

**Drivers for Successful Digital Transformation in Advancing Environmental
Sustainability in Gauteng's Manufacturing Industry.**

23984083

23984083@mygibs.co.za

A research project submitted to the Gordon Institute of Business Science, University of Pretoria, in partial fulfillment of the requirements for the degree of Master of Business Administration

4 November 2024

ABSTRACT

Digital technologies (DT) and AI are key drivers of Digital Transformation and have revolutionised how businesses operate, resulting in unprecedented progress in promoting sustainability. A critical gap in integrating environmental sustainability considerations within digital transformation (DTx) has been identified. A clear understanding of the relationship between these concepts, among key stakeholders is needed to make informed decisions regarding DTx investments.

The manufacturing sector is at a critical juncture as concerns about environmental degradation intensify and sustainable practices become imperative. Studies in a different context found that DTx has the potential to transform traditional capital-intensive manufacturing assets to enhance environmental sustainability.

Through an exploratory qualitative study, this research project aimed to identify key success drivers for DTx on environmental sustainability. In particular AI's impact on greenhouse gas emission (GHG) reduction from the large manufacturing sector companies.

This study uncovered eight key drivers for the successful integration of AI technologies for sustainability, defined along both internal and external drivers, and benefits, challenges and risks. The results indicate that while AI adoption is still in the early phase, the study found that the benefits are indirect. Findings confirmed that for a successful AI-driven DTx to advance manufacturing environmental sustainability practices, there are significant hurdles to overcome. The present study will be valuable to researchers, practitioners, and government and policymakers.

KEYWORDS

Digital Transformation; Environmental Sustainability; Sustainable manufacturing; Industry 4.0; Artificial Intelligence

PLAGIARISM DECLARATION

I declare that this research project is my own work. It is submitted in partial fulfilment of the requirements for the degree of Master of Business Administration at the Gordon Institute of Business Science, University of Pretoria. It has not been submitted before for any degree or examination in any other University. I further declare that I have obtained the necessary authorisation and consent to carry out this research.

.....

Gwendoline Nyakallo Moshoeshoe

.....

Date

CONTENTS

ABSTRACT	i
KEYWORDS.....	ii
PLAGIARISM DECLARATION.....	iii
LIST OF FIGURES	iv
LIST OF TABLES	iv
ABBREVIATIONS.....	vi
1. INTRODUCTION TO THE RESEARCH PROBLEM	1
1.1 INTRODUCTION.....	1
1.2 BACKGROUND OF THE STUDY	2
1.3 RESEARCH PROBLEM STATEMENT	4
1.4 RESEARCH GAP	6
1.5 PURPOSE STATEMENT.....	6
1.6 SIGNIFICANCE OF THE STUDY	7
1.6.1 Significance for business.....	7
1.6.2 Significance for academic scholars and practitioners.....	8
1.7 RESEARCH QUESTIONS	9
2. LITERATURE REVIEW	11
2.1 INTRODUCTION.....	11
2.2 DIGITAL LEADERSHIP FACTORS.....	13
2.3 ORGANISATIONAL READINESS.....	14
2.4 CULTURAL AND MINDSET SHIFTS FOR ENVIRONMENTAL	16
2.5 BUILDING A DIGITAL-READY WORKFORCE	17
2.6 POLICY AND REGULATION: EXTERNAL FACTOR	18
2.7 DIGITAL SUPPLY CHAIN.....	20
2.8 SUSTAINABLE MANUFACTURING	21
2.9 DIGITAL TECHNOLOGIES	23
2.10 DATA-DRIVEN SUSTAINABILITY	24
2.11 ENVIRONMENTAL SUSTAINABILITY.....	26
2.12 INVESTMENT: SUSTAINABLE DIGITAL TRANSFORMATION.....	27
2.13 BENEFITS OF DIGITAL TRANSFORMATION	28
2.15 DIGITAL INNOVATION: SUSTAINABILITY AND RISK MANAGEMENT	31
2.16 CHALLENGES OF SUSTAINABLE MANUFACTURING	32
2.17 CONCLUSION AND INSIGHT	34
3. RESEARCH QUESTIONS.....	36

