figure 6.4 evaluates the three items within the context of resilience. Each axis represents a different aspect of resilience, scored on a scale from 1.0 to 4.0, where higher values indicate higher maturity.

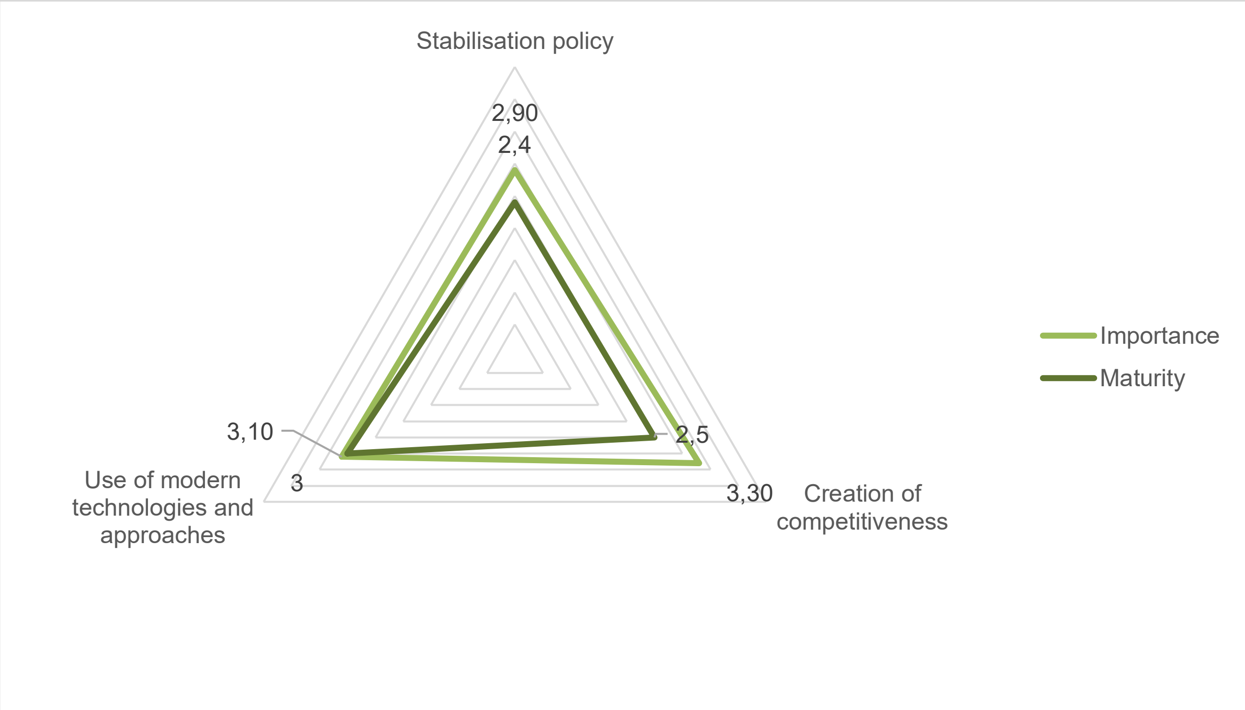

Figure 6.4: Resilience average maturity & importance level

- **The creation of competitiveness** is highly important (3.30) and aligns closely with its maturity (2.5). This suggests that organisations are moderately successful in fostering competitiveness through resilient strategies.

- **Use of modern technologies and approaches** has an importance score of 3.10, with a slightly lower maturity level (2.4). This indicates that while modern technologies are recognised as crucial for resiliency, practical implementation has room for improvement.

- **Stabilisation policy** scores 2.90 for importance but only 2.4 for maturity. This smaller gap shows some effort toward stabilising operations during market fluctuations, but organisations may need to invest further to solidify these policies.

In summary, the graph reflects a moderate alignment between the importance of resiliency measures and their maturity in the industry.

c. Sustainability

Figure 6.5 evaluates the four items within the context of sustainability. Each axis represents a different aspect of sustainability, scored on a scale from 1.0 to 4.0, where higher values indicate higher maturity.

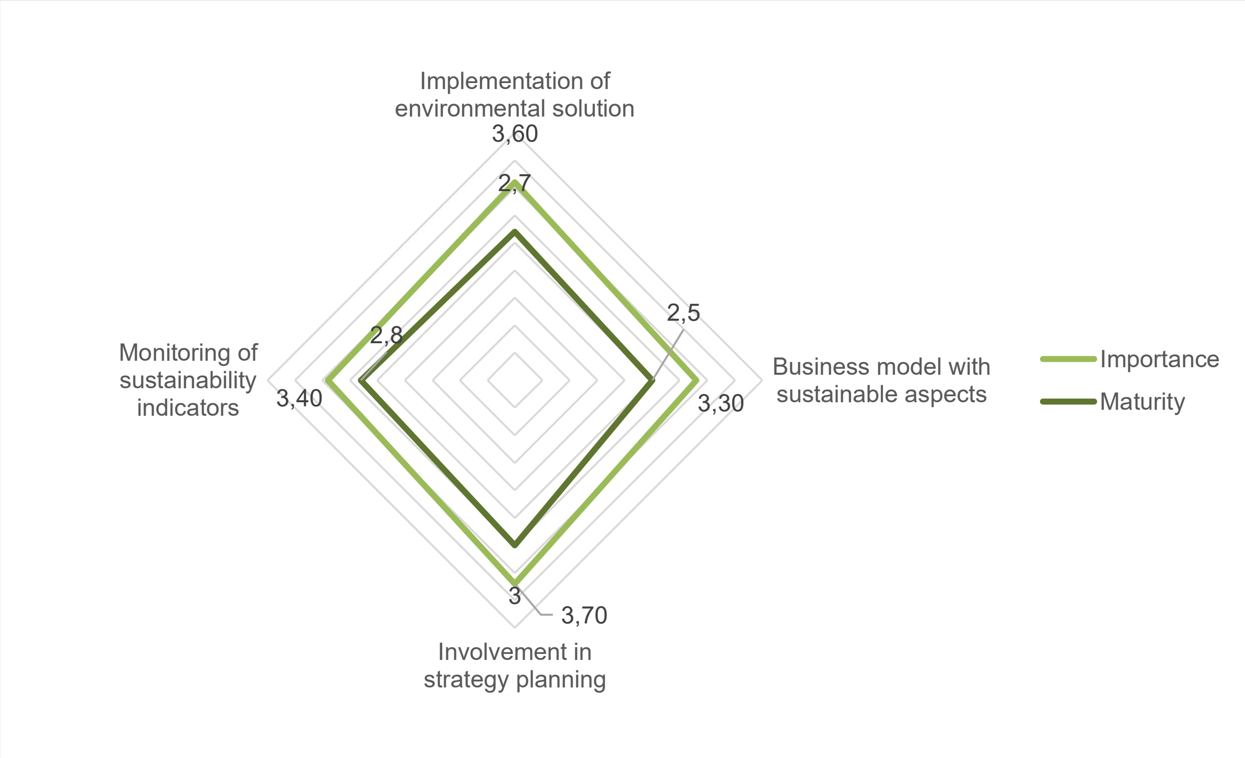

Figure 6.5: Sustainability average maturity & importance level

- **Implementation of environmental solutions** is highly regarded (3.60) but has a lower maturity score (2.7). This suggests that while organisations recognise the need for environmental initiatives, the pace of implementation is lagging.

- **Business model with sustainable aspects** shows a strong focus and importance (3.3) on integrating sustainability into business models. The maturity level (3.5) suggests that organisations have been relatively successful in embedding sustainable practices into their business operations, with a slight maturity advantage over the perceived importance of these practices.

- **Monitoring of sustainability indicators** is considered relatively important (3.40) but has a lower maturity level (2.8), highlighting the need for better systems to track progress.
- **Involvement in strategy planning** has the highest importance rating (3.7), demonstrating the critical role of strategic planning in achieving sustainability goals. The maturity level (3.0) shows a moderate alignment between strategic planning and sustainability efforts. However, there is still room for improvement to fully align practices with the strategic importance placed on this aspect.

The sustainability graph reveals a high emphasis on involvement in strategy planning and implementing environmental solutions. However, the maturity scores suggest that while organisations recognise the importance of these aspects, actual implementation and monitoring efforts are still catching up.

d. Worker, System & Customer perspective

Figure 6.6 evaluates the four items within the context of the worker, system and customer perspectives. Each axis represents a different aspect of sustainability, scored on a scale from 1.0 to 4.0, where higher values indicate higher maturity.

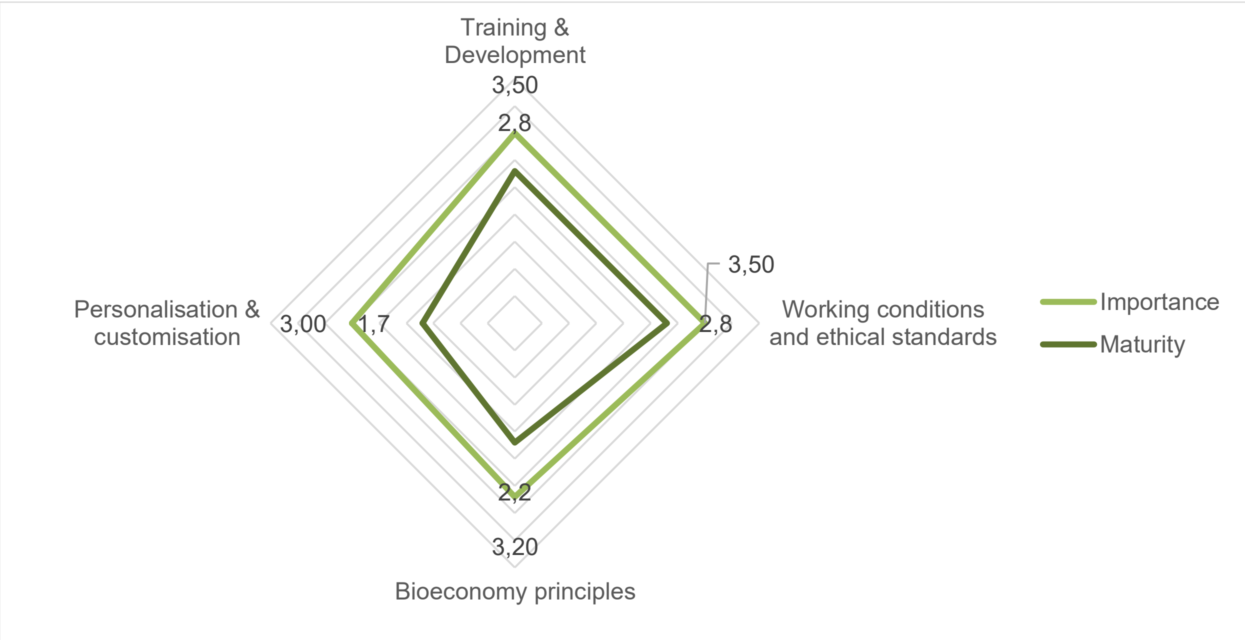

Figure 6.6: Worker, System and Customer perspective average maturity and importance level

- **Training & development** scores highest in importance (3.50) but has a lower maturity level (2.8). This reflects a need for employee training to adapt to Industry 5.0; however, existing efforts may not fully meet these requirements.
- **Working conditions and ethical standards** show a smaller gap between importance (3.00) and maturity (2.8), indicating a more balanced approach to ensuring fair working conditions.
- **Bioeconomy principles** show moderate importance (3.20) but have a lower maturity level (2.2), suggesting challenges in fully integrating bioeconomic strategies within operations.
- **Personalisation & customisation** hold lower importance (3.00) and have the lowest maturity score (1.7), suggesting that organisations may not prioritise tailored solutions for customers and workers.

In conclusion, the graph highlights that while companies place significant value on training, development, and working conditions, implementation efforts vary. The most substantial gaps are evident in training programs and the integration of the bioeconomy.

6.3.3 Analysis of weighted category

The weighted maturity analysis examines how participants assess the progress and importance of key dimensions related to Industry 5.0, such as human-centered design, resiliency, sustainability, and perspectives from the worker, system, and customer viewpoints. The resulting weighted maturity levels highlight areas where organisations are excelling and areas that require further development. The analysis provides insights into how organisations are aligning their strategies with Industry 5.0 and indicates the relative maturity of each category within their operations. The average importance level for each item was determined using the responses from all 10 participants, as shown in Table 6.10.

Table 6.10: Participant importance scores

		Participant Importance score										
Item		1	2	3	4	5	6	7	8	9	10	Ave (Zi)
1	Main driver and innovative factor for I5.0	4	4	3	3	3	3	4	4	4	4	3,6
2	Focus on employees	4	3	4	4	3	4	4	4	4	4	3,8

3	Holistic adaptation of the processes and systems	4	4	3	4	2	3	3	4	3	4	3,4
4	The basic requirement for achieving maturity levels for digitalisation and AI	3	4	4	4	4	3	2	4	4	4	3,6
5	Stabilisation policy	3	3	3	3	2	3	3	4	2	3	2,9
6	Creation of competitiveness	4	4	4	4	3	4	4	3	1	2	3,3
7	Use of modern technologies and approaches	3	3	3	3	2	3	2	4	4	4	3,1
8	Implementation of environmental solution	4	3	4	4	4	4	4	3	2	4	3,6
9	Business model with sustainable aspects	4	3	3	4	3	4	3	3	3	3	3,3
10	Involvement in strategy planning	4	4	3	3	4	4	3	4	4	4	3,7
11	Monitoring of sustainability indicators	4	4	4	3	3	3	2	4	3	4	3,4
12	Training & Development	4	4	4	4	3	3	4	3	3	3	3,5
13	Working conditions and ethical standards	4	3	3	4	3	3	4	4	4	3	3,5
14	Bioeconomy principles	3	4	3	4	3	3	3	3	3	3	3,2
15	Personalisation & customisation	4	4	2	3	2	3	3	4	1	4	3,0

Table 6.11 provides a sample extract from a single participant to illustrate how the weighted maturity calculations were conducted for all the participants.

Table 6.11: Maturity & average importance level for each item for participant A

Category (Ci)		Item (i)		Maturity Level (Mi)	Average Importance (Zi)
1	Human Centered Design	1	Main driver and innovative factor for I5.0	4	3,6
		2	Focus on employees	2	3,8
		3	Holistic adaptation of the processes and systems	2	3,4
		4	Basic requirement for achieving maturity levels for digitalisation and AI	3	3,6
2	Resiliency	5	Stabilisation policy	1	2,9

		6	Creation of competitiveness	3	3,3
		7	Use of modern technologies and approaches	3	3,1
3	Sustainability	8	Implementation of environmental solution	3	3,6
		9	Business model with sustainable aspects	3	3,3
		10	Involvement in strategy planning	3	3,7
		11	Monitoring of sustainability indicators	3	3,4
4	Worker perspective	12	Training & development	2	3,5
		13	Working conditions and ethical standards	3	3,5
5	System Perspective	14	Bioeconomy principles	3	3,2
6	Customer Perspective	15	Personalisation & Customisation	2	3,0

The calculation adapted from Arta (2024) is used to complete the maturity evaluation.

- Y: Weighted maturity level
- M: Maturity level
- C: Category
- I: Item
- Z = Importance level
- N: Number of Maturity Item

Equation (1) is used to calculate a maturity score for a category by considering both the maturity of individual items and their relative importance. The result, Y_C , represents the overall weighted maturity of the category, considering the importance of each item. The detailed calculation is shown for the category **Human centered design** for **Participant A**. Refer to Table 6.11 for the data used in the equation:

$$Y_C = \frac{\sum_{i=1}^{n} M_{CIi} \ \times \ Z_{CIi}}{\sum_{i=1}^{n} Z_{CIi}}$$

$$Y_{Human\ Centered\ Design} = \frac{(M_{I1} \ \times \ Z_{C1}) + ((M_{I2} \ \times \ Z_{C2}) + (M_{I3} \ \times \ Z_{C3}) + (M_{I4} \ \times \ Z_{C4})}{(Z_{C1} + Z_{C2} + Z_{C3} + Z_{C4})}$$

$$Y_{Human\ Centered\ Design} = \frac{(4 \times 3{,}6) + ((2 \times 3{,}8) + (2 \times 3{,}4) + (3 \times 3{,}6)}{(3{,}6 + 3{,}8 + 3{,}4 + 3{,}6)}$$

$$M_{Human\ Centered\ Design} = 2{,}75$$

After the calculations were completed for each participant A–J in each category, the following values were obtained. Table 6.12 presents the weighted maturity scores of each participant for the six categories.

Table 6.12: Weighted maturity levels of each item in a category

Participant	Human centered design	Resiliency	Sustainability	Worker Perspective	System Perspective	Customer Perspective
A	2,75	2,38	3,00	1,93	1,94	2,00
B	1,25	2,69	2,25	2,93	1,94	2,00
C	1,74	2,33	2,51	1,93	1,63	1,00
D	2,51	2,65	2,76	2,43	1,63	2,00
E	1,26	2,35	2,52	1,93	1,94	0,00
F	2,25	3,00	3,00	2,29	1,63	2,00
G	1,76	3,31	3,00	1,93	1,94	2,00
H	2,25	2,67	2,76	2,93	1,63	2,00
I	1,75	2,33	2,76	1,79	1,31	0,00
J	2,76	2,65	3,00	2,93	1,31	1,00

The results reveal diverse maturity levels across various categories, reflecting the complexity and varying focus of Industry 5.0 initiatives among participants. The scores range from relatively high maturity in areas like sustainability, where most participants score near or above 2.50, to lower maturity in systems perspective and customer perspective categories, where scores frequently dip below 2.00.

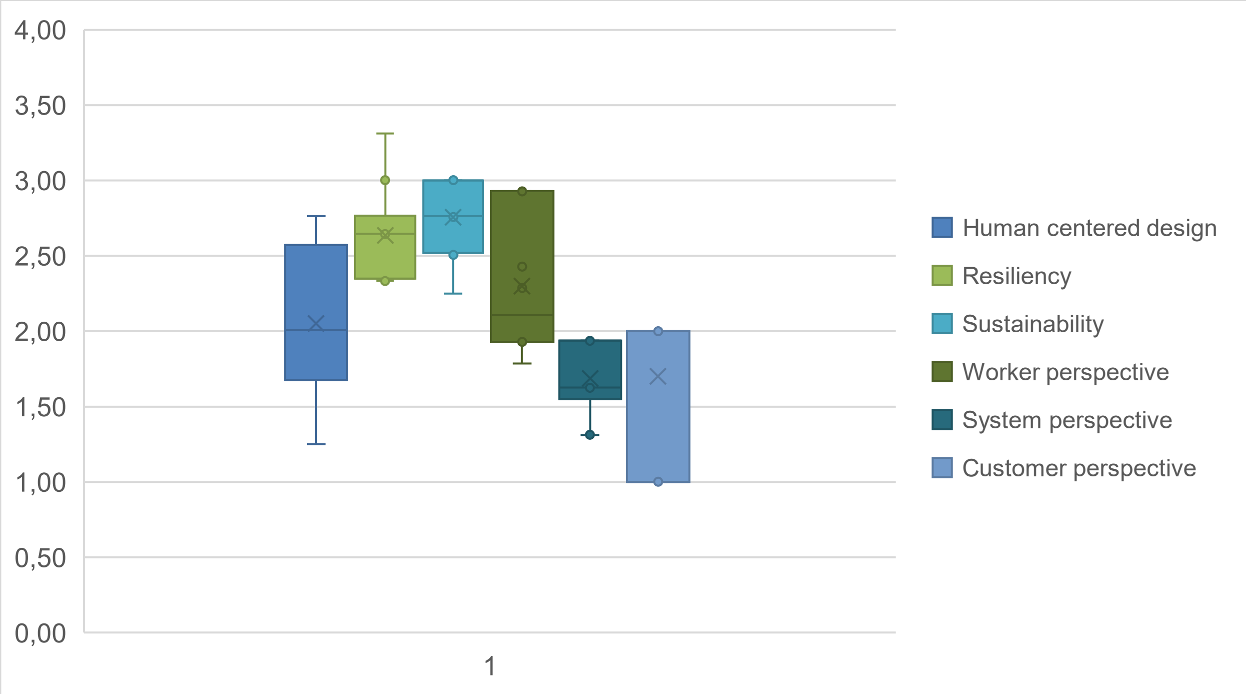

Figure 6.7: Weighted maturity levels for each category

The corresponding boxplot graph visually represents the spread of these maturity levels, with each category depicted separately. For instance, the "Sustainability" category shows consistently high maturity levels, indicating that many organisations are making strong efforts in sustainability-related aspects. On the other hand, categories such as "System perspective" and "Customer perspective" display wider variability and lower overall maturity, suggesting that these areas may require additional attention and development.

The graph also indicates that "Resilience" has a stable maturity level across participants. At the same time, the "Human centered design" shows moderate maturity with some variability, reflecting differing approaches to integrating human-centric principles in Industry 5.0 efforts. The "Worker perspective" also exhibits widespread maturity, indicating room for improvement, particularly in enhancing worker engagement with new technologies.

6.4 Discussion

This section presents a detailed discussion of the study's findings, structured around the key categories and is the final step – step 8: Interpretation of findings and qualitative insights to develop conclusions.. Each category is explored in relation to the specific items it comprises. In addition to analysing the main themes, this section also considers the challenges and opportunities that emerged during the research process. While these were not explicitly included in the original interview questions, participants frequently raised them in response to the questions. These insights, though unprompted, proved valuable in enriching the findings and providing practical depth.

In hindsight, the explicit inclusion of questions specifically targeting perceived challenges and potential opportunities might have elicited even richer, more focused feedback. Nonetheless, their spontaneous emergence underscores their relevance and reinforces their importance within the broader context of Industry 5.0 adoption in the South African mining industry. The discussion that follows aims to provide both critical reflection and synthesis, linking empirical insights with the theoretical foundations of the study. All claims presented in this section are derived from participant responses during the empirical investigation. Direct quotations and thematic summaries are used to reflect participants' views, experiences, and perceptions. No external literature or personal interpretation is introduced unless explicitly stated.

6.4.1 Human centered design

a. Collaboration

Human-centered design is recognised as critical, but its implementation varies significantly across organisations. Human-machine collaboration is evolving slowly in the mining industry due to the labour-intensive nature of deep-level mining, especially in South Africa. Participants indicated that most companies are still operating from an Industry 4.0 mindset, where the technology currently requires little to no human input and decision-making regarding collaboration. Cobots are one of the technologies that have not been consistently implemented in organisations due to their level of complexity and cost.

Collaboration examples include developing a machine learning model that generates recommendations for control room operators to optimise recovery processes. These recommendations have been integrated into Proportional-Integral-Derivative (PID) controllers, providing valuable support to decision-makers. Another example of collaboration between employees and technology is the use of mixed reality, which has been introduced to improve communication and facilitate change management. For example, augmented reality is used on coffee mugs, where scanning the mug reveals an avatar that delivers a message through an AI-generated voice. Additionally, different mugs are assigned to various departments, and to encourage collaboration, when employees interact with each other, the avatars on the mugs also interact. The change management process for these technologies is grounded in neuroscience principles, such as spaced repetition, to ensure effective adoption and implementation.

Typically, change management is seen as a challenge. Participants noted that it is frequently overlooked in technological projects, especially when budgets are tight. It is often the first area to be cut, even though it is critical in ensuring employees can adapt to new technologies. However, organisations that actively involve employees in technology selection and implementation have reported overall better adoption and long-term success through integrated change management processes. For example, one company highlighted its shift from a top-down approach to co-development, where employees are encouraged to participate in creating solutions tailored to their specific challenges. This shift has led to greater ownership of new systems and technologies, resulting in improved adoption rates. Additionally, as companies increasingly adopt digital solutions, particularly in regions like South Africa, where union strikes are a concern, the reality of upskilling the workforce is a challenge. Companies must invest in comprehensive training programs and effective change management strategies to address concerns about job displacement and cultivate a culture of innovation. Transparency and trust are vital in helping employees understand the benefits of automation and how it will improve rather than replace their roles.

b. Worker needs approach

In many cases, adopting new technologies is driven by top-down decisions, with little input from employees at the operational level. Some participants reported that it would start by addressing a business need to increase production, rather than a worker's need, and then be further developed. Industry standards set new technologies, and the Chief Executive Officer (CEO) enforces these technologies. Some organisations reported that they were working on a people-oriented technology adoption tool in collaboration with SATCAP (Successful Application of Technologies Centred Around People), a division of the Mandela Mining Precinct. Some participants reported that it is a combination of top-down and bottom-up approaches. While leaders set the digital agenda, collaboration with younger workers who bring innovative ideas is encouraged. Management would identify a business need (and be better aware of the available solutions), and service providers would conduct in-depth assessments of needs and workers to determine the best way to implement the system or technology. This approach requires input or services from Original Equipment Manufacturers (OEMs) and industry leaders.

However, in most organisations, there is still a gap in ensuring workers understand how these technologies align with their needs. In one specific instance, the operational level readily adopted the changes, but the Head Office was reluctant to do so. An audit at the Head Office level regarding digitalisation revealed a significant disconnect between their perception and what was implemented on-site. This often results in slow adoption, lack of engagement, and the perception that technologies are imposed without consultation.

c. Skill requirements

In terms of skill requirements for workers, one company attempted to create multi-skilled/disciplined operators. However, it was unsuccessful due to the different personalities/interests of each operator. Some participants noted that they conduct skills gap assessments and training needs analyses but often rely on external service providers to carry out these evaluations. Companies with higher maturity levels reported investing heavily in training and development through internal academies located across various regions. These academies offer training on digital and mining-related skills, focusing on equipping employees with Industry 5.0 skills. Another participant reported that they leverage a principle called flex capacity, where they partner with key companies to assist in implementing technologies that they cannot implement in-house. Lastly, some organisations reported initiatives such as a "data citizenship" program, designed to identify potential users of new technologies and provide them with targeted training, ensuring they can effectively leverage these tools.

d. Supporting technologies to facilitate digitalisation

The industry has implemented various supporting technologies to drive digitalisation and improve the worker experience. Some challenges remain in integrating all the solutions across different sites and operations. Key examples and use cases include the following:

- Data structures and AI integration: A few participants noted that the companies had invested heavily in ensuring data accuracy and reliability, laying a strong foundation for AI solutions, IoT, and other automation technologies. Prioritising solid data structures was important before moving towards more advanced technologies such as blockchain, which has yet to be widely implemented in this sector.

- Automation technologies: AI, big data analytics, IoT sensors, and digital twins are used in the plants to improve real-time decision-making. For example, High Graphical Processing (HGP) cameras on conveyor systems analyse material inputs, and the resulting data flows into Supervisory Control and Data Acquisition (SCADA) and Historian systems, integrating with IoT hubs for advanced analytics.

- Logistics improvements: License plate recognition, biometric authorisation, and geofencing, alongside fatigue tracking for truck drivers, improve safety and efficiency in logistics.

- Autonomous operations: Automation has been initiated in operations with self-driving machines, such as drill rigs, while mixed reality technologies are being incorporated into training centres to simulate emergency scenarios and underground experiences for first responders.

- Big Data and safety systems: IoT systems integrated across operations prevent accidents by employing proximity detection systems. Big data is leveraged to generate insights and facilitate predictive analytics.

- Paperless training: One company has transitioned to paperless training processes, digitising employee portfolios and integrating training records into IoT-enabled systems that manage access to ensure compliance with safety protocols.

- AI and predictive maintenance: There are Proof of Concept (POC) projects involving AI for optimising operations and predictive maintenance. Data collected through sensors and stored in data lakes is processed according to international standards (S95) and applied to AI algorithms for insights. Digitalised checklists and condition monitoring further enhance equipment management. One participant noted that they use unstructured CoPilot throughout their entire organisation to equip employees to analyse their data more effectively.

- Advanced decision-making: Previously, underground operations required manual analysis of data collected by Programmable Logic Controller (PLC) and SCADA networks. With big data, AI, and digitalisation, management can make faster, more informed real-time decisions. For example, behaviour analysis and predictive analytics can now be conducted from control rooms, reducing the need for manual inspections.

- Remote monitoring infrastructure: Development of a robust data collection and analysis infrastructure, enabling real-time access across all sites. Remote monitoring centres utilise predictive advisory models, while IoT sensors and digital twin models support operational optimisation. The focus is on practical technologies that provide immediate value, with advanced solutions being introduced in phases.

- Gamified training programs: One company introduced training programs inspired by Pokémon, utilising mixed realities. Digital avatars assist employees through self-service kiosks and training processes, such as leave applications, that have been digitised. Additionally, digital twin models have been employed to gamify the optimisation of plant operations, with winning solutions implemented in actual operations.

- Data and Blockchain: A centralised data lake and business warehouse facilitate big data collection from SAP systems. Blockchain is only used in diamond mining operations, while technologies like 5G and beyond are yet to be implemented due to cost and infrastructure limitations.

While technologies such as AI and IoT are well integrated, some challenges remain in managing the significant input of data, integrating systems across sites, and realising the full potential of advanced technologies like blockchain. Some sites lack the necessary infrastructure to support 5G, and mixed reality is still in the trial phase in some regions. Although Copilot and AI solutions have been rolled out, these efforts remain somewhat fragmented, with uneven access and deployment across operational and administrative levels and a reliance on infrastructure.

In conclusion, while some organisations have made significant strides in digitalisation, further investment is needed in infrastructure to leverage advanced technologies such as blockchain and 5G fully. Additionally, efforts are required to standardise and expand the implementation of AI, IoT, and mixed realities across all operational areas for better integration and effectiveness. Additionally, most participants observed that new technologies are implemented top-down and initiated by business needs rather than worker requirements. The implementation process lacks formal skills analysis and collaboration, highlighting areas for improvement.

e. Challenges & recommendations

Organisations need to adopt a human-centred approach in their technology strategies by involving employees in the early design and implementation stages. A co-development model, where site personnel and operational staff are part of the ideation and solution development process, leads to greater ownership and higher adoption rates, according to the findings. Key challenges related to human-centered design are identified, and recommendations are provided in Table 6.13 .

Table 6.13: Challenges & recommendations for human-centered design

Challenge	Recommendation
The lack of a human-centred approach in technology strategies leads to resistance and low adoption rates.	• Establish cross-functional teams that involve employees at all levels in co-developing practical and beneficial solutions. • Upskill workers to transition from technology users to collaborators. • Conduct thorough needs analyses to address both worker and business requirements effectively.

	• Perform skills gap analyses to ensure workforce readiness for adopting new technologies. • Standardise and reinforce training programs to promote sustainable use of technological solutions. • Implement participatory workshops to gather employee input on technology adoption, reducing resistance to change.
Poor foundational digital infrastructure and legacy systems hinder technological developments	• Allocate resources to upgrading legacy systems and implementing IoT devices and high-speed networks (e.g., 5G). • Establish robust data governance structures to ensure high-quality data inputs and outputs. • Develop a phased digital roadmap starting with data collection and integration before deploying advanced technologies.
Resistance to technology adoption is due to a lack of employee involvement in decision-making processes.	• Create collaborative platforms where employees can contribute ideas and participate in decision-making processes. • Organise innovation challenges to encourage employee engagement and reward impactful ideas.
Resistance to change due to inadequate communication and unclear change management frameworks	• Develop a structured change management framework to communicate the benefits of new technologies and their complementary role. • Deploy change champions across organisational levels to advocate for technology adoption and address employee concerns. • Ensure transparent and consistent communication to improve employee engagement and trust during transitions.

6.4.2 Resiliency

a. Stabilisation policy

The responses regarding market fluctuation stabilisation policies reveal a diverse approach among organisations, with very few mentioning that they have formal stabilisation policies in place. Some companies that do not have a formal stabilisation policy focus on establishing redundancy in supply chains by not relying on a single supplier for critical components. This approach still presents challenges, especially when dealing with OEMs (Original Equipment

Manufacturers). Others have policies in progress, with some already implementing strategies to transition from conventional to mechanised mining. Typical challenges include operator misuse of machinery, which in turn leads to higher machine maintenance costs. To overcome this challenge, they have incentivised the correct usage of machines to reduce cost, changing the mindset of operators to avoid unnecessary costs due to improper usage and handling.

For some, stabilisation is tied to exchange rate management and planning ahead through implementing digital technologies, such as AI and IoT, for scenario planning and real-time monitoring to adapt to changing conditions. Other organisations lack clear strategies and rely heavily on market and commodity prices, which are influenced by supply and demand. Some mitigate this by holding back reserves or negotiating long-term contracts with fixed prices to stabilise their costs.

In industries like mining, which are cyclical, companies have diversified operations to include multiple commodities such as gold, lithium, and Platinum group metals (PGMs), reducing their reliance on single resources and mitigating risks from price fluctuations. Another approach includes the lowest-cost producer strategy, with digital technologies playing a significant role in improving operational efficiency. One participant noted that it is also important to manage profitability and sustainability, not just at a shaft level, but at a complex level where different operations fund each other. Their resilience strategy includes: firstly, understanding external factors to enable future planning; secondly, increasing operational efficiency to lower the cost curve; and thirdly, having the correct data to make quick and effective decisions.

Although some organisations lack a formal stabilisation policy, they adopt strategies based on current market conditions. During favourable periods, they make capital investments to improve operations and deploy new technologies, ensuring they maintain efficiency and low-cost production during downturns, which helps protect them from losing contracts. Additionally, some companies have undergone restructuring to focus on critical work, looking at upper and lower control limits to ensure that core activities are prioritised while reducing temporary resource reliance.

b. Awareness of Industry 5.0 concepts

The awareness of Industry 5.0 concepts varies significantly across different levels of the organisations. At the leadership level, Industry 5.0 is generally recognised as a key part of the strategy, particularly for improving safety and operational efficiency. There have been initiatives, such as a program to find reputable startup companies with innovative technologies, pilot them, and scale successful solutions across the company. However, the level of awareness at the operational level, particularly among blue-collar workers, is much lower. The abstract nature of Industry 5.0 concepts seems to limit the spread of understanding. Particularly as the emphasis is placed on technology implementation rather than on embedding and educating the foundational concepts. While efforts are being made to improve digital fluency and incorporate human-centric technologies, this is still in its early stages, and Industry 5.0 concepts are not yet fully embedded across organisations. There is consensus amongst participants that better change management is needed to ensure broader adoption of these new technologies across all levels.

Some areas of the company are still more aligned with Industry 4.0, with the focus remaining on financial performance, improving production, and profit rather than on the broader goals of Industry 5.0. For instance, in South Africa, where mining remains highly labour-intensive, there is a push for mechanisation to improve safety, but the overall awareness of Industry 5.0 remains minimal. Some of the participants noted that organisations are cautious about leading the way in implementing Industry 5.0 technologies. Although there are many proofs of concept (POCs), the company often waits to see the outcomes and challenges faced by others before committing fully to new technologies.

Lastly, there is a focus on communication regarding resilience and sustainability within organisations. Still, less emphasis has been placed on the human-centric aspects of Industry 5.0, which are critical to aligning technology with employee well-being and collaboration. Organisations are taking steps to address these gaps, but there is still extensive work to be done to improve awareness and integration of Industry 5.0 throughout the entire workforce.

c. Application of technologies to improve processes

The responses offer a diverse range of examples illustrating how modern technologies are integrated into manufacturing processes, along with their associated benefits and challenges. Advanced Processing Control (APC) is used in plants to optimise recovery; however, the efficiency of this technology is dependent on ore quality and quantity. APC uses algorithms to optimise the mill-feed material. Another example includes real-time ore accounting technologies that trace gold from the blasting stage to the final output, providing valuable insights into the production chain.

In raw mining, advancements include the use of autonomous drill rigs and docking machines, shifting operators away from danger zones. Remote-controlled continuous miners and dump trucks are also utilised in coal and open-cast mines, helping reduce safety risks while increasing production efficiency. Another example includes the use of technology to complete all underground checklists. The data is sent to managers for review, enabling them to identify issues or required maintenance. Operators complete forms offline, and once they connect to specific Wi-Fi hotspots underground, the data is transmitted above ground. The system's dashboard flags any issues and triggers automated workflows to notify all relevant parties, including suppliers. The system is able to detect problems more quickly, automatically preventing the use of faulty machines until repairs are completed. The implementation of these technologies has significantly reduced the time required to locate and repair underground machines.

Machine learning has been applied in the manufacturing processes to improve predictive monitoring, which flags potential failures before they occur. However, integrating data from different systems remains a challenge for machine learning to deliver fully predictive insights. One particular success story involved the creation of a digital twin for energy networks, which saved millions by improving energy efficiency and building a strong business case. It also allowed for risk-free testing and solution validation. This is especially important when testing changes that can cause catastrophic failures in the real world, such as changing ventilation shafts underground.

Lastly, generative AI tools, such as ChatGPT, are now being utilised across various departments to streamline processes, including contract generation and communication. Data-driven initiatives, including the deployment of IoT sensors for real-time monitoring, are also improving decision-making capabilities. SCADA systems have been integrated to automate production reports, improving data ownership and plant visualisation for production planners. Additionally, IoT is used to monitor all fleet and plant operations, while augmented reality assists with completing checklists and improving operational accuracy.

In summary, a lack of formal resilience frameworks or policies persists, alongside a high reliance on market conditions for profitability, particularly in industries such as mining and manufacturing. There is also considerable work that needs to be done in terms of overall Industry 5.0 awareness across all levels of the organisation. Despite the lack of formal resilience frameworks and awareness, modern technologies are used to improve resilience in organisations. However, there is still room for improvement and ensuring their integration is cohesive and optimised.

d. Challenges and recommendations

Key challenges related to resiliency are identified, and recommendations are provided in Table 6.14.

Table 6.14: Challenges & recommendations for resiliency

Challenges	Recommendations

High costs of developing new mining shafts, low ROI, and declining ore quality in the gold sector.	• Develop formal resilience frameworks that utilise AI-driven insights for scenario planning and resource optimisation. • Invest in digital technologies such as predictive analytics to optimise resource utilisation and improve operational decisions.
Depletion of pure chrome reserves creates additional pressure in the chrome sector.	• Influence and plan for fluctuating supply and demand in various commodities, optimising resource allocation strategies.
Market fluctuations affect innovation and R&D budgets, delaying technology adoption.	• Establish flexible investment models to allocate funds for immediate operational needs and long-term technological developments.
Outdated infrastructure inhibits the integration of modern technologies.	• Allocate resources to upgrading infrastructure to support automation and advanced digital solutions.
Manual processes in mining operations often result in delayed responses.	• Invest in predictive maintenance models and digital twins to anticipate equipment failures and improve asset utilisation.
Operational systems require digital flexibility to adapt to market fluctuations and long-term goals.	• Streamline operational processes, such as water recycling and data monitoring, to improve efficiency and sustainability.
CEO-driven leadership influences the company's direction, potentially overlooking systemic needs.	• Develop a continuous evaluation process to improve the effectiveness of stabilisation policies and align them with systemic goals.

6.4.3 Sustainability

a. Environmental & social initiatives

The interviews revealed various strategies and initiatives undertaken by organisations to address environmental and societal issues. Many organisations have implemented sustainability-focused programs, with key examples including tracking water positivity and usage, CO2 reduction, and transitioning to renewable energy sources such as solar power. Battery-operated vehicles have been introduced for underground mining, and efforts have been made to improve waste management and waste reduction. Additionally, there are biodiversity-focused initiatives, such as nurseries to conserve natural plant species and biodiversity offset areas, including world-class birdwatching and fishing venues. Companies are also working to digitise and go paperless across systems, complying with environmental regulations while reducing their ecological footprint.

Several companies are researching energy consumption reduction and water conservation. Solar plants are being built to transition to more renewable energy sources.

Some organisations are also deeply involved in community development. One participant noted that a five-year social labour plan, in collaboration with local communities, has been launched to target economic upliftment. One example aims to impact 17,500 lives through health, educational, and economic outreach, with 40% of the workforce targeted for women's empowerment. Socially, AI and media tools are being utilised to gain a deeper understanding of community needs and perceptions. Organisations are aligning their goals with clients' environmental and societal objectives. They work together to pool resources, focusing on community-based initiatives, such as education and employment in remote areas. One participant noted the decentralisation of these initiatives to ensure that the programs or initiatives are tailored to the specific needs of different communities. Some companies lease the mining properties (rather than own them) to generate continuous income streams for the local communities that own the land. Additionally, investments are made in local infrastructure, such as schools and clinics, and upgrades are being made to tailings facilities in accordance with the Global Industry Standard on Tailings Management (GISTM).

Some companies primarily focus on internal programs, with less emphasis on external societal initiatives. Environmental initiatives are often driven by regulatory requirements, such as International Organisation for Standardisation (ISO standards and government regulations. Many organisations have embedded ESG goals into their business strategies. They have made significant investments in environmental initiatives, including water conservation, energy efficiency, recycling, and tailings management. These programs are critical for maintaining mining licenses. The upside of sustainability initiatives is that there is more room for experimentation, and the risk is lower when investigating these initiatives compared to interfering with production processes. Despite these initiatives, some organisations still note that the expectations regarding ESG are vague.

b. Business models

Many organisations struggle with a gap between sustainability initiatives and their actual implementation, especially at lower operational levels. While sustainability goals may be well understood at the managerial or "C-band" levels, this awareness often fails to be cascaded down to blue-collar or operational staff, largely due to a lack of ground-level champions and communication barriers. However, the level of exposure to sustainability initiatives often correlates with the employee's position in the organisation - leadership tends to have more exposure and a greater appreciation for these efforts than ground-level workers. Perception is closely tied to both exposure and Maslow's hierarchy of needs. An employee who is primarily concerned with basic survival and providing for their family is unlikely to prioritise the company's carbon emissions.

Many organisations' business models are driven by regulatory compliance, especially in sectors such as mining, where holding a licence to operate is critical. Sustainability goals are often viewed as a necessity to maintain licenses and meet stakeholder expectations. The influence of sustainability on profitability is also notable. One participant noted that profitability and sustainability are interlinked, and long-term remuneration and incentives are provided to top leadership to encourage them to meet sustainability targets. For some companies, sustainability influences capital expenditures but does not necessarily affect day-to-day operations. Capital is allocated for initiatives such as renewable energy projects, but these investments do not always result in changes to daily processes. Instead, they are often viewed as strategic investments for long-term gains, rather than immediate operational improvements with minimal impact on the business model.

These responses highlight that while sustainability is recognised as important and integrated into business models, there are gaps in communication, ground-level engagement, and operational application, which organisations need to address to realise their sustainability goals fully.

c. Strategy planning

The responses to the question about how organisations are involved in strategy planning related to sustainability and ensuring compliance with regulations highlight different approaches across regions and levels of proactivity. Some organisations have visible and trackable sustainability efforts. They focus on meeting key sustainability targets, such as operating in certain areas without safety incidents, and review these strategies regularly (e.g., daily) to ensure they remain on track. However, a question often arises on how to future-proof these strategies, indicating that while they meet current standards, there is concern about remaining competitive and compliant in the future. While many organisations meet the minimum sustainability and regulatory requirements, some push to be leaders by adopting proactive measures. These organisations do more than comply; they aim to set new standards, particularly in regulatory compliance, to stay ahead of the curve. However, in many cases, proactivity varies, and some only meet the basic requirements rather than striving for leadership. One organisation noted that sustainability initiatives are primarily undertaken for market and shareholder value and market and shareholder positioning.

The level of collaboration with regulators varies significantly across different regions. In places like the U.S., organisations actively engage in sustainability strategy planning with regulators through agreements like the Good Neighbours Agreement, which emphasises mutual collaboration. In Europe, regulations are more prescriptive but allow different applications depending on context, while in Australia, organisations enjoy more flexibility in shaping their sustainability strategies. However, South Africa's regulatory environment is perceived as having a more top-down approach, where collaboration is limited at the national level. Some organisations also collaborate with local authorities, such as the Department of Mineral Resources (DMR) and the Water Council in South Africa, to help shape regulations and ensure compliance. However, this engagement tends to vary based on the region - more remote areas often interact less with local regulators. There are efforts to engage with infrastructure providers, such as Eskom and Transnet, to maintain and improve compliance with regulatory standards. Still, again, the level of involvement is not consistent across regions. There is ongoing negotiation and communication between industry and regulatory bodies on the practical implementation of regulations.

These answers indicate that, although there is a degree of visibility and tracking of sustainability efforts, the approaches to regulations and proactive strategy planning differ significantly across regions. Some organisations are more forward-thinking, actively engaging with local regulators and stakeholders. In contrast, others maintain a more reactive stance, focusing on compliance with existing regulations rather than setting new sustainability benchmarks.

d. Transparency

The responses to the question about how organisations monitor sustainability and review the indicators show varying degrees of tracking and transparency across different companies. There is some awareness of sustainability efforts at the ground level, although communication remains a challenge. In several organisations, most communication about sustainability is focused on management, leading to a lack of transparency and engagement from operational employees.

Some organisations review sustainability indicators monthly, while others conduct daily reviews of safety and sustainability efforts. These reviews often include celebrating safety heroes or champions, with the recognition coming from top leadership, such as the CEO. Some companies track sustainability initiatives on a project-level basis and use KPIs to monitor progress. Many organisations rely on reports and dashboards to track sustainability indicators such as water, energy consumption, hydrocarbons, and emissions. These indicators are often tied to corporate reporting for transparency, particularly for companies listed on stock exchanges, where there are strict requirements for sustainability reporting; for companies with more advanced systems, sustainability metrics (e.g., water and energy consumption, health, safety, and carbon intensity) are monitored through integrated systems. These indicators are regularly reviewed to ensure alignment with the company's long-term goals and are integrated throughout its operations. In some cases, senior leadership remuneration is linked to the achievement of these sustainability targets. However, the level of detail and transparency varies and reporting practices across different operations are also non-standardised. In some cases, indicators are not easily accessible to all employees, particularly at the ground level. This gap highlights a potential area for improvement in ensuring widespread accessibility and engagement with sustainability metrics across the workforce.

Overall, organisations exhibit varying levels of maturity in monitoring and reporting on sustainability. While some have robust, integrated systems that align well with their long-term sustainability goals, others face challenges in transparency, accessibility, and consistency in reporting practices across their operations.

e. Challenges and recommendations

While many organisations are aware of sustainability, it is not integrated across all company functions and operations. Companies must align sustainability with business objectives, ensuring it becomes an integral part of their long-term growth strategy. Sustainability is a regulatory requirement for maintaining mining licences as well as managing key stakeholder investments and perceptions. It is also a key driver for future-proofing operations. Companies should prioritise investments in technologies that reduce environmental impact, such as water treatment systems, energy-efficient machinery, and the reuse of materials. Key challenges related to sustainability are identified, and recommendations are provided in Table 6.15.

Table 6.15: Challenges & recommendations for sustainability

Challenge	Recommendation
Lack of integration of sustainability across all company functions and operations.	• Embed sustainability goals, such as reducing carbon emissions and improving energy efficiency, into operational KPIs. • Link executive and managerial incentives to achieving sustainability targets, ensuring accountability across the organisation.
Limited employee awareness and engagement in sustainability initiatives	• Create transparency and awareness at all organisational levels regarding sustainability initiatives. • Develop employee training programs to foster understanding of their roles in achieving sustainability goals.

Sustainability goals are not aligned with long-term business objectives.	• Integrate sustainability goals with business objectives, highlighting their interdependence with profitability.
Regulatory compliance, rather than proactive measures, primarily drives sustainability efforts.	• Direct a portion of capital expenditures toward sustainability technologies, such as energy-efficient machinery and water treatment systems. • Partner with sustainability experts to identify improvement areas and establish ROI metrics for green technology investments.
Difficulty in balancing short-term operational needs with long-term sustainability investments.	• Prioritise investments in sustainability-driven initiatives that offer long-term savings, such as waste recycling and energy reduction practices.

6.4.4 Worker perspective

a. Training

The responses to the question about training programs, mainly related to Industry 5.0 skills, reveal a range of efforts and gaps across organisations. Some companies are in the early stages of implementing training for Industry 5.0; however, they still lack full integration into their operations. Training is typically provided to mid-management and above through learner development programs (LDPs), which include digital training from external service providers. This indicates that some companies are incorporating digitalisation into their learning strategies, though these efforts are not yet comprehensive.

In other instances, digital security, data management, and general IT awareness training are provided, but Industry 5.0-specific skills, such as artificial intelligence or robotics, are lacking. Most participants reported that technology is being used to assist in learning methods, but the skills and outcomes are not yet related to Industry 5.0 skills. Challenges arise from the varying digital literacy levels in the workforce. Some companies report that only 11% of their workforce can access online training systems, significantly limiting the potential for large-scale digital training solutions.