4. RESEARCH METHODOLOGY	39
4.1 INTRODUCTION.....	39
4.2 RESEARCH DESIGN	39
4.2.1 Philosophy: Interpretivism.....	39
4.2.2 Approach: Inductive	40
4.2.3 Purpose of Research Design: Exploratory.....	40
4.2.4 Research Strategy	41
4.2.5 Time Horizon.....	41
4.2.6 Methodological Choices.....	42
4.3 POPULATION.....	43
4.4 UNIT OF ANALYSIS	44
4.5 SAMPLING METHOD AND SIZE	45
4.6 MEASUREMENT	46
4.7 DATA GATHERING PROCESS	46
4.7.1 Interview Guide Design.....	47
4.7.2 Sample Preparation	47
4.7.3 Interviews.....	48
4.8 ANALYSIS APPROACH	48
4.8.1 Data Preparation.....	48
4.8.2 Coding and Categorisation	49
4.8.3 Data Saturation	50
4.9 DATA VALIDITY AND RELIABILITY.....	51
4.10 ETHICAL CLEARANCE	52
4.11 RESEARCH LIMITATIONS	53
5. FINDINGS/ RESULTS	55
5.1 INTRODUCTION.....	55
5.2 PARTICIPANTS OVERVIEW PROFILE	55
5.3 KEY THEMES – KEY SUCCESS DRIVERS EMERGED FROM THIS STUDY.....	59
5.3.1 Research Question 1 (Organisational Capabilities)	60
5.3.2 Research Question 2 (Impact)?	70
5.3.3 Research Question 3 (Opportunities and Challenges)	73
5.3.4 Research Questions 4 (Benefits and Challenges)	85
5.3.5 Research Question 5 (Risk).....	95
5.4 Overall Sentiments.....	98
6. DISCUSSIONS OF RESULTS	100
6.1 INTRODUCTION	100

6.2 DISCUSSION: RESEARCH QUESTION 1	100
6.2.1 Theme 1: Digital Leadership Drivers.....	101
6.2.2 Theme 2: Organisational Readiness for DTx Drivers	104
6.2.3 Theme 3: Building a Digital-Ready Workforce Drivers.....	107
6.2.4 Theme 4: Sustainable DTx: Investment Drivers	109
6.3 Research Question 2 (Impact).....	113
6.3.1 Theme 5: Holistic Performance Measurement.....	114
6.4 Research Question 3 (Opportunities and Challenges)	119
6.4.1 Theme 6: Policy and Regulation	119
6.4.2 Theme 7: Environmental Sustainability.....	123
6.4.3 Theme 8: Sustainable Manufacturing	125
6.4.4 Theme 9: Sustainability Risk Drivers	129
6.5 Research Questions 4 (Benefits and Challenges).....	133
6.5.1 Theme 10: Digital Sustainability: AI Digital Technologies Drivers	133
6.5.2 Theme 11: Benefits of DTx for Environmental Sustainability	137
6.5.3 Theme 12: Challenges in Implementing AI for Sustainable Manufacturing	140
6.6 Research Question 5 (Risk)	146
6.6.1 Theme 13: Digital Sustainability: Risk of AI Technology Adoption	146
7. CONCLUSIONS AND RECOMMENDATIONS	150
7.1 INTRODUCTION.....	150
7.2 RESEARCH FINDINGS.....	150
7.4 PROPOSED FRAMEWORK	166
7.3 PRACTICAL IMPLICATIONS FOR BUSINESS	169
7.4 PRACTICAL IMPLICATIONS FOR POLICY AND REGULATION	171
7.5 THEORETICAL IMPLICATIONS.....	174
7.6 LIMITATIONS TO THE RESEARCH STUDY	183
7.7 SUGGESTIONS FOR FUTURE RESEARCH	184
7.8 CONCLUSION	185
7.9.1 SUMMARY OF THE MAJOR STUDY CONTRIBUTION	186
7.9.2 URGENT CALL FOR ACTION	187
8. REFERENCE LIST	189
APPENDIX 1: INTERVIEW GUIDE	208
APPENDIX 2: EMAIL INVITE	212
APPENDIX 3: CONSENT FORM	213
APPENDIX 4: ETHICAL CLEARANCE	215
APPENDIX 5: AI-GENERATED CODES.....	216
APPENDIX 6: FINDINGS	265

APPENDIX 7: THEMES LINKED TO THE RESEARCH QUESTIONS.....	285
APPENDIX 8: CONSISTENCY MATRIX	286
APPENDIX 9: PROPOSED FRAMEWORK	289

LIST OF FIGURES

Figure 1: Data Saturation	50
Figure 2: Research Question 1 Summary Framework	113
Figure 3: Research Question 2 Summary Framework	118
Figure 4: Research Question 3 Summary Framework	132
Figure 5: Research Question 4 Summary Framework	145
Figure 6: Research Question 5 Summary Framework	149
Figure 7: Proposed Framework	166

LIST OF TABLES

Table 1: Interview Participant Profile	57
Table 2: Theme 1. Digital Leadership Drivers Findings	103
Table 3: Theme 2. Organisational readiness for DTx drivers Findings	106
Table 4: Theme 3. Building a digital-ready workforce drivers Findings.....	108
Table 5: Theme 4. Sustainable DTx: Investment Drivers Findings	111
Table 6: Theme 5. Holistic Performance Measurement Findings	116
Table 7: Theme 6. Policy and Regulation	122
Table 8: Theme 7. Environmental Sustainability	124
Table 9: Theme 8. Sustainable Manufacturing.....	127
Table 10: Theme 9. Sustainability Risk Drivers.....	130
Table 11: Global Lighthouse Projects.....	134
Table 12: Theme 10. Digital Sustainability: AI Digital Technologies drivers.....	136
Table 13: Theme 11. Benefits of DTx for Environmental Sustainability	139
Table 14: Theme 11. Benefits of DTx for Environmental Sustainability	143
Table 15: Theme 13. Digital Sustainability: Risk of AI technology adoption	148
Table 16: Internal drivers.....	167
Table 17: External drivers.....	168

Table 18: Benefits, Opportunities, Challenges and Risk.....	168
Table 19: Policy – Tax Incentives	172
Table 20: Policy – Subsidies and Grants	173
Table 21: AI and DTx for environmental sustainability theoretical contribution.....	179

ABBREVIATIONS

AI	Artificial Intelligence
BDA	Big Data Analytics
CE	Circular Economy
CO ₂	Carbon Dioxide
DFFE	Department of Forestry, Fisheries and the Environment
DT	Digital Technologies
DTI	Department of Trade and Industry
DTx	Digital Transformation
Ells	Energy-intensive industries
ESG	Environmental, Social and Governance
Gen AI	Generative Artificial Intelligence
GHG	Greenhouse Gas
HRM	Human Resource Management
I4.0	Fourth Industrial Technologies
IIoT	Industrial Internet of Things
IT	Information Technology
JSE	Johannesburg Stock Exchange
MES	Manufacturing Execution System
MNC	Multinational Corporates
MVA	Manufactured Value Added
NO _x	Nitrogen Oxide
POC	Proof of concepts
SCCM	Sustainable Supply Chain Management
SDG	Sustainable Development Goals
SM	Sustainable Manufacturing
SME	Small and Medium-sized Enterprises
SO _x	Sulphur Dioxide
WEF	World Economic Forum

1. INTRODUCTION TO THE RESEARCH PROBLEM

1.1 INTRODUCTION

“The illiterate of the 21st century will not be those who cannot read and write, but those who cannot learn, unlearn, and relearn.” - Alvin Toffler

Undoubtedly, digital technologies (DT) have revolutionised how businesses operate, resulting in unprecedented progress in promoting sustainability (Jonsson, Mathiassen, & Holmström, 2018). Holmstrom (2022) concluded that for today's organisations, AI is a key driver of Digital Transformation (DTx), this view is supported by Li, Hou, Yu, Lu and Yang (2017). According to Kraus, Jones, Kailer, Weinmann, Chaparro-Banegas and Roig-Tierno (2021), the manufacturing industry is particularly noteworthy as it heavily relies on physical resources, intricate production processes, and significant energy consumption. Consequently, the unique characteristics of the manufacturing sector create distinct environmental sustainability challenges.