However, there are examples of more advanced initiatives. Some organisations have partnered with platforms like LinkedIn Learning and Udemy to offer training to critical employees. Additionally, internal graduate programs mandate Industry 5.0 training, while advanced technical training is provided to data scientists and engineers to keep them current with the latest technologies. Finally, one of the organisations has recently made a range of Industry 5.0 programs available at no cost. These courses cover a range of topics, from AI to digital security, and offer varying difficulty levels, including mini degrees. However, the challenge remains that only a tiny portion (about 8%) of the workforce can access these programs, highlighting the need for more inclusive and widespread training initiatives.

In summary, while there are pockets of progress, most companies still face significant challenges in integrating Industry 5.0 skills training across their workforce, mainly due to technological access barriers and varying levels of digital fluency.

b. Working conditions and ethical standards

The interview responses regarding how organisations improve working conditions and maintain ethical standards reveal various approaches, with some aligning with the principles of Industry 5.0. Several organisations have provided nursing rooms, breastfeeding rooms, and appropriate personal protective equipment (PPE) for women, aligning with Industry 5.0's human-centric focus. There is also investment in improving facilities, such as change houses, to improve employee safety and comfort.

Many organisations have shifted their safety language and focus. For example, some have replaced the term "fatality" with "loss of life" to emphasise its severity. There are also safety initiatives, such as using autonomous trucks and remote technologies to keep workers out of dangerous environments, which include technologies like remote operations, collision detection systems, and vehicle-person interaction prevention. Although most projects are safety-focused, employees are still under pressure when compromising production for safety. It is, therefore, important that initiatives should always reduce pressure and workload, rather than creating more pressure from a production perspective.

There are also initiatives aimed at improving psychological well-being, such as leadership training designed to help managers understand their role in creating safer and more supportive environments. In terms of management training, companies are focusing on specific programs that address working with women in the mining industry, demonstrating a shift toward more inclusive workplaces. Some have introduced self-paced learning options to support leadership development. Ethical training is emphasised but not yet fully integrated with Industry 5.0 principles. Ethical training to improve working conditions is mandated in many companies, but budget constraints sometimes hinder prioritisation.

In some organisations, ethical standards are enforced through top-down policies, ensuring fairness and transparency. For example, moral standards are also embedded into automated workflows, particularly in procurement, to ensure good governance. Transparency in handling workplace issues, such as bullying, is improved by self-service kiosks that allow employees to submit anonymous complaints. Employees are also given the opportunity to submit ideas or bring issues to attention. The transparency extends to data sharing, ensuring discrepancies are visible and addressed.

In summary, organisations are progressively incorporating safety, ethical standards, and inclusivity into their working environments. However, complete alignment with Industry 5.0 principles is not yet widely seen, with many companies still working on integrating these concepts more deeply into their operational practices.

c. Challenges and recommendations

The workforce's ability to adapt to new technologies is critical for success in Industry 5.0. The findings revealed that while some employees readily adopt digital tools, many lack the necessary skills to engage with new systems fully. As technologies evolve, the skillsets of employees should also continue to improve. Continuous development programs ensure that the workforce remains agile and adaptable to future developments and improvements. Key challenges related to the worker perspective are identified, and recommendations are provided in Table 6.16.

Table 6.16: Challenges & recommendations for the worker perspective

Challenge	Recommendation
Limited access to technology for employees to practice and interact with during training sessions.	• Provide broader access to technology, ensuring employees can engage with computers and systems during training. • Offer practical, hands-on training sessions where employees interact with digital tools relevant to their roles.
A lack of digital literacy among the workforce is hindering the adoption of Industry 5.0 technologies.	• Implement company-wide digital literacy programs, focusing on Industry 5.0 skills such as AI, data analysis, and IoT. • Partner with digital education platforms like LinkedIn Learning or Udemy to deliver scalable and accessible training.
Training initiatives often target only critical or high-level staff, leaving a	• Ensure training programs are accessible to all employees, regardless of role, and monitor participation through certifications.

significant portion of employees untrained.	
The workforce lacks opportunities for lifelong learning and continuous skill development.	• Foster a culture of lifelong learning by offering regular upskilling and reskilling programs for all employees. • Establish internal career development pathways linked to technological proficiency, integrating them into performance reviews.
Difficulty in creating resilient, multiskilled employees capable of adapting to technological changes.	• Develop initiatives to train and develop multi-skilled employees, enhancing both resiliency and job satisfaction.
Limited exposure of employees to diverse functions within the organisation.	• Create multidisciplinary teams, promoting cross-functional learning and collaboration to ensure integrated solutions. • Facilitate team environments that encourage employees to learn from peers and gain exposure to various roles.

6.4.5 System perspective

a. Discussion

Some organisations are aware of bioeconomy and circular economy principles, particularly at the CEO and upper management levels. These principles have been integrated into their operations, with a focus on waste reduction and alignment with sustainability goals. However, many organisations are still in the early stages of applying bioeconomy principles, with a few having a limited understanding of and application of these principles.

Some companies excel in applying bioeconomy principles, particularly in waste reduction and recycling. These organisations are involved in large-scale recycling efforts, such as re-mining tailings and recycling metals from e-waste and batteries. Leading companies also focus on turning waste, such as mine water, into valuable products like agricultural-grade fertilisers, demonstrating a strong commitment to resource efficiency. This also contributes to the South African economy by reducing reliance on imports, particularly for agricultural-grade fertilisers. There are efforts to invest in water treatment systems to recycle contaminated water and reduce environmental impact. Companies are also managing consumables, such as hydrocarbons, more effectively through supplier collaboration.

Organisations are also required to restore mined areas to their pre-mined conditions as part of their regulatory compliance. This includes efforts related to land rehabilitation and environmental management. One challenge is that some mines become bankrupt before rehabilitation can start or be completed. Therefore, they cannot meet bioeconomy goals and regulatory requirements. Another challenge includes initiatives such as water and energy conservation, which are driven primarily by the need to comply with government and mining license regulations rather than by a proactive approach to bioeconomy principles.

The mining industry's inherently linear nature makes it difficult to adopt circular or bioeconomy principles. Additionally, these concepts can be challenging to explain to a largely unskilled workforce, and widespread adoption. Overall, while bioeconomy and circular economy principles are recognised at the higher levels of management and are being integrated into some operations, broader awareness and application remain limited. Most efforts are compliance-driven rather than proactive, and significant challenges remain in fully implementing these principles across the workforce and operations. Key challenges related to the system perspective are identified, and recommendations are provided in Table 6.17.

b. Challenges and recommendations

Table 6.17: Challenges & recommendations for the system perspective

Challenges	Recommendations
Limited awareness and understanding of bioeconomy principles, particularly at the operational level.	• Develop targeted training programs to educate employees about bioeconomy and circular economy principles. • Simplify concepts for unskilled workers using practical examples to enhance understanding and engagement.
A compliance-driven approach to bioeconomy principles rather than proactive integration.	• Embed bioeconomy goals into the organisation's vision and mission statements. • Encourage leadership to champion bioeconomy principles through consistent communication and strategy alignment actively.
Insufficient resource efficiency initiatives across operations.	• Scale up efforts like re-mining tailings and recovering metals from e-waste to improve waste reduction and resource efficiency. • Invest in innovative technologies for repurposing waste, such as converting mine water into agricultural-grade fertilisers.
Limited collaboration with suppliers and stakeholders in	• Partner with suppliers to ensure sustainable practices in managing consumables like hydrocarbons.

advancing sustainability goals.	• Collaborate with industry peers and government agencies to share best practices and co-develop bioeconomy solutions.
Challenges in land rehabilitation and meeting environmental obligations, especially in bankrupt mines.	• Develop contingency plans to ensure land rehabilitation and environmental management obligations are fulfilled. • Advocate for stricter regulatory frameworks to incentivise proactive sustainability initiatives.
Difficulty transitioning from a linear to a circular economy model in mining operations.	• Launch pilot projects to demonstrate the feasibility of adopting circular economy models in mining. • Start with incremental integration, focusing on waste reduction and recycling to gain momentum for broader changes.
Environmental impact from inadequate water treatment and resource management.	• Invest in water treatment and recycling systems to reduce environmental impact and enhance operational sustainability. • Digital tools are used to monitor and optimise resource use with real-time tracking of sustainability metrics.

6.4.6 Customer perspective

a. Discussion

Most of the customisation and personalisation is happening internally in companies. One participant noted that the company has developed an enterprise data storage (EDS) system for internal customers that houses all operational data. Managers can access this data to build their reports and analytics, enabling them to personalise insights and outputs based on their needs. Another participant noted that they focus on personalised services and not products. These include software solutions such as chatbots that provide real-time alerts. These solutions are customised to fit the specific needs of each site, improving adoption and effectiveness within the organisation. Another example includes the allowance for some degree of autonomy in terms of internal operations, where internal stakeholders are permitted to customise their change management methods without enforcing strict standard protocols.

One organisation reported that customers can interact with the company through a faceless experience on a customer portal. The focus is on ensuring uniformity in service, with a primary emphasis on the voice of the customer, product quality, and service delivery standards. The most notable response related to that customisation is more common in specific industries, such as coal mining and diamonds, where the quality of ore is adjusted according to its intended use. Additionally, customer preferences often determine commodity purities, particularly in industries such as steel and battery production, where customisation is evident in recovery processes and specialised products like lithium.

In summary, while organisations emphasise internal and strategic personalisation in niche areas, their approach to external product customisation is limited due to financial and technical limitations, as well as challenges and constraints.

b. Challenges and recommendations

Key challenges related to the customer perspective are identified, and recommendations are provided in Table 6.18.

Table 6.18: Challenges & recommendations for the customer perspective

Challenges	Recommendations
Limited capabilities in external product customisation to meet specific customer needs.	• Explore advanced technologies like AI and digital twins to enable tailored product customisation for industries such as steel and diamonds. • Invest in scalable and flexible production systems to address financial and technical limitations.
Ineffective customer interaction platforms that lack personalisation.	• Improve faceless customer portals with AI-driven tools to improve user experience and real-time support. • Balance uniformity in service delivery with the ability to address individual customer needs.
Focus on personalised services rather than products.	• Expand customised software solutions like site-specific chatbots and predictive analytics to enhance operational efficiency. • Develop tailored digital tools that address specific customer requirements, such as reporting and analytics.
Insufficient customer feedback integration into service refinement	• Implement systematic methods to capture and analyse customer feedback to identify service delivery gaps. • Use feedback to refine offerings and align them with customer expectations and industry standards.
Financial and technical constraints are hindering customisation efforts	• Partner with technology providers to co-develop cost-effective customisation solutions. • Conduct cost-benefit analyses to prioritise customisation investments with significant returns.

Lack of focus on niche areas where customisation provides a competitive advantage.	• Prioritise customisation efforts in niche areas like adjusting ore quality or producing specialised products such as lithium batteries. • Highlight these capabilities in marketing to differentiate the organisation in the marketplace.

6.5 Conclusion

The purpose of this study was to evaluate the state of the transition in the South African mining industry towards Industry 5.0, identifying the factors influencing this transition, the concepts and enabling technologies adopted, challenges faced, and recommendations to support progress.

Overarching research question: What are the factors influencing the state of technological adoption of the South African Mining Industry towards Industry 5.0?

The study found that recognition of the importance of Industry 5.0 principles significantly exceeds their current maturity across the sector, with importance scores averaging between 3.4 and 3.8. In contrast, maturity levels remain between 1.6 and 3.0 across categories. Factors influencing adoption include existing digital infrastructure and data governance, leadership commitment, employee skill levels, access to training, organisational size and resource availability, and regulatory and market pressures that shape investment decisions. This aligns with the initial factors identified through initial literature, such as Mining CEOs' priorities regarding Industry 5.0, talent management, operational costs, and a drive for modernisation ((Mandela Mining Precinct, 2023; Minerals Council South Africa, 2018; Mishra, 2025).

These factors collectively influence the pace and direction of Industry 5.0 adoption, highlighting the need for aligned strategy, employee-centred implementation, and consistent investment in foundational infrastructure.

Research objective 4: What is the current state of the Industry 5.0 application in the South African mining industry?

The mining sector demonstrates pockets of progress in digitalisation, sustainability, and safety-related automation, with technologies such as AI, IoT, big data analytics, and digital twins being actively utilised. However, the sector is still predominantly operating within an Industry 4.0 mindset, with Industry 5.0 principles such as human-centricity, system adaptability, and broad employee engagement underdeveloped (maturity levels often below 2.5).

This confirms earlier observations by Ndlovu et al. (2022), who highlighted that companies are making strides towards transformation, but most seem to still be in the planning phase. Ndlovu et al. (2022) also noted that South African mining has generally been slower compared to other industries or global counterparts, which is reflected in the maturity levels that are often below 2.5. Similarly, Mishra (2025) found that in mining, human-centric design is often secondary to efficiency-driven automation. While digital technologies like AI and IoT are operational, their deployment lacks a deliberate alignment with Industry 5.0's transformative values, such as empowerment, co-creation, and resilience. This study deepens that understanding by quantifying the maturity gap and showing that although capabilities exist, their integration remains shallow and fragmented.

Research objective 4: Which concepts have been adopted?

Key concepts partially adopted include human-centric design in safety and limited collaborative technologies, resilience through digital technologies supporting operational continuity, sustainability initiatives aligned with ESG strategies, worker upskilling through internal academies and digital training, and personalisation applied primarily internally for operational decision-making. These findings align with Muzvondiwa (2024), who noted a rising trend in digital workforce development strategies. However, concepts like holistic adaptability and bioeconomy integration are largely absent or driven by compliance rather than innovation.

Concepts such as holistic system adaptation and bioeconomy principles remain underdeveloped, with adoption driven by compliance rather than proactive integration. This reflects critiques from the Mandela Mining Precinct (2023), which argues that most South African mining innovations are compliance-triggered rather than strategically planned for future resilience. While some concepts have been adopted, the approach remains technocentric, reinforcing the feedback by Ndlovu et al. (2022) that Industry 5.0 is often misapplied as advanced automation rather than a socio-technical transformation.

Research objective 4: What components (enabling technologies) have been adopted?

Enabling technologies adopted include artificial intelligence for predictive maintenance and real-time decision support, IoT sensors for fleet and process monitoring, digital twins for scenario testing and optimisation, SCADA integration and data lakes, automation technologies in mining equipment and logistics, and gamified and digital training platforms. These findings are in line with PwC South Africa (s.a.), which reported that digital technologies are gaining traction, especially in larger mining houses. However, this study reveals that these technologies are predominantly used for control, monitoring, and operational efficiency, not to support human-centric or adaptive system goals. Technologies like blockchain and 5G remain in pilot or exploratory phases, with infrastructural and financial limitations cited as key constraints.

The results reiterate those of BDO LLP (2025), which found that smaller firms, in particular, lack the digital infrastructure necessary to adopt transformative technologies at scale. This reinforces the need for sector-wide digital equity to ensure inclusive adoption of Industry 5.0.

Research objective 5: What are the main challenges in adopting Industry 5.0 concepts and components?

The main challenges identified by interviewees in adopting Industry 5.0 concepts and components include a lack of a human-centred approach in technology strategies, with technology adoption often driven by top-down decisions rather than worker needs, and fragmented infrastructure and legacy systems limiting the deployment of advanced technology. These challenges were also raised by the Mandela Mining Precinct in 2023.

Other challenges include digital literacy gaps and limited access to training for large segments of the workforce, limited awareness of Industry 5.0 concepts at operational levels, which hinders integration, and financial and technical limitations that constrain customisation and personalisation. These findings support the concerns raised by Onwuegbuzie and Combs (2010) regarding the failure to integrate human and technical subsystems in complex organisations. This is further supported by the observations from Pelders & Schutte (2021), which indicate that resistance to change, inadequate training or skilled personnel, and high upfront costs significantly hinder the adoption of Industry 5.0.

Moreover, the study shows that most adoption is driven top-down, often overlooking the insights and needs of frontline workers. This replicates the risk highlighted by the Indeed Editorial Team (2025), who warn that without inclusive design and feedback mechanisms, transformation efforts may entrench disengagement and resistance. The compliance-first sustainability mindset observed in this study also aligns with the findings of the Minerals Council South Africa (2018), which criticised the mining sector for adopting reactive, rather than proactive, approaches to environmental and social governance.

Research objective 6: What recommendations can be made to support the South African mining industry in the transition?

Based on the interviewees' responses, to support the Industry 5.0 transition, it is recommended that organisations adopt co-development models with employee participation in technology design and implementation and develop inclusive and scalable training programmes to improve digital fluency across all workforce levels. Ambhore (2024) supports this statement by focusing on creating environments that attract talent, upskill the workforce, and foster a culture of continuous improvement. The development of scalable training programmes across all organisational levels aligns with Ndlovu et al. (2022), who emphasise the role of inclusive capacity-building in bridging technological and social gaps.

Other recommendations include upgrading digital infrastructure and implementing robust data governance to facilitate the integration of advanced technologies. Proactive integration of sustainability and bioeconomy principles beyond mere compliance is necessary to align with the broader vision of Industry 5.0, as outlined in European Commission policy papers. Asif et al. (2023) further promote the use of technology to enhance sustainability and social value.

Organisations should proactively integrate sustainability and bioeconomy principles into their business models, linking them to long-term objectives. Organisations should utilise artificial intelligence, IoT, and digital twins to enable tailored product customisation, focusing on niche areas for competitive advantage, and establish structured change management frameworks to address resistance and facilitate smooth technology transitions. Collaboration with OEMs, regulators, and technology providers should be fostered to ensure consistent and efficient implementation.

In conclusion, while the South African mining industry demonstrates a growing awareness and adoption of Industry 5.0 concepts, significant gaps exist between the importance and maturity of these concepts across all dimensions, requiring focused interventions. Addressing these gaps will enable the industry to transition towards a sustainable, resilient, and human-centric operational model aligned with Industry 5.0 principles, securing competitiveness in an evolving global landscape.

CHAPTER 7 VERIFICATION & VALIDATION

7.1 Introduction

This chapter aims to ensure that the methods used and results obtained are accurate and reliable. Verification confirms that the appropriate techniques are used correctly, whereas validation ensures that the process is applicable to answer the question. The following research questions were formulated to guide the study. Figure 7.1 illustrates the study's progress, indicating that it is currently in phase 5 of the 5-phase approach.

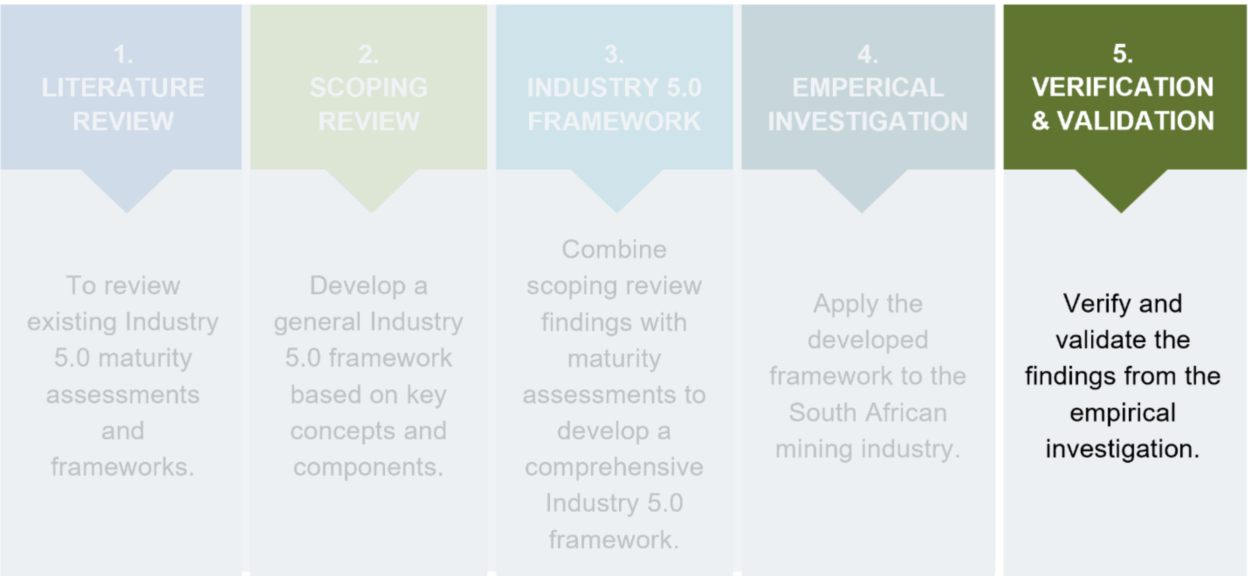

Figure 7.1: Overview of the study's progress: Phase 5/5

7.2 Verification process

Different verification methodologies are discussed in depth in Chapter 3 Methodology. Member checking was selected as the most appropriate method for the verification process, as it enhances the credibility and accuracy of the findings by allowing participants to review and confirm the interpretation of their contributions. The process consists of the following steps:

7.2.1 Steps

- **Identify participants**: 3-4 participants who represent a diversity of perspectives are involved in the member-checking process.

- **Timing**: The member-checking process is done after initial data analysis for the individual interview.

- **Summarise findings**: Concise summaries of the key findings or themes derived from the interviews are prepared, and the summaries are clear and understandable to participants.

- **Invitation**: An invitation is sent to participants explaining the purpose of member checking and how their feedback will be used. It is based on voluntary participation.

- **Instructions**: Clear instructions on how participants should review the materials and the type of feedback provided.

- **Feedback methods**: The summaries are sent via email, and written feedback is requested. Participants are guided by asking specific questions such as:

    - Accuracy: Do these summaries accurately reflect your experiences?

    - Understanding: Are there any inaccuracies or misinterpretations?

    - Completeness: Is there anything significant that was missed or misunderstood?

- **Analyse feedback**: Feedback is reviewed to identify common themes or issues and to determine if any changes are needed in the data analysis or interpretation based on the participants' input.

- **Revise**: Findings and interpretations are updated based on the feedback provided by the participants.

7.2.2 Results

The findings and invitations were shared with all participants, and seven out of the ten responded by email. This response rate exceeded the initial target of four responses. All participants indicated that they were satisfied with the summaries of their interviews, with two minor modifications to the terminology that was used.

Dear {participant A},

I hope you are doing well. As part of my research on Industry 5.0 in the South African Mining Industry, I am conducting a process called member checking to ensure that my findings accurately reflect your experiences and insights.

Attached, you will find a summary of the key themes and findings derived from our interview, along with selected excerpts. I kindly ask you to review these materials and provide your feedback on the following:

• Do these summaries accurately reflect your experiences and views?

• Are there any inaccuracies or misinterpretations?

• Is there anything important that we have missed or misunderstood?

Your feedback is invaluable and will help ensure the accuracy and credibility of the research. Please let me know if you have any questions or need further information. I look forward to your valuable insights.

Thank you for your time and participation.

Figure 7.2: Email invitation to participants to provide feedback

Figure 7.2 shows the invitation sent to the participants. Figure 7.3 is an extract of the summary of Participant A's interview that is provided during the member-checking process as an example.

Interview: Industry 5.0 in a South African Context

Collaboration between employees and technology is improving through creative approaches like mixed realities for communication and change management. AI-generated avatars on department-specific coffee mugs help facilitate interaction between employees and technology. Neuroscience principles, such as space repetition, have also been used to improve the adoption of new technologies. However, challenges around data security (e.g., BYOD policies) and building trust among employees remain, as they need assurance that their data and devices are protected.

The organization has implemented restructuring efforts, focusing on critical operations and managing core activities while controlling labour costs through temporary resources when necessary. Commodities are sold at set prices based on market trends to ensure stable production, reflecting a cautious approach to economic fluctuations. However, resilience is communicated more in terms of sustainability than in a human-centered approach.

Figure 7.3: Participant A summary extract provided for the member checking process

Table 7.1 show the summary of feedback received from participants with the relevant requested changes based on the three verification questions that were shared. "N/A" indicates that the participant did not provide any feedback.

- Do these summaries accurately reflect your experiences?
- Are there any inaccuracies or misinterpretations?
- Is there anything significant that was missed or misunderstood?

Table 7.1: Summary of participant feedback

Participant	Do these summaries accurately reflect your experiences and views?	Are there any inaccuracies or misinterpretations?	Is there anything important that was missed or misunderstood?	Notes
Participant A	Yes	The following changes were requested: • Graphical Processing Units should change to High-Graphical-Processing-Units cameras. • Add “processing” when describing the plants in the organisation. • Add “Execution of” strategies that are actively reviewed	Yes	Changes were noted and applied to the discussion chapter.
Participant B	N/A	N/A	N/A	N/A
Participant C	Yes	Yes	Yes	N/A
Participant D	Yes	Yes	Yes	N/A
Participant E	Yes	Yes	Yes	N/A
Participant F	N/A	N/A	N/A	N/A
Participant G	Yes	Yes	Yes	N/A
Participant H	Yes	Yes	Yes	N/A
Participant I	N/A	N/A	N/A	N/A
Participant J	Yes	“It is AR-Generated avatars and not AI, components of AI were used to add sound (voice over) automatically as we change the message daily for the end-users and to then translate this message into various other languages.”	Yes	Changes were noted and applied to the discussion chapter.