Guandalini (2022) identified a critical gap in integrating environmental sustainability considerations within digital transformation (DTx). Nevertheless, without a clear understanding of the relationship between these concepts, businesses, organisations, and policymakers may have struggled to make informed decisions regarding DTx investments. Consequently, this lack of clarity could lead to missed opportunities to leverage technology for sustainability goals or unintended negative environmental consequences. Recent research has emphasised that incorporating digital transformation technologies can serve as a powerful catalyst for promoting sustainable practices within the manufacturing sector (Machado, Scavarda, Caiado, & Thomé, 2021; Moghrabi, Bhat, Szczuko, AlKhaled, & Dar, 2023).

Building on Rusch, Schöggel and Baumgartner (2023) call for future research, this proposal aimed to address a significant knowledge gap by exploring the untapped potential of Artificial Intelligence (AI) in the manufacturing industry. Therefore, this suggested that DTx can revolutionise capital-intensive manufacturing assets and advance environmental sustainability (Junior, Busso, Gobbo, & Carreão, 2018;

Dubey, Gunasekaran, Childe, Blome, & Papadopoulos, 2019; Li, Dai, & Cui, 2020; Ardito, Raby, Albino, & Bertoldi, 2021).

Through an exploratory study, this research project aimed to understand the impact of DTx on environmental sustainability, specifically the impact on greenhouse gas emission (GHG) reduction, waste reduction, and energy efficiency to preserve the environment from the large manufacturing sector companies based in Gauteng.

1.2 BACKGROUND OF THE STUDY

The manufacturing sector faces a critical juncture as concerns about environmental degradation intensify and sustainable practices become imperative (Narkhede, Chinchankar, Narkhede, & Chaudhari, 2024). Environmental degradation, stemming from wastage and inefficient manufacturing practices, has been a pressing concern since the Industrial Revolution (Demir, Döven, & Sezen, 2019; Narkhede et al., 2023). Omri, Euch, Hasaballah and Al-Tit (2019) describe environmental sustainability as making responsible decisions to reduce your business's negative environmental impact. It entails making choices and implementing measures to safeguard the natural world, emphasising preserving the environment's capability to support human life.

Awasthi, Saxena and Arun (2020) balance environmental protection without compromising innovation for progress. According to the UNIDO (2023) report, the global industrial sector valued at USD 19 trillion, contributes 21.4% to the global Gross Domestic Product (GDP), with manufacturing accounting for 75% (USD 15 trillion). SA's manufacturing sector contributes R 813 billion (14%) to SA's GDP (de Beer, 2023). Despite declining since 2014, manufacturing still accounts for 19% of total greenhouse gas (GHG) emissions (South African Reserve Bank, 2020).

Gauteng is SA's manufacturing hub, accounting for 40.5% of the total manufacturing industry stated de Beer (2023). SA greenhouse emissions increased from 185 million (1970) to 405 million in 2022, driven by industrial activity (Tiseo, 2023). According to Steyn, Genthe, Banoo, Thwala, Roos, Walters and Ramakhwatho (2020), the SA

industry consumes 7% of the water consumption and generates the highest effluent. Despite the current challenges of meeting environmental targets, Bekun (2024) stated that the South African economy is poised for further growth driven by industrialisation and urbanisation. The expansion entails potential greenhouse gas emission increases, particularly carbon dioxide due to environmental trade-offs (Udeagha & Muchapondwa, 2023). There remains a considerable journey ahead in advancing environmental sustainability within communities where the manufacturing sector is present (Moghrabi et al., 2023). Recognising the existence of an "awareness gap" is vital, as it underscores the fact that sustainability is not only a moral obligation but also a crucial element for business prosperity (Kraus et al., 2021).

DTx global spending is projected to increase from USD 1.85 trillion in 2022 to USD 3.9 trillion in 2027, with a compound annual growth rate (CAGR) of 13.24% (Sherif, 2024). Artificial Intelligence (AI) economic impact is estimated at USD 15.7 Trillion by 2030 (Rao & Verweij, 2017), and SAAI economic potential contribution is USD 52.2 billion (Mashishi, 2023). IDC projected that by 2019, 40% of digital transformation initiatives would incorporate AI services, and by 2021, 75% of business applications would utilise AI (Jimenez, Lim, Cheok, & Ng, 2018). This focus on AI-specific digital technology is driven by its ability to enhance efficiency, automate complex tasks, and provide valuable insights, thereby significantly contributing to innovation and strategic business objectives.

Gaffley and Pelsers's (2021) study revealed SA's Manufacturing Sector DTx standing at 47.7%. In addition, a recent survey by Accenture of 50 C-suite executives in SA highlights a strong commitment to DTx within the manufacturing sector (Mngxati & Seedat, 2023). The survey indicated a high adoption rate (74%) of enterprise-wide DTx strategy execution. Notably, the commitment remains strong (84%) despite potential economic headwinds, such as a recession.

According to Guandalini (2022), there is a lack of consistent definitions and terminology of DTx across literature; Abdallah, Shehab and Al-Ashaab (2022) state that digital is a generic term. Despite the lack of a universally agreed definition, LeHong and Waller (2022) describe DTx as leveraging ever-rapidly evolving disruptive DTx and capabilities to create a new business model that can withstand the ever-evolving digital landscape. Chiarini (2021) posits that the integration of

digital technology in manufacturing, facilitated by Industry 4.0 (I4.0), encompasses a comprehensive suite of technologies. This entails Industrial Internet of Things (IIoT), cloud computing, automated mobile robots (AMR), autonomous guided vehicles (AGV), collaborative robots (cobots), analytics and artificial intelligence (AI), simulation, smart sensors and products, radio-frequency identification (RFID), additive manufacturing, and augmented reality (Chiarini, 2021).

This convergence of technologies enables the transformation of traditional manufacturing paradigms into advanced, data-driven, and interconnected industrial systems. According to Moghrabi et al. (2023), the main goal of DTx is to drive revenue growth and ensure the business's survival in the current era of rapid technological development. The World Economic Forum (WEF), in collaboration with McKinsey & Company, has established the Global Lighthouse Network to identify and showcase leading manufacturers successfully implementing I4.0 solutions, namely AI, big data analytics (BDA), IIoT, digital twin to drive achieving environmental sustainability outcomes (Betti, Desnos, Giraud, & Torti, 2023; de Boer & Torti, 2023).

1.3 RESEARCH PROBLEM STATEMENT

Previous studies found that DTx has the potential to transform traditional capital-intensive manufacturing assets and offer a range of opportunities to enhance environmental sustainability (Junior et al., 2018; Dubey et al., 2019; Li et al., 2020; Ardito et al., 2021). However, the majority of these studies were conducted in different contexts; (Denicolai, Zucchella, & Magnani, 2021; Bag, Gupta, Kumar, & Sivarajah, 2021a; Truong, 2022; Muthuswamy & Ali, 2023; Schöggli, Rusch, Stumpf, & Baumgartner, 2023). Meanwhile, studies that examined the South African context, Bag, Wood, Xu, Dhamija and Kayikci (2020) and Bag, Gupta and Dwivedi (2021b), automotive industry sustainability and circular economy (CE); Gaffley and Pelser (2021) focused on DTx in general. While previous studies stated the benefits, however, research by Ngepah, Saba and Kajewole (2024) indicated a significant association between I4.0 adoption and a decrease in South Africa's manufacturing value added (MVA).

In addition, although previous research has suggested a positive link between digital transformation and sustainability, recent studies by George, Merrill and Schillebeeckx (2022) and Guandalini (2022) have found conflicting results. This finding points towards possible challenges hindering the effectiveness of I4.0 implementation in South Africa's manufacturing sector. Chiarini's (2021) study in Italian Manufacturing revealed that AI plays a crucial role in enabling proactive maintenance, enhancements in processes, and data-driven decision-making, ultimately promoting sustainable manufacturing (SM) practices. This perspective is aligned with the work of Rusch et al. (2023) and Schöggl et al. (2023) which argued that the integration of AI in the manufacturing sector has the potential to revolutionise environmental sustainability.

An earlier study in Germany's manufacturing sector by Veile, Kiel, Müller and Voigt (2020) revealed that small and medium-sized enterprises (SMEs) are generally lagging in their readiness for the adoption of DT or I4.0 technologies. While the study found that certain drivers, such as competitiveness and innovation, have a positive impact on DT readiness and adoption into organisations, there is no evidence that barriers, such as lack of expertise and financial resources, significantly hinder SME readiness. The study concluded by proposing future research considers differentiated analysis regarding varying company size, value chain positions and other contextual factors such as nations and industry sectors.