7.3 Validation process

Different validation methodologies are discussed in depth in Chapter 3 Methodology. Peer review was selected as the most appropriate strategy for the validation process, providing an external and critical evaluation of the research outputs. The validation process consists of the following steps:

7.3.1 Steps

- **Identifying reviewers**: A selection of 1 or 2 colleagues, field experts, or mentors with relevant experience was made. Reviewers were chosen to ensure a diverse range of expertise covering various aspects of the research.
- **Preparation of materials**: A comprehensive research proposal or draft thesis, consisting of the research design, methodology, and preliminary findings, was provided to the reviewers. Specific areas where feedback was sought were highlighted to guide the review process. The validation presentation is available in Appendix C.

  Material outline:

  - Research problem, Purpose & Objectives: Summary provided on slides
  - Research methodology: Summary provided on slides
  - Findings & Discussion: Presenter discussed content in Chapter 6 during the session.
- **Feedback:** The reviewers were first asked to share their opinion of the current progress before the findings were shared. The prepared materials were shown to the selected reviewers during an online interview to initiate a discussion and facilitate feedback.
- **Incorporating feedback:** Common themes and suggestions were identified upon receiving the input. Appropriate revisions were made to the research design, methodology, and findings in response to the reviewers' input.
- **Documenting the process:** Detailed feedback records and subsequent revisions were maintained. A section in the thesis described the peer review process, outlining how it contributed to enhancing the validity and reliability of the research.

7.3.2 Results

Feedback was gathered in three stages: first, participants were invited to share their initial opinions before the study findings were presented; next, they were encouraged to provide input during the discussion; and finally, they were asked for concluding remarks once the discussion of the findings was concluded.

a. Reviewer A's feedback

Stage 1: Pre-findings feedback

- What is your understanding of the South African mining industry's current status in adopting Industry 5.0 principles?
- What do you think are the challenges and opportunities of the industry?

The reviewer observed that, from their perspective, the mining industry shows very minimal adoption of Industry 5.0 technologies, with little preparation underway for such advancements. They noted, “I can't see it being implemented or utilised correctly within the next 5 to 10 years.” The reviewer further explained that many mining sites lack the foundational elements of Industry 4.0, which are critical to enabling the transition to Industry 5.0. Even with experienced personnel familiar with site-specific technology, the necessary infrastructure and data resources are often absent.

A key challenge highlighted by the reviewer is the need for a stronger focus on sociotechnical systems and systems thinking. In the mining sector, technology adaptation often relies heavily on the workforce that is actively involved in the demanding physical work underground. For example, while new drilling technologies may offer improvements in speed, cleanliness, and efficiency, if these tools are heavier, workers may prefer traditional drills to avoid added strain and effort while working in these harsh underground conditions. The reviewer emphasised that greater attention should be given to the human-centric pillar, as well as exploring practical ways to integrate sociotechnical systems.

In discussing potential challenges and opportunities, the reviewer identified a definite need for digitalisation in mining. For instance, extracting data from as deep as four kilometres underground, such as information on compressed air, water reticulation, and ventilation systems, remains a significant technical hurdle, with no practical solutions currently in place or available to adopt. On a positive note, the reviewer mentioned that mining companies are increasingly aware of the importance of environmental, social, and governance (ESG) aspects, recognising their growing relevance in the industry.

Stage 2: Discussion during feedback session

The reviewer highlighted that the variation and wide distribution in perceptions of human-centricity in a mining operation is understandable, as different levels of management tend to prioritise human-centred initiatives differently. They agreed on resilience-improving examples, such as implementing "flex capacity" and capability-building initiatives, recognising these principles as valuable for organisational adaptability. However, they pointed out that Industry 5.0 initiatives face challenges when they may interfere with production demands. The reviewer also emphasised the need for tools like digital twins and simulations to assess the potential impact of such initiatives before full-scale implementation. Additionally, the reviewer commented on challenges related to digital and general literacy levels within mines. They also noted that these issues, alongside Maslow’s hierarchy of needs, affect employee engagement in sustainability goals; workers will prioritise basic needs over broader environmental initiatives. On the topic of customisation, they noted that, in most commodities, customisation is not critical, and organisations will often prioritise achieving the highest recovery rates possible.

Further challenges include the fact that many proposed projects are rejected due to limited life-of-mine. The outsourcing of technology solutions to external experts also introduces gaps between external recommendations and the internal capabilities available in the organisation to implement these solutions. This disconnect can be further exacerbated when managerial turnover occurs during ongoing projects, leading to misalignment in priorities, goals, and strategic vision. The reviewer also noted a general concern among employees that AI might replace jobs, a fear particularly prevalent in mining operations. They shared an example of resistance to Radio Frequency Identification (RFID) tags for locating personnel in mines; while intended for safety, the unions initially viewed the system as a surveillance measure to track and invade the privacy of employees. This resistance was only overcome when the perception regarding the technology was adjusted so that employees’ information would stay anonymous. This example demonstrated that perception and trust remain critical barriers to the adoption of digital tools in the mining sector.

Stage 3: Does your understanding align with the findings?

The reviewer noted that the findings closely align with their own observations within the industry, offering no surprising insights. They highlighted how current priorities and trends often shape perceptions of maturity levels; for instance, with sustainability and ESG being the centre stage focuses now, mines may rate these areas as more mature due to increased awareness of stakeholder interests and ESG ratings. In contrast, aspects that receive less attention may be rated lower in terms of maturity. They suggested that future research could investigate how these maturity levels fluctuate in relation to industry trends and shifts in perceived importance. Overall, they agreed that the study accurately reflects the current state of Industry 5.0 adoption in South African mining, providing a foundation for policymakers and industry leaders to develop actionable strategies.

b. Reviewer B feedback

Stage 1: Pre-findings feedback

- What is your understanding of the South African mining industry's current status in adopting Industry 5.0 principles?
- What do you think are the challenges and opportunities of the industry?

The reviewer’s initial assessment highlighted the industry's struggle to embrace and adopt Industry 4.0 and its corresponding technologies fully. They pointed out that there is an initial awareness of the importance of human-centeredness and sustainability in the development of these technologies. Human centricity refers not only to the operator but also to the broader landscape of communities. The reviewer noted that the conventional way of doing things will change with Industry 5.0 and that a value system is needed to facilitate this change. It creates more complexity in an already complex environment, where the human-centric side remains very primitive. This adds to the fact that it will be difficult to enforce and integrate into the mining industry.

On resilience, the reviewer noted significant challenges stemming from the mining sector's reactive rather than proactive approach to market fluctuations. There are no formal structures in place to guide the industry in navigating these instabilities. The interviewee also observed that organisational practices often focus on immediate economic drivers rather than long-term resilience-building measures. As soon as the market or share prices decline, the values and priorities of the mining industry shift, and noble causes are forgotten. In terms of sustainability, there was recognition of the growing awareness of environmental considerations and that the current resources are finite. Environmental limitations are considered in design parameters and system creation. However, the industry remains compliance-driven rather than proactive when it comes to environmental initiatives such as rehabilitation, re-mining and repurposing.

Overall, challenges include the lack of skilled workers who are able to use and adopt these technologies. The reviewer highlighted that with the transition towards Industry 5.0 comes a lot of upfront costs that do not necessarily relate to or increase productivity. The dependence on government-related services and support, such as power, connectivity and transport, also plays a significant role in the advancement of the South African mining industry.

Stage 2: Discussion during feedback session

During the feedback session, the reviewer engaged in a deeper discussion of the findings, offering critical insights and validating many of the identified challenges. They underlined the systemic issues within the mining sector, particularly the outdated infrastructure and siloed organisational structures that hinder horizontal and vertical integration. Connectivity challenges, especially in rural mining areas, were highlighted as a significant barrier to adopting digital tools such as IoT and digital twins, which require reliable infrastructure. Furthermore, the lack of a unified enterprise architecture was identified as a key obstacle to sustained progress. The reviewer also elaborated on the importance of leadership in shaping the industry's direction. They observed that many human-centric and sustainability initiatives depend heavily on the CEO's vision and personal motivation, leading to inconsistent implementation across organisations. This leadership-dependent model creates volatility, where strategies initiated under one leader often lose momentum or are reversed under another.

In discussing sustainability, the reviewer provided an interesting perspective on circular economy principles, arguing that a largely unskilled workforce might unintentionally contribute to circular practices through activities such as salvaging and repurposing materials to sustain themselves. While not formalised, these efforts represent a potential entry point for promoting circular economy practices in the sector. However, the lack of structured frameworks to guide these initiatives limits their scalability and impact. The reviewer also agreed that sustainability initiatives will always take a back seat to production. Typically, in engineering, it does not always come naturally, but rather is enforced through compliance and measures. Lastly, it was noted that the low and wide distribution of the customer perspective category strengthened the reasoning that Industry 4.0 has not been fully integrated into the industry.

Stage 3: Does your understanding align with the findings?

In the final stage, the reviewer reflected on the findings presented by the interviewer, broadly aligning with the identified challenges and gaps. They appreciated the structured approach to evaluating Industry 5.0 readiness and acknowledged the validity of the observed issues, particularly the fragmented adoption of human-centric and sustainability principles. The reviewer emphasised the importance of addressing these challenges through long-term strategies rather than short-term, compliance-driven actions.

Additionally, they raised a thought-provoking critique of the concept of Industry 5.0, questioning whether it represents a genuine industrial revolution or simply an evolution of existing principles from Industry 4.0. They argued that the shift toward human- and environment-focused practices might be better understood as a natural progression rather than a distinct revolution, and how it correlates to systems thinking and engineering. This perspective provides a recommendation for future studies regarding how Industry 5.0 is conceptualised and implemented.

7.4 Conclusion

The chapter has systematically demonstrated the credibility and reliability of this research. The member-checking process, with a response rate exceeding the initial target, confirmed the alignment of the findings with reviewers' experiences, addressing key feedback and refining interpretations where necessary. Similarly, the validation process, which relied on peer review, provided expert insights and critical evaluations that helped refine the findings and recommendations for future research.

The analysis of the reviewers' feedback across the three stages revealed a comprehensive understanding of the challenges and opportunities facing the South African mining industry in its transition toward Industry 5.0. Stage 1 emphasised the industry's struggle to fully adopt Industry 4.0 principles fully, thereby highlighting significant barriers to Industry 5.0 adoption, such as outdated infrastructure, limited digital literacy, and the reactive nature of market responses. The discussions during Stage 2 deepened these insights, particularly regarding the fragmented integration of sustainability initiatives, the dependency on leadership vision, and the systemic challenges stemming from siloed organisational structures. Stage 3 confirmed alignment with the study's findings while introducing recommendations for future studies.

The chapter concludes that while Industry 5.0 holds significant promise, its adoption within the South African mining sector remains in its infancy, with substantial systemic and operational challenges that need to be addressed. Nonetheless, the feedback gathered through verification and validation confirms the study's contribution to understanding these dynamics. It provides a foundation for future research to refine and expand Industry 5.0 frameworks in the mining context.

CHAPTER 8 CONCLUSION

8.1 Introduction

The global transition to Industry 5.0 has become a critical focus for industries, emphasising the integration of advanced technologies like artificial intelligence (AI), robotics, and the Internet of Things (IoT) with a human-centric approach. This shift holds particular importance for the South African mining industry, a critical aspect of the country's economy. As the sector struggles with ageing infrastructure, high reliance on labour, and global pressures to become more sustainable, understanding the progress and challenges in adopting Industry 5.0 is critical.

This study aimed to bridge the knowledge gap by evaluating the current status of Industry 5.0 maturity and adoption in the South African mining industry, identifying key challenges and opportunities, and providing a foundation for policymakers and industry leaders to form strategic actions. The study contributed to the gap in the literature regarding general industry 5.0 frameworks as well as the gap in the overall progress of the South African mining industry towards industry 5.0. The thesis is structured around a systematic five-phase process, ensuring a logical progression of the study while comprehensively addressing the research objectives and questions. A summary of the thesis layout is shown in Table 8.1.

Table 8.1: Chapter division according to the research questions and objectives

Chapter	Research objectives	Research questions
Chapter 2: Literature study	To explore current Industry 5.0 research in the mining industry.	• What is Industry 5.0? • What current research exists on the transition of the mining industry towards Industry 5.0?
Chapter 2: Literature study	To explore existing Industry 5.0 frameworks and theoretical models.	• What Industry 5.0 maturity assessments exist? • What is the theory underlying the study?
Chapter 4: Scoping review & Chapter 5: Industry 5.0 framework	To develop a conceptual Industry 5.0 framework.	• What are the key concepts of the Industry 5.0 framework? • What are the key components of the Industry 5.0 framework? • What is the Industry 5.0 framework?
Chapter 6: Results & Discussion	To assess the current level of Industry 5.0 adoption in the South African mining industry.	• What is the current state of the Industry 5.0 application in the South African mining industry? • Which concepts have been adopted? • What components (enabling technologies) have been adopted?

Chapter 6: Results & Discussion	To identify the challenges and barriers hindering the transition towards Industry 5.0 within the sector.	• What are the main challenges in adopting Industry 5.0 concepts and components?
Chapter 6: Results & Discussion	To generate strategic recommendations for industry leaders and policymakers to support and accelerate the transition to Industry 5.0.	• What recommendations can be made to support the South African mining industry in the transition?

8.2 Research objectives and questions

This study was guided by an overarching research question: What are the factors influencing the state of technological adoption of the South African Mining Industry towards Industry 5.0? The findings across each objective are summarised below, highlighting the specific contributions this study makes to academic knowledge and industrial practice.

8.2.1 Objective 1: To explore current Industry 5.0 research in the mining industry

This study addressed the questions: *What is Industry 5.0?* and *What current research exists on the transition of the mining industry towards Industry 5.0?* This study contributes to the limited but evolving body of knowledge on Industry 5.0 within the mining sector by contextualising global theoretical discourse within the realities of the South African mining industry. It advances the understanding of what Industry 5.0 is by articulating it as a human-centric, resilient, and sustainable evolution from Industry 4.0, foregrounding the role of technological integration in improving human-machine collaboration rather than replacing human input.

In addressing the current research on the transition of the mining industry towards Industry 5.0, the study identified fragmented and often generic insights in the global literature, highlighting a significant gap in localised applications. This research contributes by providing empirical evidence of how Industry 5.0 principles align with the labour-intensive, infrastructure-constrained South African mining environment, offering insights that other emerging economies can adapt for their contexts.

The investigation of current Industry 5.0 research in the mining industry revealed that research is both evolving and fragmented. While global studies have focused on technological advancements and human-centric approaches, the unique challenges of the South African mining sector, such as labour intensity and infrastructure limitations, remain unexplored. This research addressed these gaps by providing localised insights into Industry 5.0's application within South Africa.

8.2.2 Objective 2: To explore existing Industry 5.0 frameworks and theoretical models

The research examined existing maturity assessments and theoretical foundations to answer the question: *What Industry 5.0 maturity assessments exist?* and *What is the theory underlying the study?* The study advances theoretical contributions by systematically reviewing and synthesising existing Industry 5.0 frameworks and maturity models to determine their relevance for mining. Addressing what Industry 5.0 maturity assessments exist and what is the theory underlying the study, it integrates sociotechnical systems theory and human-centric design principles with Industry 5.0 dimensions, demonstrating the need for frameworks that consider the mining sector's operational complexities and workforce structures.

The development of a conceptual Industry 5.0 framework rooted in these theories contributes a structured lens through which mining organisations can assess their current state and plan their transition, filling a gap in practical tools for strategic alignment towards Industry 5.0 in heavy industry contexts.

8.2.3 Objective 3: To develop a conceptual Industry 5.0 framework

To answer the questions: *What are the key concepts and components of the Industry 5.0 framework*? and *What is the Industry 5.0 framework?,* a new framework was developed. The research contributes a contextualised Industry 5.0 framework specifically tailored for the mining sector, answering what the key concepts and components of the Industry 5.0 framework are, and what the Industry 5.0 framework is. The developed framework integrates dimensions of human-centricity, resilience, sustainability, and the perspectives of workers, systems, and customers, aligning these with enabling technologies such as AI, IoT, and digital twins within mining operations. This framework serves not only as an academic artefact but as a practical tool for industry leaders, enabling structured evaluation and continuous improvement towards Industry 5.0 readiness, while

Through a scoping review and investigating existing Industry 5.0 frameworks, a general Industry 5.0 framework was developed, consisting of key dimensions such as human-centricity, sustainability, resilience, worker, system, and customer perspectives. This framework served as a baseline for evaluating the industry's progress. It helped identify specific areas that needed further development, such as integrating human-centric design principles into mining operations.

8.2.4 Objective 4: To assess the current level of Industry 5.0 adoption in the South African mining industry

The study investigated: *What is the current state of Industry 5.0 application in the South African mining industry?* and *Which concepts and components have been adopted?* The empirical investigation provided a detailed understanding of how Industry 5.0 principles are being applied in the South African mining sector. It highlighted the difference in adoption and maturity levels across different organisations, emphasising the need for more tailored strategies to bridge the gap between leadership-level initiatives and operational-level implementation. The findings also highlighted the importance of including employees in decision-making processes to cultivate a culture of ownership and engagement with new technologies.

By empirically assessing the current state of Industry 5.0 applications in the South African mining industry and identifying the concepts and components that have been adopted, this study contributes a structured measurement of Industry 5.0 adoption maturity within the South African mining industry, using weighted category analysis. The findings reveal that while organisations recognise the importance of Industry 5.0 principles, actual maturity lags, particularly in human-centric design and holistic system adaptation, with enabling technologies deployed in fragmented silos. This contribution highlights the disparity between strategic intent and operational execution, providing industry-specific evidence critical for informing targeted interventions.

8.2.5 Objective 5: To identify the challenges and barriers hindering the transition towards Industry 5.0 within the sector

The study identifies context-specific challenges in adopting Industry 5.0 concepts, addressing the main challenges associated with implementing *Industry 5.0 concepts and components*. It contributes by detailing barriers such as the lack of employee inclusion in technology strategy, digital literacy gaps, infrastructure constraints, and the limited proactive integration of sustainability and human-centric principles in technology adoption. These findings are significant as they provide evidence-based insights into the socio-technical barriers unique to the South African mining context, highlighting areas where targeted change management and strategic alignment are required to enable a meaningful transition to Industry 5.0.

8.2.6 Objective 6: To generate strategic recommendations for industry leaders and policymakers to support and accelerate the transition to Industry 5.0

Addressing *recommendations that can support the South African mining industry in its transition, this study provides* actionable, evidence-based recommendations grounded in empirical findings. Recommendations include the adoption of co-development technology strategies that actively involve employees, investment in robust digital infrastructure and governance, and the prioritisation of inclusive training initiatives aligned with Industry 5.0 skills needs.

Furthermore, the study recommends embedding sustainability and bioeconomy principles within operational and strategic frameworks, leveraging advanced technologies for customisation and decision-making, and developing comprehensive change management frameworks to overcome resistance and build trust. These recommendations aim to operationalise the Industry 5.0 transition, providing a pathway for leaders and policymakers to align technology strategies with human-centric and sustainability goals.

8.3 Implications of the study

The study's findings have significant implications for the South African mining industry, providing key insights for transitioning to Industry 5.0. The insights can help industry leaders identify critical areas for improvement and understand the importance of a balanced approach that combines technological innovation with human-centric values. For policymakers, the study offers a strategic perspective on how to support the mining sector's transition through targeted incentives, regulatory frameworks, and infrastructure development. The study also contributes to the broader academic landscape of Industry 5.0, offering an understanding that can inform and help shape future research and practical applications in similar industries.

8.3.1 Theoretical underpinning

This study is grounded in the principles of Sociotechnical Systems Theory (STS), which emphasises the interdependence between technology and human elements within an organisational context. STS provides a holistic lens through which the complexities of Industry 5.0 adoption in the South African mining industry can be examined, particularly in terms of human-centric design, adaptability, and resilience. By highlighting the interactions between workers, organisational structures, and emerging technologies, the study underscores how successful digital transformation and technological integration are not solely about technology but require alignment with human factors.

The findings of this study align closely with the principles of STS, which emphasise the balance between social and technical aspects within complex work environments. Specifically, the insights gained on human-machine collaboration, organisational resilience, and the need for robust change management reflect STS's focus on creating systems where technology supports, rather than undermines or replaces, human input and effectiveness. As observed, resistance to new technologies often stems from a lack of inclusion in decision-making processes and a lack of alignment between organisational goals and employees' day-to-day realities. This reinforces STS's argument that for technology to be effectively implemented, it must be accompanied by systems that consider worker needs, organisational culture, and existing structures.

Furthermore, the research reveals how technological initiatives, such as the introduction of Industry 5.0 technologies, face challenges in adaptation and integration due to the complex socio-technical landscape of the mining industry. The study suggests that without addressing both technical and social dimensions, such as skill development, employee engagement, and communication frameworks, Industry 5.0 initiatives may fail to achieve their intended impact. This observation is consistent with STS's view that technological change is most sustainable when it is integrated into a comprehensive and holistic system that encompasses social structures, processes, and technologies.

By applying STS as an underlying framework, this study not only maps the current state of Industry 5.0 readiness in South African mining but also offers a broader understanding and view of how human and technical elements must collaborate to support sustainable digital transformation and adoption. This approach provides a foundation for practical recommendations that benefit both employees and the organisation in this process of moving towards Industry 5.0 in the South African Mining industry.

8.3.2 Summary of key findings

The study found that technological adoption within the South African mining sector is highly variable, with certain areas of operation, such as plants, showing significant progress in automation, AI, and IoT integration. However, in contrast, many manual processes exist, especially in rural operations where limited network connectivity hinders the deployment of advanced digital technologies like 5G and Integrated Operations Centers (IOCs). The integration of technologies like digital twins, AI for predictive maintenance, and real-time monitoring remains in its early stages, highlighting the need for more comprehensive strategies to fully embrace Industry 5.0.

The key challenges identified in the study include resistance to technological changes among employees, the lack of structured training programs tailored for Industry 5.0 skills, outdated infrastructure that requires significant investment for upgrades, and cybersecurity concerns. Furthermore, market fluctuations and economic downturns lead to budget cuts in research and development, hindering innovation. Despite these challenges, there are opportunities to leverage Industry 5.0 principles and improve operational efficiency, enhance safety through automation, and foster a culture of innovation and collaboration among employees. The sector's move toward mechanisation, human-centric technologies, and sustainable practices marks a crucial opportunity for growth and competitiveness.

The study's strategic recommendations centre around prioritising infrastructure investment to enable digital readiness, especially in remote mining operations. There is a strong need for tailored training programs to upskill the workforce in Industry 5.0 technologies, thus addressing the skills gap and reducing resistance to change. Emphasising collaborative change management practices can facilitate smoother transitions and greater buy-in from employees. Additionally, policymakers and industry leaders are encouraged to adopt resilience strategies that can mitigate market risks, such as diversifying commodities and leveraging AI for better scenario planning, as well as utilising technologies to increase operational effectiveness.

8.4 Limitations of the study

This study has several limitations that should be considered. Given the emerging nature of Industry 5.0, the limited availability of literature and empirical data presents a constraint. This can influence the depth and quality of the findings and conclusions. The study is based on available data and reports, which may not fully reflect the current state of technology adoption and workforce readiness in the South African mining sector, introducing possible inaccuracies in the conclusions drawn. Furthermore, developing a general Industry 5.0 assessment framework within this study carries inherent risks due to the lack of a universally accepted definition of Industry 5.0. This framework requires further validation and refinement, which falls outside the scope of this research. The study also might not fully capture the perspectives of the entire workforce, given the variations in awareness and understanding of Industry 5.0 concepts across different levels within the industry. Additionally, the rapid pace of technological development and change can quickly render some findings outdated and irrelevant. This highlights the need for ongoing research to maintain relevance.

The scoping review may have overlooked relevant studies due to the emerging nature of Industry 5.0, which could lead to biases in developing the Industry 5.0 framework and its application to the mining sector. Additionally, the review targeted specific key terms, which might have excluded research discussing Industry 5.0 principles and components that did not explicitly identify them as part of Industry 5.0.

8.5 Recommendations for future research

Future research should consider longitudinal studies to track the progress of Industry 5.0 adoption in the South African mining industry over time. This would provide a more dynamic understanding of how technological integration evolves and the long-term impact on productivity, safety, and worker engagement. Comparative studies between different mining regions or industries would also offer valuable insights into best practices for adapting Industry 5.0 principles. Additionally, research into the development of sector-specific training programs and change management strategies would be beneficial in addressing the skills gap and fostering a more inclusive approach to technological adoption.

Future research could expand this study’s scope by examining Industry 5.0 adoption in various regions or sectors, providing comparative insights into how these principles are applied under different circumstances. Additionally, examining perceptions and maturity of Industry 5.0 across organisational levels would help evaluate differences between leadership and operational blue-collar workers. Further studies may also explore how current trends affect perceived maturity levels and compare these perceptions with actual maturity to identify potential gaps in understanding and implementation. These suggestions aim to build on the findings of this study and contribute to a deeper understanding of the pathways to successful Industry 5.0 adoption, not only within the South African mining industry but also across other sectors and industries undergoing similar transitions.

BIBLIOGRAPHY

Adel, A. 2022. Future of industry 5.0 in society: human-centric solutions, challenges and prospective research areas. *Journal of Cloud Computing*. 11(1):40.

Ahamed, M., Rahim, M.F.A. & Ahmad, A.A. 2022. Humanizing the fourth industry revolution in sustainable supply chain management. *Proceedings of the International Conference on Technology and Innovation Management (ICTIM 2022)*. https://www.atlantis-press.com/proceedings/ictim-22/125980125.

Akundi, A., Euresti, D., Luna, S., Ankobiah, W., Lopes, A. & Edinbarough, I. 2022. State of Industry 5.0—Analysis and identification of current research trends. *Applied System Innovation*. 5(1). https://www.mdpi.com/2571-5577/5/1/27.

Alsaawi, A. 2014. A Critical Review of Qualitative Interviews. 3:149–156.

Ambhore, D.S. 2024. *Navigating Industry 4.0 to Industry 5.0 : Challenges and Strategies for Workforce Transition and its Relation to SDGs*. https://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-343503 Date of access: 28 May 2025.

Amin, M., Nørgaard, L., Cavaco, A., Witry, M., Hillman, L., … Desselle, S. 2020. Establishing trustworthiness and authenticity in qualitative pharmacy research. *Research in social & administrative pharmacy : RSAP*. (February, 11).

Andres, B., Diaz-Madroñero, M., Soares, A.L. & Poler, R. 2024. Enabling Technologies to Support Supply Chain Logistics 5.0. *IEEE Access*. 12:43889–43906.

Anon. 2024. A breakdown of mining in South Africa. *Miningreview.com*. https://www.miningreview.com/base-metals/a-breakdown-of-mining-in-south-africa/ Date of access: 15 Jun. 2024.

Apriliyanti, M. 2022. Challenges of The Industrial Revolution Era 1.0 to 5.0 : University Digital Library In Indoensia. *Library Philosophy and Practice*. https://www.proquest.com/openview/38874b0b424c67252447423fa8b17d9d/1?pq-origsite=gscholar&cbl=54903.

Arta, M.C., Mandagi, N.F., Kurniawan, I. & Abdurachman, E. 2024. Industry 5.0 Readiness Assessment: A Maturity Model For Indonesian Companies. *Eduvest-Journal of Universal Studies*. 4(5):4355–4374.

Asif, M., Searcy, C. & Castka, P. 2023. ESG and Industry 5.0: The role of technologies in enhancing ESG disclosure. *Technological Forecasting and Social Change*. 195:122806.

Baker, J. 2012. The Technology–Organization–Environment Framework. In: Y.K. Dwivedi, M.R. Wade, & S.L. Schneberger, eds. *Information Systems Theory: Explaining and Predicting Our Digital Society, Vol. 1*. New York, NY: Springer. pp. 231–245.

BDO LLP. 2025. *Annual Mining Report 2025*. BDO LLP. https://www.bdo.co.za/getattachment/45cc7fa0-9cb2-44df-b6a4-d807a210bd1c/Global-_-Annual-Mining-Report-2025-compressed.pdf?lang=en-ZA.

Becker, J., Knackstedt, R. & Pöppelbuß, J. 2009. Developing Maturity Models for IT Management. *Business & Information Systems Engineering*. 1(3):213–222.

Bekker, M. 2024. Large language models and academic writing: Five tiers of engagement. *South African Journal of Science*. 120(1–2):1–5.

Benzane, M.P. 2019. Assessing Digital Transformation within a South African Mining Firm.

Berger, R. 2015. *Now I see it, now I don't: researcher's position and reflexivity in qualitative research - Roni Berger, 2015*. https://journals.sagepub.com/doi/abs/10.1177/1468794112468475 Date of access: 28 May 2025.

Birt, L., Scott, S., Cavers, D., Campbell, C. & Walter, F. 2016. Member Checking: A Tool to Enhance Trustworthiness or Merely a Nod to Validation? *Qualitative Health Research*. 26(13):1802–1811.

Bisht, D.R. 2024. Qualitative vs Quantitative Research - Differences, Examples, Methods | Researcher.Life. https://researcher.life/blog/article/qualitative-vs-quantitative-research/ Date of access: 18 Aug. 2024.

Breque, M., De Nul, L. & Petridis, A. 2021. *Industry 5.0 – Towards a sustainable, human-centric and resilient European industry*. Publications Office of the European Union.

Bryman, A. 2016. *Social research methods*. Fifth edition ed. Oxford: Oxford University Press.

Bryman, A. & Bell, E. 2011. *Business research methods 3e*. USA: Oxford university press.

Campbell, R., Goodman-Williams, R., Feeney, H. & Fehler-Cabral, G. 2020. Assessing Triangulation Across Methodologies, Methods, and Stakeholder Groups: The Joys, Woes, and Politics of Interpreting Convergent and Divergent Data. *American Journal of Evaluation*. 41(1):125–144.

Cao, G. 2007. The Pattern-matching Role of Systems Thinking in Improving Research Trustworthiness. *Systemic Practice and Action Research*. 20(6):441–453.

Chabane, B., Komljenovic, D. & Abdul-Nour, G. 2023. Converging on human-centred industry, resilient processes, and sustainable outcomes in asset management frameworks. *Environment Systems and Decisions*. 43(4):663–679.

Cohen, L., Manion, L. & Morrison, K. 2013. *Research Methods in Education*. 7th ed. London: Routledge.

Creswell, J.W. & Creswell, J.D. 2017. *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. SAGE Publications.

Creswell, J.W. & Poth, C.N. 2016. *Qualitative inquiry and research design: Choosing among five approaches*. Sage publications. https://books.google.com/books?hl=en&lr=&id=DLbBDQAAQBAJ&oi=fnd&pg=PP1&dq=Creswell,+J.+W.,+%26+Poth,+C.+N.+(2018).+Qualitative+Inquiry+and+Research+Design:+Choosing+Among+Five+Approaches+(4th+ed.).+SAGE+Publications.&ots=-ip71fJNSu&sig=6uhttm5jrn9WPxR1_t7-j7H8uZU Date of access: 22 Sep. 2024.

Delve, H., L & Limpaecher, A. 2020. *When to Use Theoretical Sampling*. *Delve*. https://delvetool.com/blog/theoretical-sampling Date of access: 29 Jul. 2025.

Demir, K.A., Döven, G. & Sezen, B. 2019. Industry 5.0 and Human-Robot Co-working. *Procedia Computer Science*. 158:688–695.

Department of Justice and Constitutional Development (South Africa). 2021. PROTECTION OF PERSONAL INFORMATION ACT, 2013 (ACT NO. 4 OF 2013). *GOVERNMENT GAZETTE*. (No. 44383).

Dimirakopoulos, G., Gutt, T., Ehm, H., Hoess, A., Karathanasopoulou, K. & Lackner, A. 2023. On the Way to Realize the 5th Industrial Revolution: Achievements, Challenges and Research Areas. *NOMS 2023-2023 IEEE/IFIP Network Operations and Management Symposium*.

Driscoll, D.L., Appiah-Yeboah, A., Salib, P. & Rupert, D.J. 2007. Merging Qualitative and Quantitative Data in Mixed Methods Research: How To and Why Not. *Ecological and Environmental Anthropology (University of Georgia)*. (January, 1). https://digitalcommons.unl.edu/icwdmeea/18.

European Commission. 2020. *Enabling Technologies for Industry 5.0 - European Commission*. https://research-and-innovation.ec.europa.eu/knowledge-publications-tools-and-data/publications/all-publications/enabling-technologies-industry-50_en Date of access: 07 Jun. 2024.

European Commission. 2021. *Industry 5.0 - Towards a sustainable, human-centric and resilient European industry - European Commission*. https://research-and-innovation.ec.europa.eu/knowledge-publications-tools-and-data/publications/all-publications/industry-50-towards-sustainable-human-centric-and-resilient-european-industry_en Date of access: 07 Jun. 2024.

Gafner, J., Garcia, R., Herrity, J. & Eads, A. 2025. *What Are Maturity Models? (With Definition, Types and Benefits)*. *Indeed Career Guide*. https://www.indeed.com/career-advice/career-development/what-are-maturity-models Date of access: 28 May 2025.

Gangadhar, S. & Seethi, N. 2023. *Importance of Research Design — A Quick Overview*. *SciSpace Resources*. https://scispace.com/resources/importance-of-research-design/ Date of access: 26 Jul. 2025.

George, A. & George, A. 2020. Industrial revolution 5.0: the transformation of the modern manufacturing process to enable man and machine to work hand in hand. *Journal of Seybold Report ISSN NO*. https://www.researchgate.net/publication/344106085_INDUSTRIAL_REVOLUTION_50_THE_TRANSFORMATION_OF_THE_MODERN_MANUFACTURING_PROCESS_TO_ENABLE_MAN_AND_MACHINE_TO_WORK_HAND_IN_HAND.

Górny, A. 2023. Developing Industry 5.0 To Effectively Harness Production Capacities. *MANAGEMENT SYSTEMS IN PRODUCTION ENGINEERING*. 31(4):456–463.

Grabowska, S., Saniuk, S. & Gajdzik, B. 2022. Industry 5.0: improving humanization and sustainability of Industry 4.0. *Scientometrics*.

Guest, G., Bunce, A. & Johnson, L. 2006. How Many Interviews Are Enough?: An Experiment with Data Saturation and Variability. *Field Methods*. 18(1):59–82.

Gumede, N.P. & Tladi, B. 2023. Socio-technical systems: using actor-network theory to make the social more tangible in a technical space. *South African Journal of Industrial Engineering*. 34(3):140–155.

Hammersley, M. & Atkinson, P. 2019. *Ethnography | Principles in Practice*. 4th ed. London. https://www.taylorfrancis.com/books/mono/10.4324/9781315146027/ethnography-martyn-hammersley-paul-atkinson Date of access: 29 Jul. 2025.

Holmes, A.G.D. 2020. Researcher Positionality - A Consideration of Its Influence and Place in Qualitative Research - A New Researcher Guide. *Shanlax International Journal of Education*. 8(4):1–10.

Innopharma Education. 2024. Digital Transformation 101: What is Industry 5.0? *Innopharma Education*. https://www.innopharmaeducation.com/blog/what-is-industry-5-0 Date of access: 28 May 2025.

Iqbal, M., Lee, C.K.M. & Ren, J.Z. 2022. Industry 5.0: From Manufacturing Industry to Sustainable Society. *2022 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*. 1416–1421.

Javaid, M., Haleem, A., Singh, R.P., Haq, M.I.U., Raina, A. & Suman, R. 2020. Industry 5.0: Potential Applications in COVID-19. *Journal of Industrial Integration and Management*. 05(04):507–530.

Jere, J.N. & Ngidi, N. 2020. A technology, organisation and environment framework analysis of information and communication technology adoption by small and medium enterprises in Pietermaritzburg. *South African Journal of Information Management*. 22(1):1–9.

Kallio, H., Pietilä, A.-M., Johnson, M. & Kangasniemi, M. 2016. Systematic methodological review: developing a framework for a qualitative semi-structured interview guide. *Journal of Advanced Nursing*. 72(12):2954–2965.

Kovari, A. 2024. Industry 5.0: Generalized Definition, Key Applications, Opportunities and Threats. *Acta Polytechnica Hungarica*. https://acta.uni-obuda.hu/Kovari_143.pdf.

Kraaijenbrink, J. 2022. *What Is Industry 5.0 And How It Will Radically Change Your Business Strategy?* https://www.forbes.com/sites/jeroenkraaijenbrink/2022/05/24/what-is-industry-50-and-how-it-will-radically-change-your-business-strategy/ Date of access: 12 Nov. 2024.

Lee, S. 2025. *Verification in Qualitative Research*. https://www.numberanalytics.com/blog/verification-in-qualitative-research-methods Date of access: 27 Jul. 2025.

Leng, J., Sha, W., Wang, B., Zheng, P., Zhuang, C., … Wang, L. 2022. Industry 5.0: Prospect and retrospect. *Journal of Manufacturing Systems*. 65:279–295.

Leung, L. 2015. Validity, reliability, and generalizability in qualitative research. *Journal of Family Medicine and Primary Care*. 4(3):324–327.

Longo, F., Padovano, A. & Umbrello, S. 2020. Value-Oriented and Ethical Technology Engineering in Industry 5.0: A Human-Centric Perspective for the Design of the Factory of the Future. *APPLIED SCIENCES-BASEL*. 10(12).

Lu, Y., Zheng, H., Chand, S., Xia, W., Liu, Z., … Bao, J. 2022. Outlook on human-centric manufacturing towards Industry 5.0. *Journal of Manufacturing Systems*. 62:612–627.

Luca, D. & Dolga, V.-I. 2021. From Industry 3.0 to Industry 4.0. *The International Journal of Engineering and Science (IJES)*. 10(9):44–49.

Lumadi, Vw. & Nyasha, S. 2024. Technology and growth in the South African mining industry: An assessment of critical success factors and challenges. *Journal of the Southern African Institute of Mining and Metallurgy*. 124(4):163–171.

Lv, Z. 2023. Digital Twins in Industry 5.0. *Research*. 6:0071.

Mafuwane, B.M. 2011. The contribution of instructional leadership to learner performance. University of Pretoria. http://hdl.handle.net/2263/24016 Date of access: 26 Jul. 2025.

Malterud, K. 2001. Qualitative research: standards, challenges, and guidelines. *The Lancet*. 358(9280):483–488.

Mandela Mining Precinct. 2023. *TEN INSIGHTS INTO 4IR: THE STATE OF DIGITAL TRANSFORMATION IN THE SA MINING INDUSTRY*. *Mandela Mining Precinct*. https://mandelaminingprecinct.org.za/ten-insights-into-4ir-the-state-of-digital-transformation-in-the-sa-mining-industry/ Date of access: 10 Aug. 2024.

Marshall, B., Cardon, P., Poddar, A. & Fontenot, R. 2013. Does Sample Size Matter in Qualitative Research?: A Review of Qualitative Interviews in is Research. 54(1):11–22.

Martin-Gomez, A., Agote-Garrido, A. & Lama-Ruiz, J. 2024. A Framework for Sustainable Manufacturing: Integrating Industry 4.0 Technologies with Industry 5.0 Values. *SUSTAINABILITY*. 16(4).

Masuku, B. 2023. *SAIMM - Skills development in mining — a solution to a changing industry*. https://www.saimm.co.za/press-releases/1063-skills-development-in-mining-a-solution-to-a-changing-industry Date of access: 15 Jun. 2024.

Mathur, A., Dabas, A. & Sharma, N. 2022. Evolution From Industry 1.0 to Industry 5.0. In: *2022 4th International Conference on Advances in Computing, Communication Control and Networking (ICAC3N)*. pp. 1390–1394.

Maxwell, J.A. 2013. *Qualitative Research Design: An Interactive Approach: An Interactive Approach*. 3rd ed. George Mason University: Sage Publications. https://books.google.co.za/books?hl=en&lr=&id=DFZc28cayiUC&oi=fnd&pg=PR5&dq=Maxwell,+J.+A.+(2013).+Qualitative+Research+Design:+An+Interactive+Approach+(3rd+ed.).+Sage+Publication&ots=LMyBdBwH3k&sig=OeW4P4jcm3W1mDeqn54z6IMsZg4&redir_esc=y#v=onepage&q&f=false Date of access: 27 Jul. 2025.

Merriam, S.B. & Tisdell, E.J. 2015. *Qualitative research: A guide to design and implementation*. John Wiley & Sons. https://books.google.com/books?hl=en&lr=&id=JFN_BwAAQBAJ&oi=fnd&pg=PR1&dq=Merriam,+S.+B.,+%26+Tisdell,+E.+J.+(2016).+Qualitative+Research:+A+Guide+to+Design+and+Implementation+(4th+ed.).+Jossey-Bass.&ots=wPYWLK3I30&sig=FprD46SHwOTgDVh7q1Cp-DntnfA Date of access: 24 Sep. 2024.

Merriam, E.J., S B & Stuckey-Peyrot, H.L. 2025. *Qualitative research: A guide to design and implementation*. John Wiley & Sons.

Mesjasz-Lech, A. 2023. Can Industry 5.0 be seen as a remedy for the problem of waste in industrial companies? *27th International Conference on Knowledge Based and Intelligent Information and Engineering Sytems (KES 2023)*. 225:1816–1825.

Middleton, F. 2019. *Reliability vs. Validity in Research | Difference, Types and Examples*. *Scribbr*. https://www.scribbr.com/methodology/reliability-vs-validity/ Date of access: 18 Aug. 2024.

Miles, M.B., Huberman, A.M. & Saldaña, J. 2014. *Qualitative Data Analysis: A Methods Sourcebook (3rd ed.)*. Sage Publications.

Minerals Council South Africa. 2018. *PEOPLE-CENTRED MODERNISATION IN MINING*. https://www.mineralscouncil.org.za/all-categories?task=download.send&id=767:people-centred-modernisation-in-mining&catid=37 Date of access: 28 May 2025.

Minion, D.J.T. 2023. Managing Qualitative Research Data. (September, 30).

Mishra, D.G. 2025. *The Mining Industry in 2025: Challenges, Innovation, and the Road Ahead*. *THE SOUTHERN AFRICAN INSTITUTE OF MINING AND METALLURGY*. https://www.saimm.co.za/news/1248-the-mining-industry-in-2025-challenges-innovation-and-the-road-ahead Date of access: 28 May 2025.

Mistry, K. 2022. Exploring the Inhibitors of Digital Transformation in the South African Mining Industry.

Momenta. n.d. *Industry 5.0 | Industry 5.0 Strategy | Industry 5.0 Technologies*. https://www.momenta.one/industry5.0 Date of access: 12 Nov. 2024.

Moran, D. 2000. *Introduction to Phenomenology | Dermont Moran | Taylor & Francis eBook*. 1st ed. London. https://www.taylorfrancis.com/books/mono/10.4324/9780203196632/introduction-phenomenology-dermont-moran Date of access: 29 Jul. 2025.

Morrow, S.L. 2005. Quality and trustworthiness in qualitative research in counseling psychology. *Journal of Counseling Psychology*. 52:250–260.

Morse, J.M. 2009. *Mixed Method Design | Principles and Procedures | Janice M Morse | Tay*. 1st Edition ed. https://doi.org/10.4324/9781315424538 Date of access: 27 Jul. 2025.

Mouhib, H., Amar, S., Elrhanimi, S. & Abbadi, L.E. 2023. An Extended Review of the Manufacturing Transition Under the Era of Industry 5.0. *2023 7th IEEE Congress on Information Science and Technology (CiSt)*. 709–714.

Mourtzis, D. 2021. Towards the 5th industrial revolution: A literature review and a framework for process optimization based on big data analytics and semantics. *Journal of Machine Engineering*. 21(3):5–39.

Mourtzis, D., Angelopoulos, J. & Panopoulos, N. 2022. OPERATOR 5.0: A SURVEY ON ENABLING TECHNOLOGIES AND A FRAMEWORK FOR DIGITAL MANUFACTURING BASED ON EXTENDED REALITY. *Journal of Machine Engineering*. 22(1):43–69.

Muzvondiwa, M.W. 2024. Constraints leading to the resistance in the adoption of Industry 5.0 in mining sustainability transitions. University of Pretoria. https://repository.up.ac.za/server/api/core/bitstreams/f922b19c-fb83-4b60-8d65-4b810b1f9de7/content Date of access: 28 May 2025.

Nahavandi, S. 2019. Industry 5.0—A human-centric solution. *Sustainability*. 11(16):4371.

Nair, A., Pillai, S. & Kumar, S. 2024. Towards emerging Industry 5.0-a review-based framework. *JOURNAL OF STRATEGY AND MANAGEMENT*. (January).

Narkhede, G., Chinchanikar, S., Narkhede, R. & Chaudhari, T. 2024. Role of Industry 5.0 for driving sustainability in the manufacturing sector: an emerging research agenda. *Journal of Strategy and Management*.

Nathaniel, A. 2023. The logic and language of classic grounded theory: induction, abduction, and deduction. *Grounded Theory Review*. 22(1):17–22.

National Academies of Sciences, E., Affairs, P. and G., Committee on Science, E., Information, B. on R.D. and, Sciences, D. on E. and P., … Science, C. on R. and R. in. 2019. Understanding Reproducibility and Replicability. In: *Reproducibility and Replicability in Science*. National Academies Press (US). https://www.ncbi.nlm.nih.gov/books/NBK547546/ Date of access: 18 Aug. 2024.

Nazarian, H. & Khan, S.A. 2024. The impact of industry 5.0 on supply chain performance. *International Journal of Engineering Business Management*. (October, 25).

Ndlovu, X.A., Ngwane, Z. & Mongae, M. 2022. The Fourth Industrial Revolution and the Political Settlement in South Africa's Mining Industry. *The Thinker*. 90(1).

Nexus Integra. 2020. Industry 5.0: the new revolution. *Nexus Integra EN*. https://nexusintegra.io/industry-5-0-the-new-revolution/ Date of access: 12 Nov. 2024.

Nowell, L.S., Norris, J.M., White, D.E. & Moules, N.J. 2017. Thematic Analysis: Striving to Meet the Trustworthiness Criteria. *International Journal of Qualitative Methods*. 16(1):1609406917733847.

Onwuegbuzie, A.J. 2025. On quantitizing revisited. *Frontiers in Psychology*. 15.

Onwuegbuzie, A.J. & Combs, J.P. 2010. Emergent Data Analysis Techniques in Mixed Methods Research: A Synthesis. *SAGE Handbook of Mixed Methods in Social & Behavioral Research*. 397–430.

Palinkas, L.A., Horwitz, S.M., Green, C.A., Wisdom, J.P., Duan, N. & Hoagwood, K. 2015. Purposeful sampling for qualitative data collection and analysis in mixed method implementation research. *Administration and policy in mental health*. 42(5):533–544.

Patton, M.Q. 2014. *Qualitative research & evaluation methods: Integrating theory and practice*. Sage publications. https://books.google.com/books?hl=en&lr=&id=ovAkBQAAQBAJ&oi=fnd&pg=PP1&dq=Patton,+M.+Q.+(2015).+Qualitative+Research+%26+Evaluation+Methods+(4th+ed.).+SAGE+Publications.&ots=ZSY-2syJD2&sig=jIHm1F1IY81iP7rw5xv7pG0C4Vc Date of access: 24 Sep. 2024.

Pelders, J. & Schutte, S. 2021. Worker inclusion in equipment development processes in the modernizing minerals sector in South Africa. *Journal of the Southern African Institute of Mining and Metallurgy*. https://scielo.org.za/scielo.php?script=sci_arttext&pid=S2225-62532021000200004 Date of access: 28 May 2025.

PhD Assistance Editors. 2019. Why is Theoretical Framework Important in Research. *PhD Assistance*. https://www.phdassistance.com/blog/why-is-theoretical-framework-important-in-research/ Date of access: 11 Aug. 2024.

Pöppelbuß, J. & Röglinger, M. 2011. What makes a useful maturity model? A framework of general design principles for maturity models and its demonstration in business process management. https://aisel.aisnet.org/ecis2011/28/ Date of access: 11 Aug. 2024.

Pretorius, L. 2024. Theoretical and conceptual frameworks in research. https://www.lynettepretorius.com/the_scholars_way_blog/theoretical-and-conceptual-frameworks-in-research/ Date of access: 11 Aug. 2024.