Therefore, there is still a significant knowledge gap that exists regarding success drivers and how manufacturing leaders can effectively leverage DT such as AI, to achieve environmental sustainability, particularly greenhouse emissions through DTx. This oversight is particularly concerning given the critical need for sustainable practices in developing economies like SA. As highlighted by Yadav, Kumar, Luthra, Garza-Reyes, Kumar and Batista (2020), there is a significant gap in sustainability practices in developing countries. In addition, the study emphasises that sustainability is crucial for businesses, neglecting it can lead to significant financial consequences. Moreover, the 2030 sustainability targets will not be met. Furthermore, there is a growing risk of boycotts from consumers who are increasingly concerned about environmental issues.

As Guandalini (2022) astutely observes, the question of how DTx can improve sustainability remains largely unaddressed. Addressing this knowledge gap is crucial

for the development of AI-driven strategies that can support the transition towards environmental SM practices, mitigate environmental degradation, and promote eco-friendly production in the region.

1.4 RESEARCH GAP

Despite the promise of DTx for a sustainable future and enterprise long-term benefits, a significant knowledge gap exists regarding the drivers of success for effective implementation and adoption of AI-driven environmental sustainability solutions in the manufacturing sector, particularly in the context of Gauteng, South Africa. Building on the call for future research, Schöggli et al. (2023), proposed future research to explore the underutilised potential of AI and further detail drivers and barriers of DTx implementation for achieving environmental sustainability in different contexts.

In addition, building on the drivers and barriers study by Veile et al., (2020), this study aimed to investigate how AI can be leveraged to support environmental sustainability in the manufacturing sector in Gauteng and what organisational internal and external factors drivers of success are crucial to facilitate the adoption of AI-driven sustainability solutions. This research was crucial for addressing the current shortcomings in meeting the needs of manufacturing industries in the digital era, where digital transformation is essential for achieving environmental sustainability goals. By exploring this knowledge gap, this study can contribute to the development of effective strategies for promoting environmental sustainability practices and reducing the ecological footprint of the manufacturing sector in South Africa.

1.5 PURPOSE STATEMENT

According to a recent study by Kraus et al. (2021), the manufacturing and oil and gas industries are emerging players in the Digital Transformation (DT) journey. While there is a great deal of interest in this topic among scholars and practitioners alike, Guandalini's (2022) systematic literature review on sustainability through digital

transformation highlights that the question of how digital transformation can improve sustainability still requires significant attention. The researcher suggests that academic research should keep pace with the real-world application of digital tools to advance sustainability efforts.

This qualitative research investigates the key drivers of successful DT initiatives that advance environmental sustainability in Gauteng's manufacturing industry. Specifically, this study explored the key drivers of success for the integration of DT, challenges and barriers, opportunities, and effects for the adoption and effective implementation of AI and I4.0 technologies to advance environmental sustainability practices within the manufacturing sector. The aim of this research study was to equip manufacturers with actionable insights to overcome obstacles and advance toward a more sustainable future while also providing valuable insights and guidance for policymakers and academic scholars.

By bridging the knowledge gap and broadening our understanding of DTx's role in promoting sustainability, this research addresses the development of sustainable manufacturing through the adoption of digital technologies in the South African context. Moreover, the study made a significant theoretical contribution relating to the factors influencing digital technology adoption, the role of the drivers and barriers, and added to the development of digital transformation for sustainable manufacturing for the Gauteng Manufacturing sector.

1.6 SIGNIFICANCE OF THE STUDY

1.6.1 Significance for business

The importance of the study lies in its exploration of the untapped potential of AI in the manufacturing industry to drive sustainable practices and contribute to manufacturers' long-term strategic objectives. The urgency of the study stems from the critical need to address environmental degradation and promote sustainable practices within the manufacturing sector to meet Sustainable Development Goals.

The study addressed a significant knowledge gap by exploring how DTx can transform capital-intensive manufacturing assets and advance environmental

sustainability. The research aimed to explore and understand the key drivers of the success of digital transformation impact on environmental sustainability specifically focused on GHG emissions reduction, waste reduction, and energy efficiency in large manufacturing companies based in Gauteng. The study highlights the critical need for sustainable practices in the manufacturing sector, given the sector's substantial contribution to environmental degradation and greenhouse gas emissions.