Priya, A. 2021. Case Study Methodology of Qualitative Research: Key Attributes and Navigating the Conundrums in Its Application. *Sociological Bulletin*. 70(1):94–110.

Pujala, N., Reddy, Ck.K., Pujala, K. & Doss, S. 2025. Unleashing the Potential: Soft Computing in the Era of Industry 5.0. In: V.K. Gunjan, S. Senatore, & A. Kumar, eds. *Cybernetics, Human Cognition, and Machine Learning in Communicative Applications*. Singapore: Springer Nature. pp. 181–203.

PwC, Minerals Council & Mandela Mining Precinct. 2023. *Ten insights into 4IR in South African mining 2023*. https://www.pwc.co.za/en/press-room/ten-insights-into-4ir-2023.html Date of access: 28 May 2025.

Rada, M. 2020. INDUSTRY 5.0 definition. *Medium*. https://michael-rada.medium.com/industry-5-0-definition-6a2f9922dc48 Date of access: 12 Nov. 2024.

Raja Santhi, A. & Muthuswamy, P. 2023. Industry 5.0 or industry 4.0S? Introduction to industry 4.0 and a peek into the prospective industry 5.0 technologies. *International Journal on Interactive Design and Manufacturing (IJIDeM)*. 17(2):947–979.

Rehman, A.A. & Alharthi, K. 2016. An introduction to research paradigms. *International journal of educational investigations*. 3(8):51–59.

Riessman, C.K. 2008. *Narrative methods for the human sciences*. Sage.

Rijwani, T., Kumari, S., Srinivas, R., Abhishek, K., Iyer, G., … Gupta, M. 2025. Industry 5.0: a review of emerging trends and transformative technologies in the next industrial revolution. *International Journal on Interactive Design and Manufacturing (IJIDeM)*. 19(2):667–679.

Ritchie, J., Ormston, R., McNaughton Nicholls, C. & Lewis, J. 2013. *Qualitative Research Practice : A Guide for Social Science Students and Researchers*. SAGE Publications. https://www.academia.edu/download/56258992/Qualitative_Research_Practice-_A_Guide_for_Social_Science_Students_and_Researchers.pdf Date of access: 27 Jul. 2025.

Sacred Heart University, R. 2020. *Organizing Academic Research Papers: Theoretical Framework*. *Sacred Heart University Library*. https://library.sacredheart.edu/c.php?g=29803&p=185919 Date of access: 11 Aug. 2024.

Sandelowski, M., Voils, C.I. & Knafl, G. 2009. On Quantitizing. *Journal of Mixed Methods Research*. 3(3):208–222.

Saunders, M., Lewis, P. & Thornhill, A. 2009. *Research methods for business students*. Pearson education.

Savin-Baden, M. & Major, C.H. 2023. *Qualitative Research: The Essential Guide to Theory and Practice*. London: Routledge.

Serfontein-Jordaan, M. & Dlungwane, S. 2022. Achieving sustainable corporate social responsibility outcomes: a multiple case study in the South African mining industry. *Communitas*. 27:1–20.

Shenton, A.K. 2004. Strategies for ensuring trustworthiness in qualitative research projects. *Education for Information*. 22(2):63–75.

Sheppard, V. 2020. 3.2 Exploration, Description, Explanation. (April, 6). https://pressbooks.bccampus.ca/jibcresearchmethods/chapter/3-2-exploration-description-explanation/ Date of access: 29 Jul. 2025.

Simkus, J. 2023. *Snowball Sampling Method: Techniques & Examples*. https://www.simplypsychology.org/snowball-sampling.html Date of access: 29 Jul. 2025.

Sindhwani, R., Afridi, S., Kumar, A., Banaitis, A., Luthra, S. & Singh, P.L. 2022. Can industry 5.0 revolutionize the wave of resilience and social value creation? A multi-criteria framework to analyze enablers. *Technology in Society*. 68:101887.

Sooleen, A. 2023. Different Types of Sampling Techniques in Qualitative Research. *Sago*. https://sago.com/en/resources/blog/different-types-of-sampling-techniques-in-qualitative-research/ Date of access: 29 Jul. 2025.

Soomro, Z., Ali, Q. & Parveen, S. 2022. Diffusion of Industry 5.0 in the financial sector: A developmental study. *Proceedings of the BAM*. "https://www.researchgate.net/profile/Qaisar-Ali-6/publication/363740427_Diffusion_of_Industry_50_in_the_financial_sector_A_developmental_study/links/632c49d770cc936cd329abb1/Diffusion-of-Industry-50-in-the-financial-sector-A-developmental-study.pdf"].

Statistics South Africa. 2017. Mining: a brief history | Statistics South Africa. https://www.statssa.gov.za/?p=9720 Date of access: 15 Jun. 2024.

Sue, V.M. & Ritter, L.A. 2007. Sage Research Methods - Conducting Online Surveys - Introduction. https://methods.sagepub.com/book/mono/conducting-online-surveys/chpt/introduction Date of access: 29 Jul. 2025.

Tallat, R., Hawbani, A., Wang, X., Al-Dubai, A & Zhao, L. 2023. Navigating industry 5.0: A survey of key enabling technologies, trends, challenges, and opportunities. *… Surveys &Tutorials*. https://ieeexplore.ieee.org/abstract/document/10305081/.

Tay, S., Te Chuan, L., Chan, S.W., Alipal, J. & Hamid, N. 2019. An Overview of the Rising Challenges in Implementing Industry 4.0. 8:2019.

TGM Research. s.a. *What Is Non-probability Sampling? Types, Examples, and Best Practices*. *TGM Research*. https://tgmresearch.com/https%3A%2F%2Ftgmresearch.com%2Fnon-probability-sampling.html Date of access: 29 Jul. 2025.

Tricco, A.C., Lillie, E., Zarin, W., O'Brien, K.K., Colquhoun, H., … Straus, S.E. 2018. PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation. *Annals of Internal Medicine*. 169(7):467–473.

Tufte, E. 2006. *Beautiful evidence*. https://scholar.google.com/scholar_lookup?author=E.+R.+Tufte+&publication_year=2006&title=Beautiful+Evidence Date of access: 27 Jul. 2025.

University of Stirling. s.a. *Understanding ethics | Research*. *University of Stirling*. https://www.stir.ac.uk/research/research-ethics-and-integrity/understanding-ethics/ Date of access: 18 Aug. 2024.

Vogt, W.P., Gardner, D.C. & Haeffele, L.M. 2012. *When to Use What Research Design*. Guilford Press.

Voulgaridis, K., Lagkas, T. & Sarigiannidis, P. 2022. Towards Industry 5.0 and Digital Circular Economy: Current Research and Application Trends. *2022 18th International Conference on Distributed Computing in Sensor Systems (DCOSS)*. 153–158.

Walker, G.H., Stanton, N.A., Salmon, P.M. & Jenkins, D.P. 2008. A review of sociotechnical systems theory: a classic concept for new command and control paradigms. *Theoretical Issues in Ergonomics Science*. 9(6):479–499.

White, R.E. & Cooper, K. 2022. Grounded Theory. In: R.E. White & K. Cooper, eds. *Qualitative Research in the Post-Modern Era: Critical Approaches and Selected Methodologies*. Cham: Springer International Publishing. pp. 339–385.

Williams, E. & Morrow, S. 2009. Achieving trustworthiness in qualitative research: A pan-paradigmatic perspective. *Psychotherapy Research*. 19:576–582.

Xu, X., Lu, Y., Vogel-Heuser, B. & Wang, L. 2021. Industry 4.0 and Industry 5.0—Inception, conception and perception. *Journal of Manufacturing Systems*. 61:530–535.

Yin, R.K. 2018. *Case study research and applications*. Vol. Vol. 6. Thousand Oaks, CA: Sage.

Zhen, Z. & Yao, Y. 2025. The Confluence of Digital Twin and Blockchan Technologies in Industry 5.0: Transforming Supply Chain Management for Innovation and Sustainability. *Journal of the Knowledge Economy*. 16(1):5295–5321.

Zulu, L.D. 2019.

Zulu, M.S., Pretorius, M.W. & van der Lingen, E. 2021. The strategic competitiveness of the South African mining industry in the age of the Fourth Industrial Revolution. *South African Journal of Industrial Engineering*. 32(3):185–200.

ANNEXURES A: PAPER 132 IN SAIIE34 PROCEEDINGS 2024

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INDUSTRY 5.0 CONCEPTS AND COMPONENTS: A SCOPING LITERATURE REVIEW

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ABSTRACT

The term "Industry 5.0" was coined to represent a new phase of industrialisation. It builds on the technological advances of Industry 4.0, with a stronger focus on human centricity, sustainability, resilience, personalisation and customisation, and bioeconomy. Through human-machine collaboration, it is shifting the focus from economic value to societal value and well-being. A scoping literature review was conducted to explore existing studies on the Industry 5.0 frameworks. The findings reveal key concepts of Industry 5.0 and the key components that drive these components such as Cobots, AI, Digital Twins, Internet of Things, Big Data, Mixed realities, and Blockchain. The study's implications highlight the need for organisations to integrate these frameworks to enhance productivity and sustainability. This review offers valuable insights for practitioners and policymakers aiming to navigate the transition towards Industry 5.0.

Keywords: industry 5.0, human-centric, resilience, sustainability, scoping literature review, framework

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1 INTRODUCTION

There have been numerous industrial revolutions, from the mechanisation of production and steam power during the First Industrial Revolution to the ecosystem of ideas and technologies such as the Internet of Things (IoT) and the Cyber-Physical System (CPS) in Industry 4.0 [1]. However, as with any industrial revolution, it has a few shortcomings. Industry 4.0 lacked a strong emphasis on human interaction and collaboration, sustainable and ethical practices, and a beneficial drive for business and social success [2] [1]. These shortcomings paved the way for the emergence of Industry 5.0.

The term "Industry 5.0" was coined by the European Commission to represent a new phase of industrialisation [3]. It builds on the technological advancements of Industry 4.0, with a stronger focus on human-machine collaboration, customisation, innovation, resilience and sustainability, shifting the focus from economic value to social value and well-being [4]. It places the well-being of the industry worker at the centre of focus and emphasises the collaboration of human skills such as creativity, decision-making, and complex problem-solving with advanced technologies [1].

As this concept is still emerging, there is a unique opportunity to explore what the key concepts and components of the Industry 5.0 framework consist of. Most existing papers focus on specific scenarios or address only one or two elements of Industry 5.0. Therefore, this study plans to investigate the available literature on the general frameworks and elements of Industry 5.0 to assist organisations in implementing Industry 5.0.

It is important to clarify the use of frameworks and models. According to Difference Between [5], a framework provides an overall structure and shows the relationship between key different elements. It can help to organise and structure concepts and theories. A model is typically more prescriptive and detailed and aims to achieve a specific outcome [6].

In summary, while both frameworks and models are used to structure and organise knowledge, frameworks are more general and descriptive, focussing on the relationships between concepts, whereas models are more specific and detailed, aiming to explain or predict specific behaviours or outcomes. Therefore, a framework is best suited to the nature of the study to provide a general knowledge structure of Industry 5.0.

2 METHODOLOGY

A scoping review is the optimal methodology for this investigation due to the broad nature of the research questions [7]. It excels at mapping existing frameworks, clarifying key concepts, and identifying knowledge gaps - ideal for exploring Industry 5.0 frameworks.

The review will follow the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) guidelines and protocol. The protocol provides the plan for the scoping review and is important in limiting the occurrence of reporting bias. After creating the detailed protocol, the eligibility criteria for selecting studies or evidence sources are clearly defined. The review identifies and searches relevant databases and search engines to retrieve studies or evidence.

A search strategy is formulated to identify relevant studies, and a systematic process is used to select sources based on eligibility criteria. Data from the selected sources are extracted and organised through a charting process. The findings of individual sources are synthesised to identify common themes, patterns, or gaps in the literature.

The general results of the findings, common themes, and trends are discussed. The review concludes with a summary of the evidence, a discussion of limitations and implications for practice, policy, or future research, along with any recommendations. Finally, the resources allocated and the role of the funders are described.

Industry 5.0, the next iteration of industrial automation, emphasises a human-centred approach alongside the technological advances of Industry 4.0. The objective is to identify key elements in the new industrial revolution through the following research questions.

- **RQ 1: What are the key concepts in the Industry 5.0 frameworks?**

  Concepts are the higher-level ideas and theories that underpin the Industry 5.0 paradigm.

- **RQ 2: What are the key components of the Industry 5.0 frameworks?**

  Components are the specific technologies, systems, and approaches that make up the Industry 5.0 framework.

Through this investigation, we can establish a foundation for future Industry 5.0 frameworks, ensuring that they provide all the necessary guidance for successful industry-wide adoption. The following inclusion and exclusion criteria are established as part of the protocol.

Table 1: Inclusion & Exclusion Criteria

PRISMA Phase	Type of the criteria	Description of the criteria
Identification	Inclusion	Publication year > 2016
		Title, abstracts, or keywords containing terms: ("Industry 5.0" or "Fifth industrial revolution" or "5th industrial revolution") and "manufacturing"
	Exclusion	Duplicated Articles
		Articles not published in English
Screening	Inclusion	Industry 5.0 concepts or components are the main or one of several topics that are reviewed, surveyed, or discussed.
	Exclusion	Articles out of the scope based on titles and abstract assessment
		Studies solely focused on Industry 4.0 or earlier industrial revolutions (unless explicitly compared to Industry 5.0)
		Full text not available

The following engineering-related databases are used: ScienceDirect, Scopus, IEEE Xplore, Web of Science, and Google Scholar. The keywords used in the search strategy are shown in Table 2. To limit the number of studies relevant to the study topic, no synonyms for 'Framework' are used in the search strategy.

Table 2: Keywords for Search Strategy

Keywords	Synonyms
Industry 5.0	'Fifth Industrial Revolution', '5IR', '5th Industrial Revolution'
Framework	n/a

3 RESULTS

The search strategies were drafted by the authors and further refined. The final search strategy is found in the table below, conducted on 18 May 2024.

Table 3: Search terms and results

Search terms and database	Science Direct	Scopus	IEEE Xplore	Web of Science	Google Scholar	Total
("industry 5.0" OR "fifth industrial revolution" OR "5th industrial revolution" OR 5IR) AND (framework)	96	447	174	216	71	1004

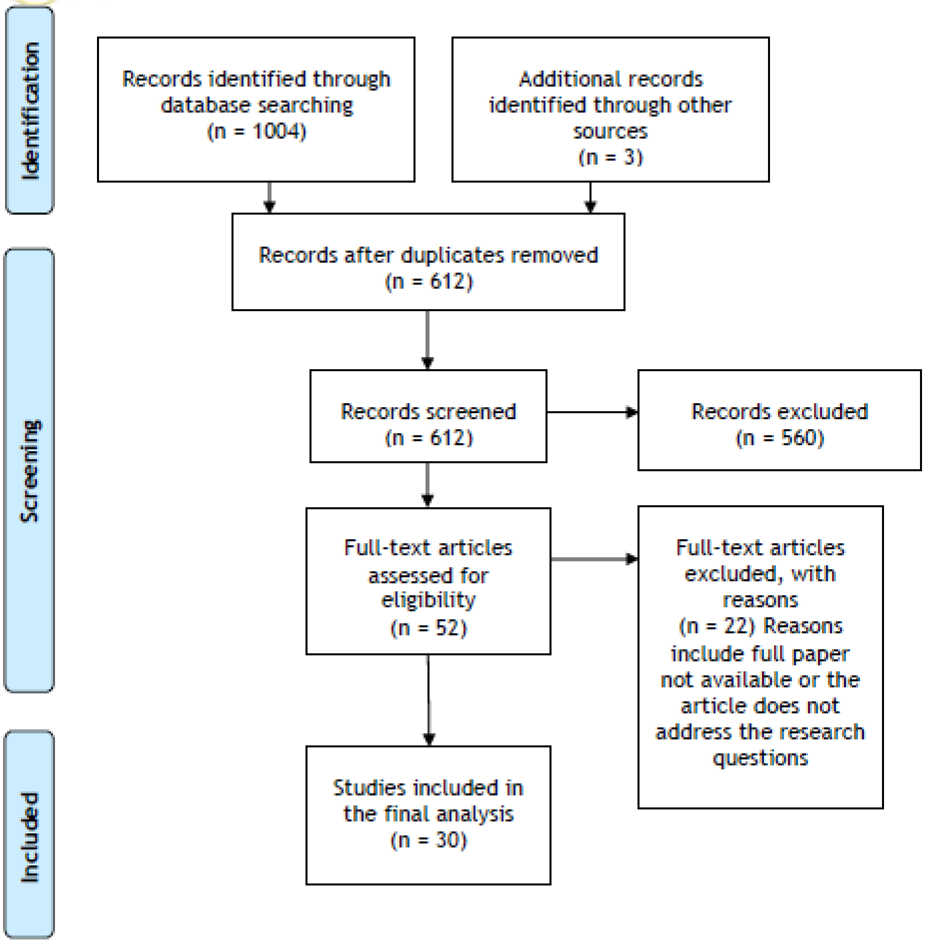
Search terms were used to search the title, abstract and keywords. However, since Google Scholar is a search engine, not a database, to limit the number of articles, only keywords were searched. Other sources include publications by the European Commission since they are a key driver and initiator of this transition.

The final search results were exported to Rayyan, a web application designed to organise, manage and facilitate the screening process. Based on the search, 1008 resources were gathered from 5 databases. After the duplicates were removed, a total of 612 citations were identified from searches of electronic databases and review article references. Based on the research protocol used to perform an initial screening, 560 were excluded, with 52 full-text articles to be retrieved and evaluated for eligibility and to ensure they directly address the research questions and objectives and provide relevant information about the industry 5.0 frameworks.

Of these, 22 were excluded for the following reasons:

- Unable to retrieve the full article.
- Focus on a very specific application of a technology.
- Industry 5.0 is only used as a reference and is not discussed in the paper.
- Focus only on challenges, opportunities, advantages, disadvantages or risks.
- Focus only on industry 4.0 technology frameworks.

The remaining 30 studies were considered eligible for this review.



3.1 RQ 1: What are the key concepts in the Industry 5.0 frameworks?

Figure 1 shows the most common to least discussed concepts in the 30 included articles. Each of these concepts will be discussed individually to understand the definition and application.

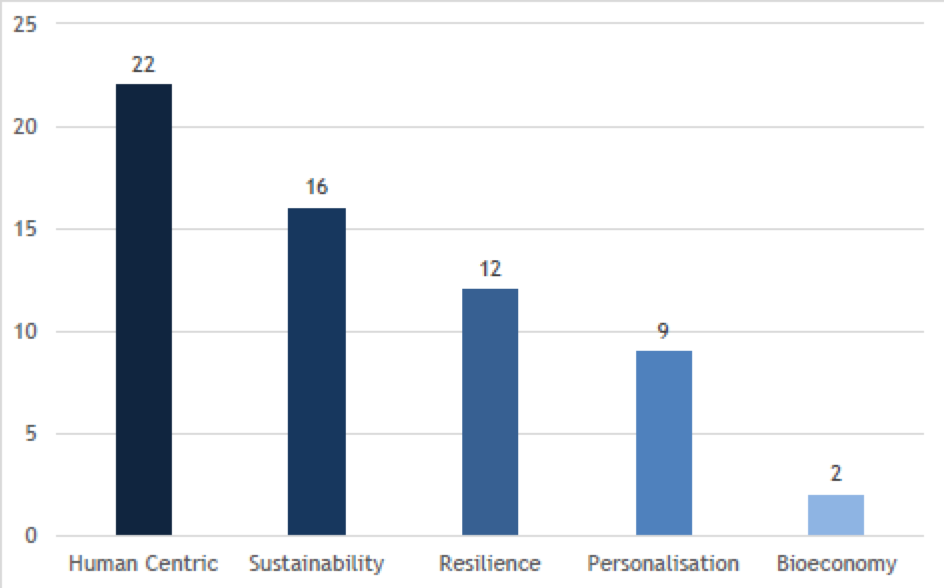


Figure 1: Number of articles discussing Industry 5.0 Concepts

3.1.1 Human-centric design

The authors emphasise that technology is not a replacement for humans, but a collaboration between people and machines to create more value-added for customers [8], [9]. It enhances their role in manufacturing by placing more importance on human intelligence and improvement of quality [10]. Industry 5.0 will eliminate monotonous and tedious tasks and pave the way for curiosity, empathy, creativity, and judgment [8], [11]. Humans will take on greater responsibility and increased supervision of systems [11]. Therefore it is imperative to hire the right people with the right skills to work safely alongside machines [12].The goal is to enhance workplace safety, minimise errors, and increase productivity through human-machine interaction [13].

Human centricity focuses on improving physical and mental well-being and viewing humans as assets. This includes incorporating principles such as autonomy, development, and psychological safety [14]. The 5C human-machine relations framework is introduced to implement the principles of coexistence, cooperation, collaboration, compassion, and coevolution [15]. A human-centric interaction model is created that consists of three elements: 1) human-machine understanding (2) human-machine collaborative intelligence, and (3) human-machine communication [15].

Technology will be used to benefit humanity, generate new employment opportunities, and increase productivity. This will lead to the upgrading and reskilling of workers [16]. Somroo [17] also states that modern automated industries are considering adding the human element back into their technological systems and strategies to get the most value from automation. It combines the best of both worlds, the speed and precision of automation with the cognitive abilities and critical thinking of humans [9]. Machines and humans should work as collaborators and not as competitors [9].

3.1.2 Sustainability

Organisations concentrating only on profit are finding it increasingly difficult to succeed in a global, unpredictable, and competitive environment. For companies to be sustainable, they need to achieve a symbiosis between economic, technological, social, and ecological aspects [9], [11]. Ahamed [11] states that Industry 5.0 emphasises sustainable supply chain management, incorporating elements such as 'employee education and training, working conditions, the balance between productivity and wages, technology versus human redundancy, optimal product quality, sustainable governance, and a business ethics code'. Sustainability is also argued to be driven by the implementation of digital transformation and pro-social and pro-environmental solutions in organisations [18]. There is a shift in typical economic models to circular economy models to improve overall sustainability considering social and environmental needs and challenges [18].

There is also a rise in environmental policies to reduce waste material and improve waste management. More companies are prioritising environmental sustainability, aligning with the growing demands of international organisations, government regulations, and customer expectations [8]. The 6R principles of upcycling are introduced to accompany Industry 5.0 namely, recognising, reconsidering, realising, reducing, reusing and recycling [17],[18], [19]. Akundi [20] also mentions the 6R principles as a means to promote human values and needs.

3.1.3 Resilience

Resilience is the organisation's ability to return to a stable state after expected and unexpected conditions such as geopolitical shifts and global crises, ensuring that critical infrastructure remains operational during challenges [21] [22]. It involves building robust supply chains, systems, networks, and societies capable of responding quickly to threats and recovering efficiently from failures [14]. Industry 5.0 improves resilience in manufacturing by using flexible, agile, and adaptable technologies [18].

There are two types of resilience, "self-resilience" for employees and "system resilience" for human-machine systems, this encourages collaboration to reach goals that neither could reach independently [21]. This allows for a robust system that can adapt to changes [23]. The European Commission found that enforcing environmental and social governance criteria leads to better resilience [24]. Resilience in organisations is especially important where they provide critical services such as healthcare or security [24].

3.1.4 Personalisation and Customisation

A key concept in Industry 5.0 is moving from mass production to mass personalisation and customisation [8]. This can be achieved through the collaboration between humans and advanced, intelligent, high speed and precise machines [17]. By including critical thinking within processes, mass personalisation can be achieved based on customer needs and expectations.

The demand for human touch is expected to grow as customers increasingly seek to express their individuality through their purchases. This trend reflects a new level of personalisation and a sense of luxury that businesses must address [11]. Kovari [13] states that the combination of human skills and smart factories will enable companies to respond quickly to market changes and demands.

3.1.5 Bioeconomy

The bioeconomy is described as one of the visions for Industry 5.0 by focussing on breakthroughs in agriculture, healthcare, and biosciences [25]. Sindhwani [25] defines a bioeconomy as 'the conversion and production of renewable biological sources into value-added products such as food, bioenergy and biobased products'. This includes a wide variety of industries such as agriculture, forestry, fisheries, technology, energy, and manufacturing industries.

Bioeconomy will act as an enabler for the symbioses between ecology, industry, and economy through the use of bioinspired technologies [14], [21]. The demand for bioinspired technologies is expected to increase due to the growing need for clean, affordable, and sustainable energy. These technologies will be part of bioinspired systems [26].

3.2 RQ2: What are the key components of the Industry 5.0 frameworks?

A recent report by the European Commission outlines six desired characteristics of technologies that support the concept of Industry 5.0 [27]:

- Human-Centric Solutions
- Bio-Inspired Technologies
- Real-Time Digital Twins
- Cyber-Safe Data Transmission
- Artificial intelligence
- Technologies for Energy Efficiency and Trustworthy Autonomy

Figure 2 shows the components most common to least discussed in the 30 articles included. Each of these components will be discussed individually to understand the definition and application.

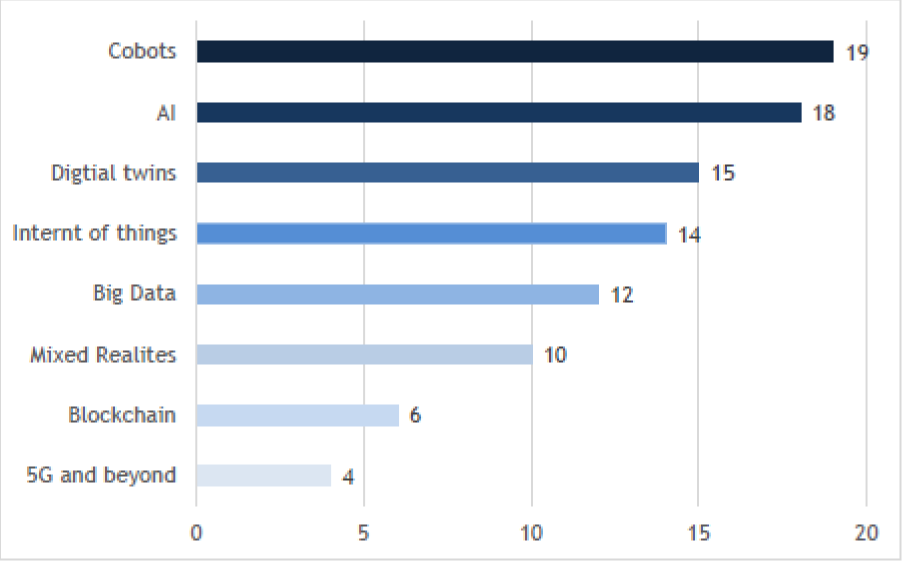


Figure 2: Number of articles discussing industry 5.0 Components

3.2.1 Collaborative Robots (Cobots):

According to George [8], the definition of a cobot is a robot designed to physically interact with people in a shared workplace where safety is prioritised. These robots collaborate with humans on the production line and learn from them. Cobots can recognise and adapt to the activities of their colleagues, creating a safer and more efficient work environment [13].

Specifically in a manufacturing setup, there are two concepts: a) Allowing humans to work on customised, personalised and creative tasks. b) Utilising robots for repetitive and labour-intensive tasks. This can help mitigate risks on the job [20]. By integrating human intelligence and cognitive processes into computers through cognitive computing, they can create more value add. Cobots are also discussed when describing smart factories and improved communication between components and humans [17]. Humans are connected to smart factories through intelligent devices [9].

Another author discussed cobots' role in intelligent healthcare, where cobots can monitor patients' conditions and assist doctors in performing surgeries and handling routine medical tasks allowing doctors to focus on more complex tasks [13]. In manufacturing, consider an example where a technician is performing maintenance on a piece of machinery. The cobot, equipped with a camera, observes the technician's actions, analyses the images using machine learning, and predicts the technician's next steps using fNIRS (functional Near-Infrared Spectroscopy) and deep learning. The cobot then provides the necessary tools and parts to assist the technician when needed [21].

3.2.2 *Artificial Intelligence (AI):*

AI is a collection of technologies based on AI models and techniques, including machine learning and natural language generation. It is designed to provide services or insights that are challenging or impossible to attain solely through human effort or conventional technologies [28].

By leveraging AI technology together with human-centred digitalisation, we can increase the productivity and sustainability of an organisation. It is the responsibility of organisations to realise the benefits of AI by adopting, extending, and implementing AI tools [29]. For example, artificial intelligence is used to improve predictive forecasts and, therefore, reduce excess manufacturing [18]. According to Akundi [20], AI can meet the personalisation needs of customers in the manufacturing industry and provide faster feedback [30].

3.2.3 *Digital Twins*

Digital twins are virtual replicas of physical devices or systems that collect real-time data and are used to gather insights and analytics [28]. These twins assist organisations in developing and optimising production processes and can improve predictive maintenance in the manufacturing industry [13]. In the banking sector, Digital Twins can customise products and services, improve the accuracy of automated financial statements, quickly identify technical issues, improve risk management, and avoid investments in high-risk projects [17].

3.2.4 *Internet of Things (IoT)*

It refers to the network of interconnected software, sensors, and devices that communicate data with other devices, systems, applications, and users to create a comprehensive network infrastructure [28]. It connects different people, systems, data, devices and processes [30]. With the use of smart sensors, IoT devices, and human insights, organisations can gather and analyse data to gain insight into processes [13] [14]. IoT data gathering and analysis are useful when monitoring products and machinery to achieve predictive maintenance [30]. In the banking sector, IoT is used to address challenges related to customer retention and satisfaction [17].

3.2.5 *Mixed Realities (Augmented Reality (AR) and Virtual Reality (VR))*

Augmented reality integrates digital information with the physical world through computer-generated content such as text, video, or animated 3D models [28]. Virtual reality provides a fully virtual experience that completely isolates the user from the real world, utilising advanced user-computer interfaces for simulation and real-time interaction [28].

This type of technology allows workers to interact and engage with processes and equipment in virtual environments [13]. Since the operator is in a safe environment, this makes it a great tool for training and education and is cost-effective and time-saving [31] [32].

3.2.6 *Big Data Analytics*

Big data is large volumes and a variety of data sets that need to be handled and processed accordingly [14] [28]. Using big data can support decision-making strategies and automation [30]. Big data analytics helps to understand customer behaviour, product promotions, and process customisation thus improving production efficiency, and reducing costs [17]. It enables organisations to develop successful business strategies and maintain their competitive edge. The use of human creativity and data insights is vital for optimising the value derived from big data [10].

3.2.7 *Blockchain*

Blockchain creates transparency and provides secure storage for encrypted data [30]. Blockchain technology is used to improve energy efficiency and resource use through process management [18]. It is used to create secure and transparent transactions when improving ESG reporting [14]. Blockchain also has significant potential to improve supply chains by increasing transaction efficiency, reducing costs, and improving security [10].

3.2.8 *Other Technologies*

Other technologies mentioned or briefly discussed in the articles include exoskeletons, drones, additive technology, edge computing, cloud computing, cyber security, multilingual speech and gesture recognition, tracking technologies, bioinspired safety and support equipment, decision support systems, smart grids, machine learning, federated learning, internet of intelligence, quantum computing, cognitive robotics, bioinspired technology, smart cities, holography, bionics, hybrid intelligence, radio frequency identification (RFID), cognitive cyber-physical systems, human interaction and recognition technologies, intelligent energy management system (IEMS), industrial smart wearable (ISW), horizontal and vertical system integration, and 5G and beyond.

4 DISCUSSION

While Industry 4.0 is focused on technology, Industry 5.0 is focused on value. Industry 4.0 provides the tools and technologies, and Industry 5.0 uses them to create a positive impact on societal and environmental levels. This scoping review has identified key concepts and components essential for the successful implementation of Industry 5.0 frameworks, offering valuable insights into the future of industrial practices. Based on the results above an Industry 5.0 framework is created and visualised in Figure 3.

Figure 3: Industry 5.0 Framework: Key Concepts & Components

Industry 5.0 places human well-being at its core, emphasising the collaboration between humans and machines using the 5C principles (Coexistence, Cooperation, Collaboration, Compassion, Coevolution). Integrating human skills such as creativity, decision-making, and problem-solving with advanced technologies like collaborative robots (cobots) enhances workplace safety, reduces errors, and leads to the reskilling and upskilling of the workforce. Humans still need to make certain immediate or unscheduled decisions that robots will not be able to.

Sustainability in Industry 5.0 encompasses economic, technological, ecological and social dimensions. It involves sustainable supply chain management practices, circular economy models, and the application of the 6R principles (recognising, reconsidering, realising, reducing, reusing, and recycling). Organisations need to work within the limits of our planet. Companies must balance profit with social and environmental responsibilities to succeed in a global, unpredictable environment. Resilience is critical for organisations to withstand and recover from disruptions. Industry 5.0 enhances resilience through flexible, agile, and adaptable technologies. Building robust supply chains and systems capable of quick response and recovery is essential. Enforcing Environmental and Social Governance (ESG) criteria further strengthens organisational resilience.

Resilience is the ability of an organisation to maintain stability during crises, ensuring critical infrastructure remains operational. It involves building robust supply chains, systems, and networks that respond quickly and recover efficiently. Industry 5.0 enhances resilience through flexible, agile, and adaptable technologies. The two types of resilience are "self-resilience" for employees and "system resilience" for human-machine systems, promoting collaboration for achieving shared goals.

From a customer perspective moving from mass production to mass personalisation and customisation is key in Industry 5.0. Advanced technologies like AI and digital twins enable companies to tailor products and services to individual customer needs, enhancing satisfaction and loyalty. From a system perspective, the bioeconomy focuses on the sustainable production and conversion of renewable biological resources. Bioinspired technologies, driven by the need for clean, affordable, and sustainable energy, promote the symbiosis between ecology, industry, and the economy.

Lastly, Industry 5.0 will positively impact employees by exploring different and alternative job roles and training through reskilling and upskilling. It will enhance the quality and health of their working environment through innovative solutions and better organisational governance and ethics. The review identified several critical components supporting the Industry 5.0 framework, including collaborative robots, artificial intelligence, digital twins, the Internet of Things, mixed realities (AR and VR), big data analytics, blockchain, and other emerging technologies. These components collectively enhance human-machine interaction, improve operational efficiency, and drive innovation.

The transition to Industry 5.0 presents several challenges, including legal, psychological, regulatory, and social issues. The evolving roles of HR and IT departments will need to address these challenges by fostering a culture that supports human-machine collaboration and continuous learning. Additionally, integration and technological challenges, such as ensuring interoperability between systems and maintaining data security, require robust leadership and strategic planning.

5 CONCLUSION

Industry 5.0 represents a transformative phase in industrialisation, focusing on human-centric, sustainable, and resilient practices. By integrating advanced technologies with human skills, organisations can achieve greater productivity, customisation, and sustainability. The concepts and components identified in this review provide a foundational framework for the successful implementation of Industry 5.0, guiding organisations towards a future where technological advancements and human well-being are harmoniously balanced.

This study is limited by the scope of the available literature and the rapidly evolving nature of Industry 5.0 technologies and frameworks. Future studies should focus on developing comprehensive implementation strategies for Industry 5.0, considering the unique needs of various industries. This paper lays a robust foundation for future empirical investigations across various industries. Industrial engineers can utilise this framework to assess the transition and implementation of Industry 5.0 within different sectors. Research should also investigate the long-term impacts of Industry 5.0 on workforce dynamics, environmental sustainability, and economic growth. Recommendations to organisations include investing in employee training and development, fostering innovation through collaboration, and adopting flexible, adaptive technologies to improve resilience. Additionally, policymakers should create supportive regulatory environments that encourage sustainable practices and technological integration.

6 REFERENCES

[1] A. Raja Santhi and P. Muthuswamy, "Industry 5.0 or industry 4.0S? Introduction to industry 4.0 and a peek into the prospective industry 5.0 technologies," Int J Interact Des Manuf, vol. 17, no. 2, pp. 947-979, Apr. 2023, doi: 10.1007/s12008-023-01217-8.

[2] A. Adel, "Future of industry 5.0 in society: human-centric solutions, challenges and prospective research areas," Journal of Cloud Computing, vol. 11, no. 1, p. 40, Sep. 2022, doi: 10.1186/s13677-022-00314-5.

[3] "Industry 5.0 - European Commission." Accessed: Mar. 22, 2024. [Online]. Available: https://research-and-innovation.ec.europa.eu/research-area/industrial-research-and-innovation/industry-50_en

[4] X. Xu, Y. Lu, B. Vogel-Heuser, and L. Wang, "Industry 4.0 and Industry 5.0—Inception, conception and perception," Journal of Manufacturing Systems, vol. 61, pp. 530-535, Oct. 2021, doi: 10.1016/j.jmsy.2021.10.006.

[5] "Difference Between Model and Framework | Compare the Difference Between Similar Terms." Accessed: May 10, 2024. [Online]. Available: https://www.differencebetween.com/difference-between-model-and-vs-framework/

[6] P. Nilsen, "Making sense of implementation theories, models and frameworks," Implementation Science, vol. 10, no. 1, p. 53, Apr. 2015, doi: 10.1186/s13012-015-0242-0.

[7] A. C. Tricco et al., "PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation," Ann Intern Med, vol. 169, no. 7, pp. 467-473, Oct. 2018, doi: 10.7326/M18-0850.

[8] A. George and A. George, "Industrial revolution 5.0: the transformation of the modern manufacturing process to enable man and machine to work hand in hand," Journal of Seybold Report ISSN NO, 2020.

[9] S. Grabowska, S. Saniuk, and B. Gajdzik, "Industry 5.0: improving humanization and sustainability of Industry 4.0," Scientometrics, 2022, doi: 10.1007/s11192-022-04370-1.

[10] R. Tallat, A. Hawbani, X. Wang, and ..., "Navigating industry 5.0: A survey of key enabling technologies, trends, challenges, and opportunities," ... Surveys &Tutorials, 2023, [Online]. Available: https://ieeexplore.ieee.org/abstract/document/10305081/

[11] M. Ahamed, M. A. Rahim, and ..., "Humanizing the fourth industry revolution in sustainable supply chain management," ... on Technology and ..., 2022, [Online]. Available: ["https://www.atlantis-press.com/proceedings/ictim-22/125980125", "https://www.atlantis-press.com/article/125980125.pdf"]

[12] M. Iqbal, C. K. M. Lee, and J. Z. Ren, "Industry 5.0: From Manufacturing Industry to Sustainable Society," 2022 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), pp. 1416-1421, 2022, doi: 10.1109/IEEM55944.2022.9989705.

[13] A. Kovari, "Industry 5.0: Generalized Definition, Key Applications, Opportunities and Threats," Acta Polytechnica Hungarica, 2024, [Online]. Available: ["https://acta.uni-obuda.hu/Kovari_143.pdf", "https://acta.uni-obuda.hu/Kovari_143.pdf"]

[14] M. Asif, C. Searcy, and P. Castka, "ESG and Industry 5.0: The role of technologies in enhancing ESG disclosure," Technological Forecasting and Social Change, vol. 195, p. 122806, Oct. 2023, doi: https://doi.org/10.1016/j.techfore.2023.122806.

[15] Y. Lu et al., "Outlook on human-centric manufacturing towards Industry 5.0," Journal of Manufacturing Systems, vol. 62, pp. 612-627, Jan. 2022, doi: https://doi.org/10.1016/j.jmsy.2022.02.001.

[16] A. Nair, S. Pillai, and S. Kumar, "Towards emerging Industry 5.0-a review-based framework," JOURNAL OF STRATEGY AND MANAGEMENT, Jan. 2024, doi: 10.1108/JSMA-04-2023-0067.

[17] Z. Soomro, Q. Ali, and S. Parveen, "Diffusion of Industry 5.0 in the financial sector: A developmental study," Proceedings of the BAM, 2022, [Online]. Available: ["https://www.researchgate.net/profile/Qaisar-Ali-6/publication/363740427_Diffusion_of_Industry_50_in_the_financial_sector_A_developmental_study/links/632c49d770cc936cd329abb1/Diffusion-of-Industry-50-in-the-financial-sector-A-developmental-study.pdf", "https://www.researchgate.net/profile/Qaisar-Ali-6/publication/363740427_Diffusion_of_Industry_50_in_the_financial_sector_A_developmental_study/links/632c49d770cc936cd329abb1/Diffusion-of-Industry-50-in-the-financial-sector-A-developmental-study.pdf"]

[18] A. Mesjasz-Lech, "Can Industry 5.0 be seen as a remedy for the problem of waste in industrial companies?," 27th International Conference on Knowledge Based and Intelligent Information and Engineering Sytems (KES 2023), vol. 225, pp. 1816-1825, Jan. 2023, doi: https://doi.org/10.1016/j.procs.2023.10.171.

[19] B. Chabane, D. Komljenovic, and G. Abdul-Nour, "Converging on human-centred industry, resilient processes, and sustainable outcomes in asset management frameworks," Environment Systems and Decisions, vol. 43, no. 4, pp. 663-679, 2023, doi: 10.1007/s10669-023-09943-w.

[20] A. Akundi, D. Euresti, S. Luna, W. Ankobiah, and ..., "State of Industry 5.0—Analysis and identification of current research trends," Applied System ..., 2022, [Online]. Available: ["https://www.mdpi.com/2571-5577/5/1/27", "https://www.mdpi.com/2571-5577/5/1/27"]

[21] H. Mouhib, S. Amar, S. Elrhanimi, and L. E. Abbadi, "An Extended Review of the Manufacturing Transition Under the Era of Industry 5.0," 2023 7th IEEE Congress on Information Science and Technology (CiSt), pp. 709-714, 2023, doi: 10.1109/CiSt56084.2023.10410003.

[22] A. Górny, "Developing Industry 5.0 To Effectively Harness Production Capacities," MANAGEMENT SYSTEMS IN PRODUCTION ENGINEERING, vol. 31, no. 4, pp. 456-463, Dec. 2023, doi: 10.2478/mspe-2023-0052 WE - Emerging Sources Citation Index (ESCI).

[23] A. Martin-Gomez, A. Agote-Garrido, and J. Lama-Ruiz, "A Framework for Sustainable Manufacturing: Integrating Industry 4.0 Technologies with Industry 5.0 Values," SUSTAINABILITY, vol. 16, no. 4, Feb. 2024, doi: 10.3390/su16041364 WE - Science Citation Index Expanded (SCI-EXPANDED) WE - Social Science Citation Index (SSCI).

[24] "Industry 5.0 - Towards a sustainable, human-centric and resilient European industry - European Commission." Accessed: Jun. 07, 2024. [Online]. Available: https://research-and-innovation.ec.europa.eu/knowledge-publications-tools-and-data/publications/all-publications/industry-50-towards-sustainable-human-centric-and-resilient-european-industry_en

[25] R. Sindhwani, S. Afridi, A. Kumar, A. Banaitis, S. Luthra, and P. L. Singh, "Can industry 5.0 revolutionize the wave of resilience and social value creation? A multi-criteria framework to analyze enablers," Technology in Society, vol. 68, p. 101887, Feb. 2022, doi: https://doi.org/10.1016/j.techsoc.2022.101887.

[26] G. Narkhede, S. Chinchanikar, R. Narkhede, and T. Chaudhari, "Role of Industry 5.0 for driving sustainability in the manufacturing sector: an emerging research agenda," Journal of Strategy and Management, 2024, doi: 10.1108/JSMA-06-2023-0144.

[27] "Enabling Technologies for Industry 5.0 - European Commission." Accessed: Jun. 07, 2024. [Online]. Available: https://research-and-innovation.ec.europa.eu/knowledge-publications-tools-and-data/publications/all-publications/enabling-technologies-industry-50_en

[28] B. Andres, M. Diaz-Madroñero, A. L. Soares, and R. Poler, "Enabling Technologies to Support Supply Chain Logistics 5.0," IEEE Access, vol. 12, pp. 43889-43906, 2024, doi: 10.1109/ACCESS.2024.3374194.

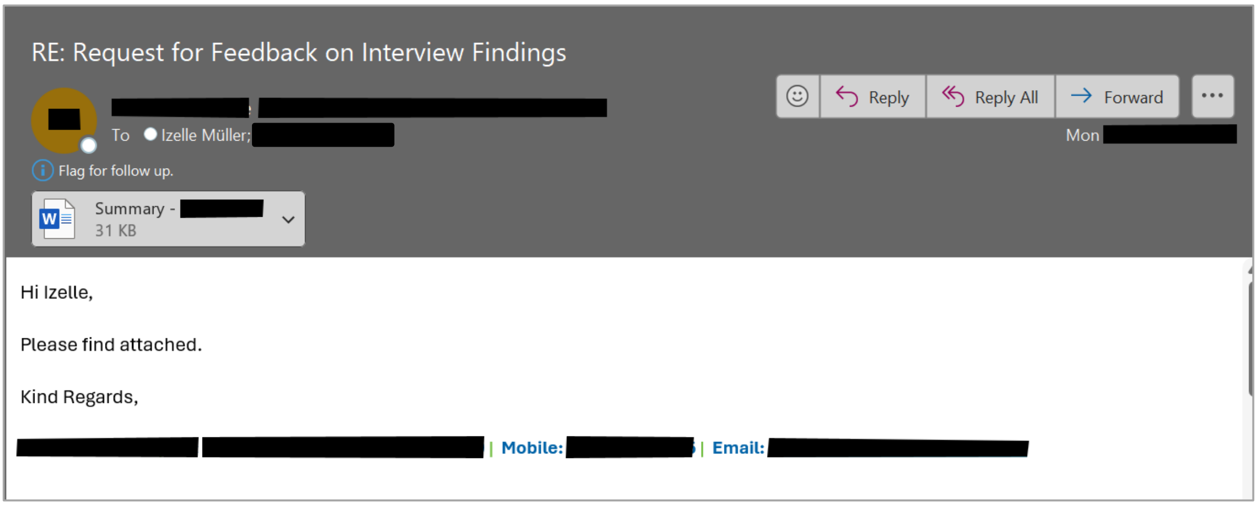
[29] G. Dimirakopoulos, T. Gutt, H. Ehm, and ..., "On the Way to Realize the 5th Industrial Revolution: Achievements, Challenges and Research Areas," NOMS 2023-2023 ..., 2023, [Online]. Available: https://ieeexplore.ieee.org/abstract/document/10154446/

[30] K. Voulgaridis, T. Lagkas, and P. Sarigiannidis, "Towards Industry 5.0 and Digital Circular Economy: Current Research and Application Trends," 2022 18th International Conference on Distributed Computing in Sensor Systems (DCOSS), pp. 153-158, 2022, doi: 10.1109/DCOSS54816.2022.00037.

[31] D. Mourtzis, "Towards the 5th industrial revolution: A literature review and a framework for process optimization based on big data analytics and semantics," Journal of Machine Engineering, vol. 21, no. 3, pp. 5-39, 2021, doi: 10.36897/jme/141834.

[32] D. Mourtzis, J. Angelopoulos, and N. Panopoulos, "OPERATOR 5.0: A SURVEY ON ENABLING TECHNOLOGIES AND A FRAMEWORK FOR DIGITAL MANUFACTURING BASED ON EXTENDED REALITY," Journal of Machine Engineering, vol. 22, no. 1, pp. 43-69, 2022, doi: 10.36897/jme/147160.

ANNEXURES B: PARTICIPANT VERIFICATION FEEDBACK



RE: Request for Feedback on Interview Findings

[redacted]

To Izelle Müller; [redacted]

Mon [redacted]

Reply | Reply All | Forward

Flag for follow up.

Summary - [redacted]
31 KB

Hi Izelle,

Please find attached.

Kind Regards,

[redacted] | Mobile: [redacted] | Email: [redacted]

Figure B.1: Participant A verification feedback

Re: Request for Feedback on Interview Findings

[redacted]

To Izelle Müller

2024/10/13

Flag for follow up.