This research is crucial for addressing the deficiencies in meeting the requirements of the manufacturing industries within the digital era, where digital transformation is a catalyst (Kraus et al., 2021) for achieving regulatory environmental sustainability targets.

1.6.2 Significance for academic scholars and practitioners

The significance of this study for academic scholars and practitioners lies in its exploration of the factors driving successful digital transformation to enhance environmental sustainability within the manufacturing sector. By bridging the knowledge gap, provides valuable theoretical insights and practical implications. Furthermore, it provides contextual relevance and articulates future research direction.

Bridging knowledge gap: Building upon the previous research of Schöggli et al. (2023) and Veile et al. (2020), which highlighted the need for further exploration of AI's potential and the drivers, challenges, and risk of DTx implementation, this study contributes to the literature and the existing body of knowledge. The study explored the drivers of success, challenges, benefits and risks of integrating AI digital technologies through digital transformation. A contribution to a more comprehensive understanding of the intersection between digital transformation and environmental sustainability for the manufacturing sector.

Theoretical contribution: The research study provides valuable theoretical insights that enhance the understanding of how DTx, through the adoption of DT, specifically AI technologies, can drive sustainable practices in the manufacturing industry. The key drivers of success for the adoption and implementation of AI-driven environmental sustainability explored in this study contribute to the theoretical

framework on the factors influencing DT adoption to transform traditional manufacturing into sustainable manufacturing. Moreover, the role of drivers, barriers and challenges, and risk in promoting sustainable manufacturing.

Contextual factors: This study focused on the manufacturing sector in South Africa to explore the success drivers of integrating AI to drive sustainable manufacturing. Previous studies on DTx suggested contextual factors are crucial for the integration and adoption of DT inspired by 4IR (Mikalef, Boura, Lekakos, & Krogstie, 2019). This study, first in the SA context, seeks to understand how the integration of AI technologies can drive sustainable manufacturing. What are the key drivers of success, barriers, challenges, benefits and risks? The contextual factors surfaced lived experiences, values and insights.

Practical implications: The findings of this study have significant implications for industry players, policymakers and practitioners. The study aimed to provide actionable insight to the South African manufacturing industry.

Future research direction: Given the exploratory nature of the study and its small, non-purposive sample, the findings cannot be generalised to the broader population of manufacturing companies in Gauteng. Future research could open new opportunities to further explore the untapped potential of AI in addressing sustainability in traditional manufacturing.

1.7 RESEARCH QUESTIONS

The thematic literature review identified several knowledge gaps. This study prioritised and explored the key drivers of successful DTx in advancing environmental sustainability practices in the manufacturing sector in Gauteng, South Africa. Specifically, it explored the impact of AI integration on environmental sustainability, with a focus on GHG emissions reduction. The main research question was broken down into several specific questions to guide the research process.

The research questions (RQ#) for the study:

RQ1 (Organisational Capabilities): What are the key drivers for the successful adoption of DT AI in the Manufacturing sector to achieve the environmental sustainability dimension of greenhouse gas emission reduction? (Mhlungu, Chen, & Alkema, 2019; Horvath & Szabo, 2019; Debnath, Shakur, Bari, Saha, Porna, Mishu, ... & Rahman 2023; Bag et al., 2021b)

RQ2 (Impact): How is success measured for measuring the effect of adopting DT for environmental sustainability dimension? (Awasthi et al., 2020; Dauvergne, 2022)

RQ3 (Opportunities and Challenges): What policy initiatives and regulatory frameworks are necessary to promote sustainable development in the South African manufacturing sector? (Dubey, Gunasekaran, Childe, Bryde, Giannakis, Foropon, ... & Hazen, 2020; Udeagha & Muchapondwa, 2023)

RQ4 (Challenges): What are the potential environmental benefits and challenges, barriers, and constraints faced by manufacturing organisations when implementing DTx for sustainability purposes? (Horvath & Szabo, 2019; Schöggl et al., 2023)

RQ5 (Risk): What are the potential negative effects, direct and indirect, of implementing DT such as AI for environmental sustainability? (Chiarini, 2021; Truong, 2022)

The subsequent chapter delves into the existing literature pertaining to this qualitative and exploratory study. By examining relevant research, this research aimed to establish the study's context within the broader field of research and offers valuable insights that influence and shape the formulations of the research questions.