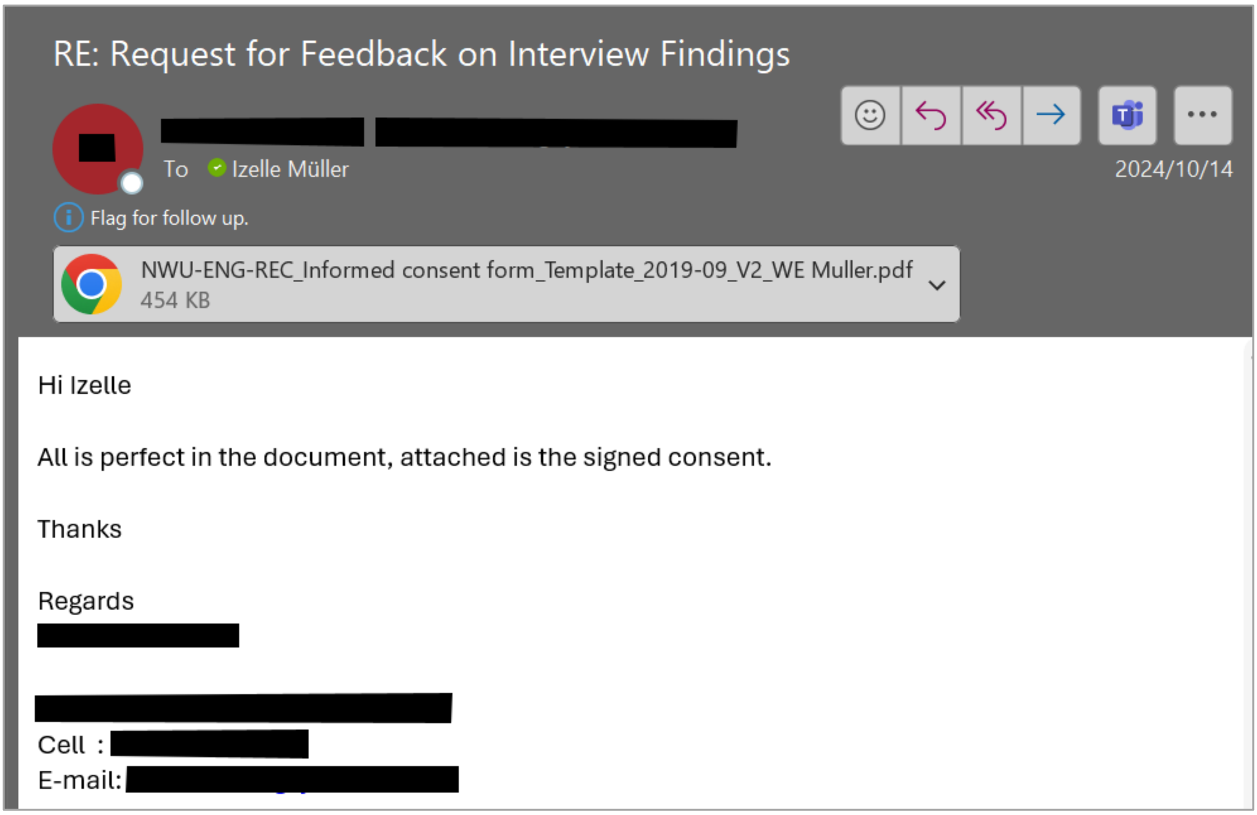
Hi Izelle,

I'm happy with the recorded information, which is an accurate summary of the interview.

Regards,

[redacted]
email; [redacted]
cell: [redacted]

Figure B.2: Participant C verification feedback



RE: Request for Feedback on Interview Findings

[redacted]

To Izelle Müller

2024/10/14

Flag for follow up.

NWU-ENG-REC_Informed consent form_Template_2019-09_V2_WE Muller.pdf
454 KB

Hi Izelle

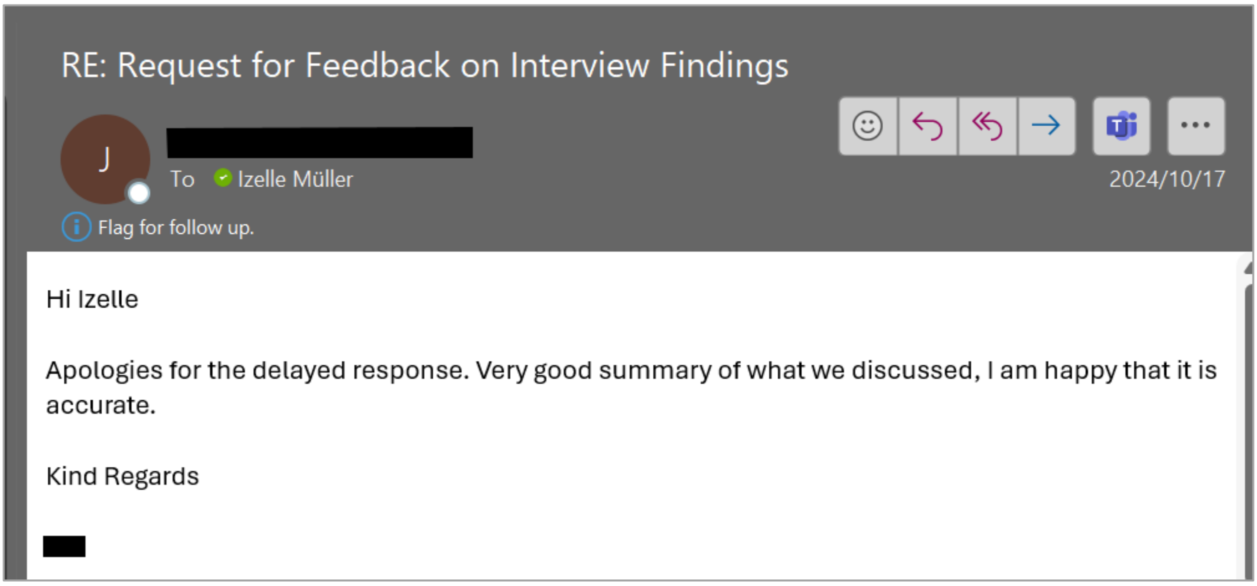
All is perfect in the document, attached is the signed consent.

Thanks

Regards
[redacted]

[redacted]
Cell : [redacted]
E-mail: [redacted]

Figure B.3: Participant D verification feedback



RE: Request for Feedback on Interview Findings

J [redacted]

To Izelle Müller

2024/10/17

Flag for follow up.

Hi Izelle

Apologies for the delayed response. Very good summary of what we discussed, I am happy that it is accurate.

Kind Regards

[redacted]

Figure B.4: Participant E verification feedback

RE: Request for Feedback on Interview Findings

AF [redacted]

To Izelle Müller

Reply | Reply All | Forward

Fri [redacted]

Flag for follow up.
You replied to this message on [redacted]

Hi Izelle, this is great! No further comments on my side!

When is your due date to have the interviews completed?

Regards,

[redacted]
Corporate | [redacted]
Mobile: [redacted]

Figure B.5 Participant G verification feedback

Re: Request for Feedback on Interview Findings

WH [redacted]

To Izelle Müller

Reply | Reply All | Forward

Thu [redacted]

Follow up. Start by Friday, 08 November 2024. Due by Friday, 08 November 2024.

Hi Izelle,

All good.

Good luck with the remaining interviews.

Figure B.6 Participant H verification feedback

RE: Request for Feedback on Interview Findings

HC [redacted]

To Izelle Müller

Reply | Reply All | Forward

Mon [redacted]

Flag for follow up.

Summary [redacted]
15 KB

NWU-ENG-REC_Informed consent form_Template_2019-09_V2_WE Muller.pdf
344 KB

Good morning, Izelle.

Just one small change in the summary – it is AR-Generated avatars and not AI, components of AI was used to add sound (voice over) automatically as we change the message daily for the end-users and to then translate this message into various other languages.

Also signed the other doc for you.

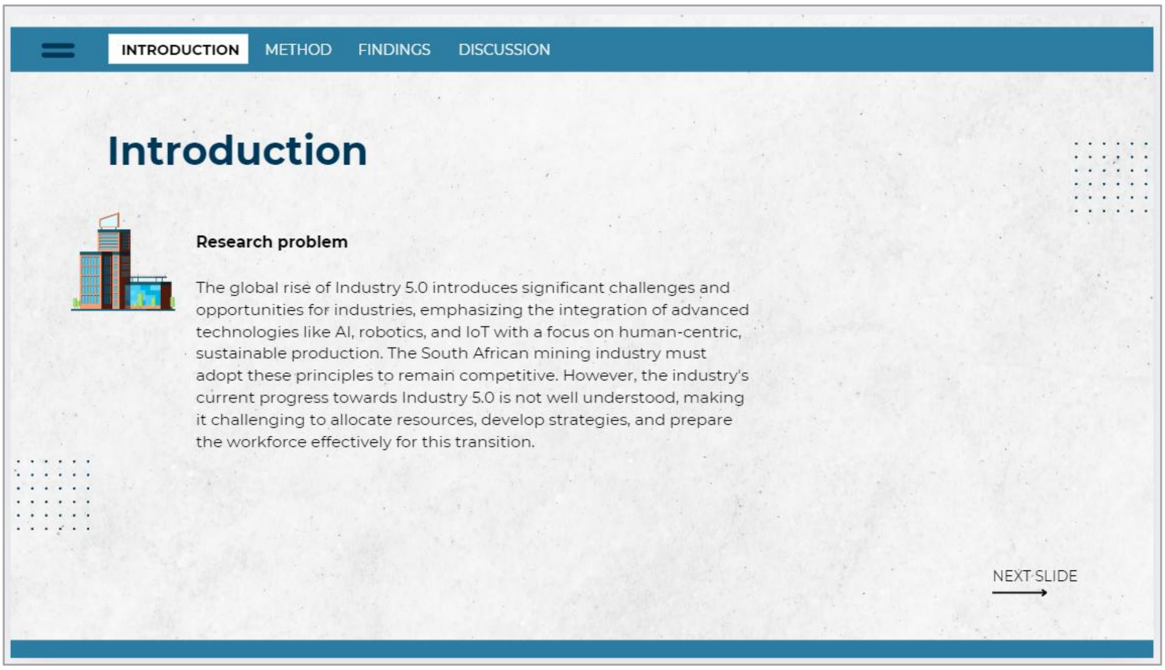
Have a great day and week.

Kind regards

Kind Regards,

Figure B.7 Participant J verification feedback

ANNEXURE C: VALIDATION PRESENTATION



INTRODUCTION METHOD FINDINGS DISCUSSION

Introduction

Purpose

The primary purpose of this research is to evaluate the progress of the South African mining industry in its transition towards Industry 5.0. This study aims to assess the current state of technological adoption, identify the challenges and opportunities faced by the industry, and to enable policymakers and industry leaders to provide strategic recommendations to facilitate this transition. Assessing current technological adoption.

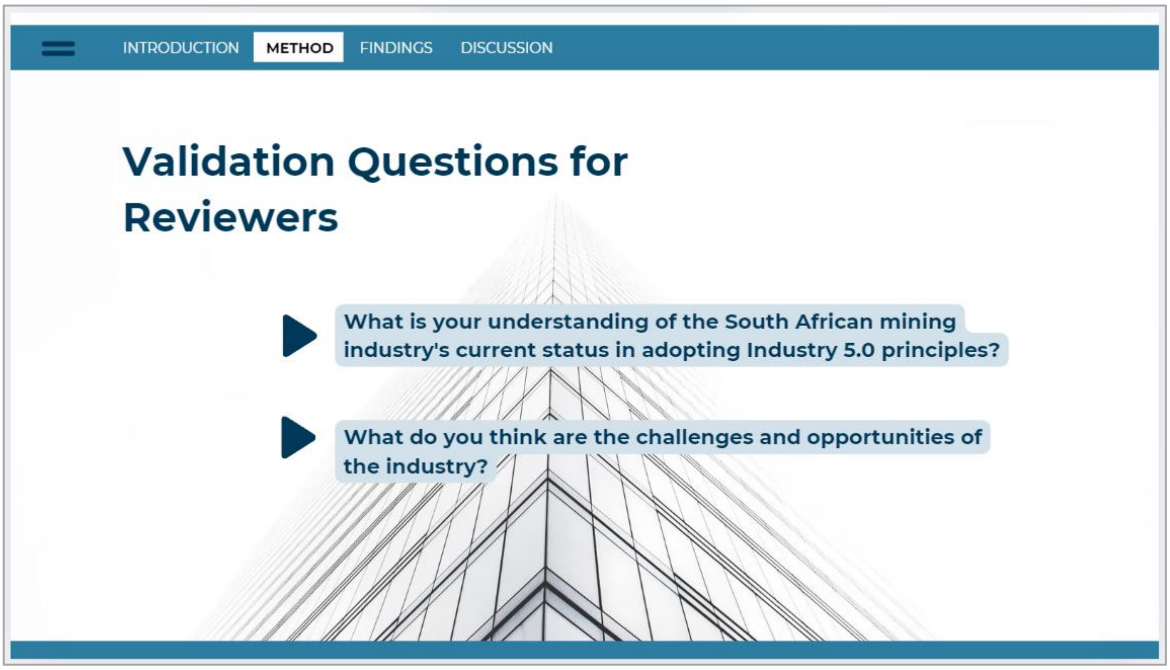
Objectives

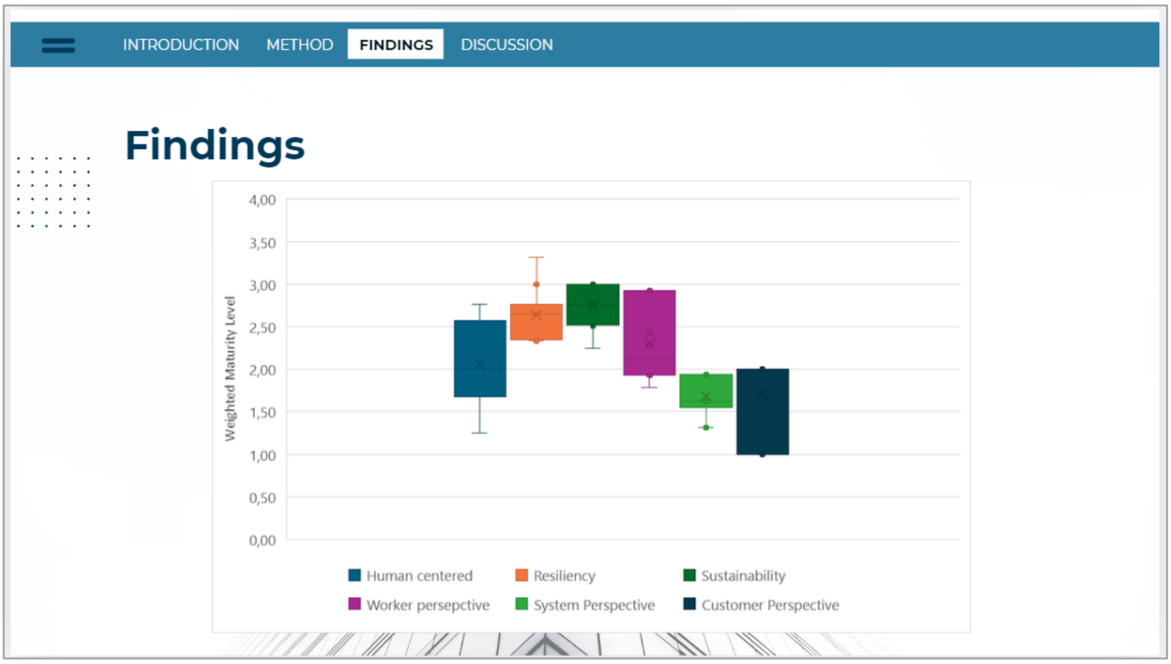
1. To explore current industry 5.0 research in the mining industry.
2. Explore existing Industry 5.0 frameworks through a scoping literature review and develop a general Industry 5.0 framework.
3. Empirical investigation - Evaluate the application of Industry 5.0 in the mining industry.
4. Conduct verification & validation.

INTRODUCTION METHOD FINDINGS DISCUSSION

Method

- In summary, this research employs a pragmatic, inductive approach to explore the South African mining industry's transition to Industry 5.0.
- The methodology integrates a scoping literature review, guided by PRISMA, to identify key themes and develop a structured framework.
- This is followed by a qualitative case study, utilising semi-structured interviews with industry stakeholders to gather in depth insights.
- Data collection involves both convenience and snowball sampling, with interviews conducted in person or virtually, and analysed through thematic analysis.
- This comprehensive approach ensures a thorough understanding of the complex interplay between technology and social factors in the industry's evolution.


INTRODUCTION
METHOD
FINDINGS
DISCUSSION
Validation Questions for Reviewers
What is your understanding of the South African mining industry's current status in adopting Industry 5.0 principles?
What do you think are the challenges and opportunities of the industry?


INTRODUCTION
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DISCUSSION
Findings
Weighted Maturity Level
4,00
3,50
3,00
2,50
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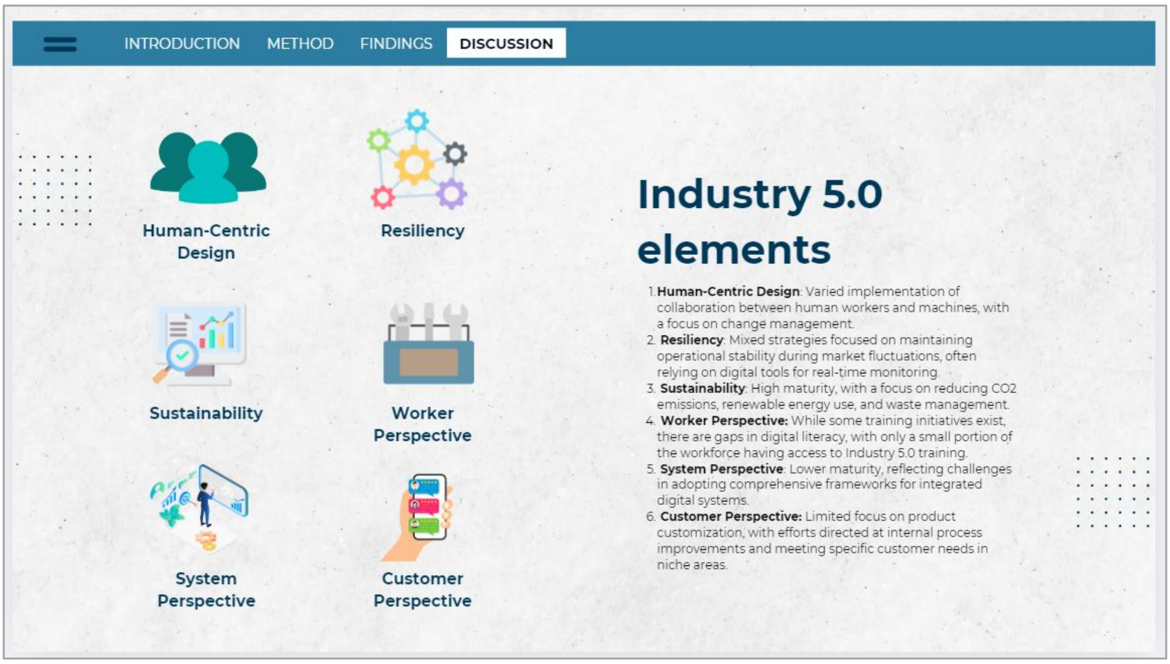
1,50
1,00
0,50
0,00
Human centered
Resiliency
Sustainability
Worker persepctive
System Perspective
Customer Perspective


INTRODUCTION
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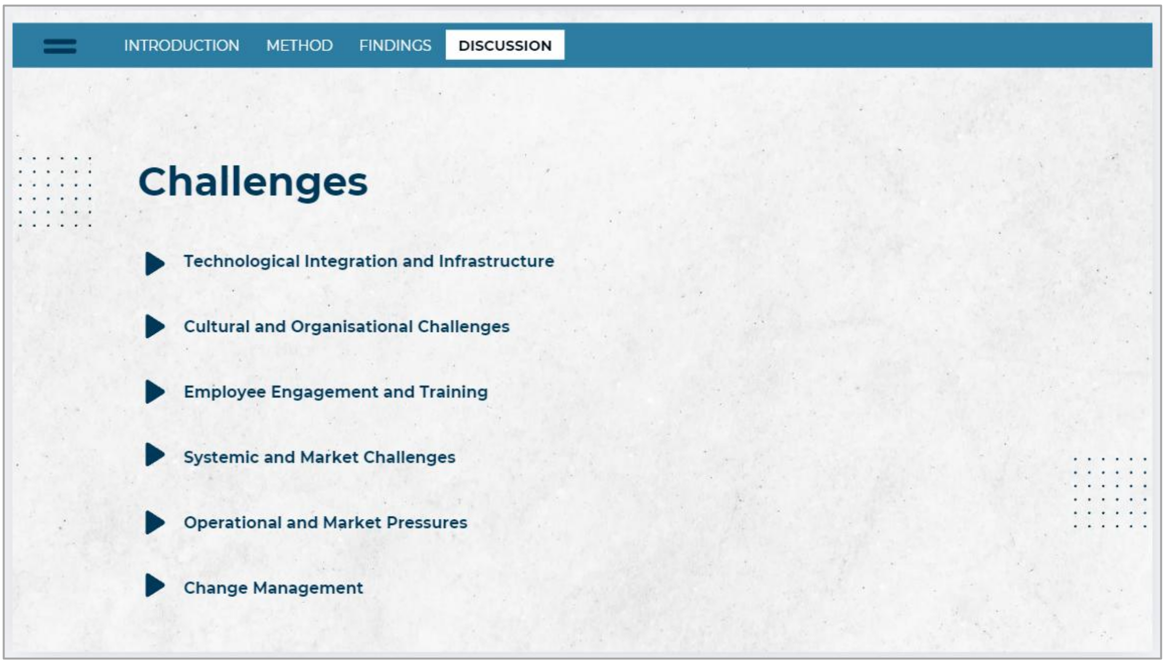
DISCUSSION
Human-Centric Design
Resiliency
Sustainability
Worker Perspective
System Perspective
Customer Perspective
Industry 5.0 elements
1. Human-Centric Design: Varied implementation of collaboration between human workers and machines, with a focus on change management.
2. Resiliency: Mixed strategies focused on maintaining operational stability during market fluctuations, often relying on digital tools for real-time monitoring.
3. Sustainability: High maturity, with a focus on reducing CO2 emissions, renewable energy use, and waste management.
4. Worker Perspective: While some training initiatives exist, there are gaps in digital literacy, with only a small portion of the workforce having access to Industry 5.0 training.
5. System Perspective: Lower maturity, reflecting challenges in adopting comprehensive frameworks for integrated digital systems.
6. Customer Perspective: Limited focus on product customization, with efforts directed at internal process improvements and meeting specific customer needs in niche areas.


INTRODUCTION
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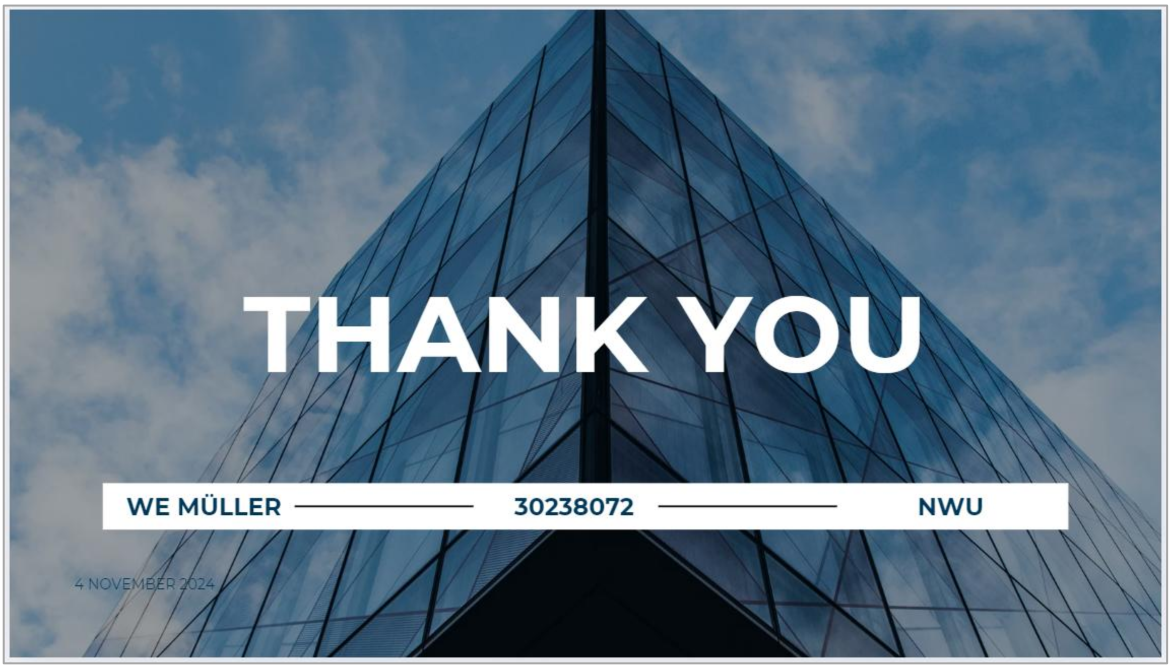
Technological Integration and Infrastructure
Cultural and Organisational Challenges
Employee Engagement and Training
Systemic and Market Challenges
Operational and Market Pressures
Change Management


THANK YOU
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4 NOVEMBER 2024