2. LITERATURE REVIEW

2.1 INTRODUCTION

In the ever-changing landscape of academic research, one crucial aspect that remains constant is the significance of the literature review. Through a systematic review of the existing literature, researchers aimed to identify gaps, explore established theories, and chart paths for new insights and discoveries. For this research, the thematic literature review was adopted to delve into a specific topic of interest, aiming to synthesise existing knowledge and shed light on unexplored problems. A thematic literature review is related to categorising and analysing diverse narratives pertaining to a specific subject matter. It enables researchers to discern overarching themes within a field by clustering related information. Snyder (2019) asserted that a thematic literature review is a semi-systematic review suited for covering broad topics and for understanding complex areas. This perspective is aligned with the study by Nowell, Norris, White and Moules (2017) who stated that thematic reviews offer a flexible approach and are well-suited for complex research topics with diverse methodologies and theoretical frameworks.

This approach helps us uncover the most important ideas, theories, and challenges in a field of study, giving us a deeper understanding of the research landscape and the conversations that are driving it forward. In addition, by examining the key themes within the literature, this review aimed to establish the current state of knowledge, highlight established theories and concepts, identify any gaps or inconsistencies in the existing research, and analyse the methodologies adopted in previous studies (Nowell et al., 2017). Guandalini (2022) study argued the multifaceted nature of achieving sustainability through DTx.

This final thematic literature review integrates new themes identified from the qualitative data analysis process and requires a systematic approach (Braun & Clarke, 2006). The review started with the re-evaluation of existing themes to examine connections and potential overlaps to determine if the new themes can be integrated or require distinct categories. Reorganisation of the review, including the addition of new sections or subsections, may be required to maintain logical

coherence. Analysing interrelationships between themes and updating the introduction and conclusion to reflect new themes are essential for a comprehensive analysis (Ryan & Bernard, 2003).

Finally, the integrated thematic review provides a comprehensive analysis of the factors driving successful digital transformation initiatives in the Gauteng manufacturing industry, with a particular focus on advancing environmental sustainability through the adoption of digital technology AI to reduce greenhouse gas emissions, reduce waste and improve energy efficiency. Through a systematic categorisation and analysis of the extant literature, this review aim was to identify pivotal themes, discernible patterns, and knowledge gaps within the research domain. This approach enabled this study to delve deeper and understand the key drivers, challenges and opportunities, benefits and risks associated with digital transformation for promoting sustainable manufacturing practices. By synthesising research findings across thematic areas, this study aimed to achieve a deeper understanding of the key drives fostering successful DTx in advancing environmental sustainability in Gauteng's Manufacturing Industry.

The thematic analysis has yielded several overarching categories that encompass the key drivers of digital transformation and environmental sustainability. Building upon these insights, the following themes emerged as vital components in understanding the interplay between digital technologies and sustainability:

The foundations of digital transformation emphasise key themes such as digital leadership, organisational readiness, and the importance of building a digital-ready workforce. Building upon these foundational themes, the thematic analysis also identified environmental sustainability-related themes, cultural shifts, the influence of policy and regulation, and the implementation of sustainable practices within supply chains and manufacturing processes.

The analysis also highlights the role of digital technologies in enhancing sustainability and managing risks. Furthermore, it underscored the significance of enabling the outcomes factors, such as investment in supporting these initiatives, the benefits of digital transformation, and the need for holistic performance measurement to assess the overall impact of both digital and sustainability efforts.

2.2 DIGITAL LEADERSHIP FACTORS

The integration of different critical concepts, environmental sustainability and the combination of AI and DTX necessitates fundamentals to the role of leadership. Effective leadership strategies and best practices are crucial for driving DTx for environmental sustainability in the manufacturing sector. A previous study by Gaffley and Pelser (2021) revealed that Chief Executive Officers (CEOs) and C-suite Executive teams must lead digital strategies. These findings align with Abdalla (2022) that leadership and strategy are key elements that contribute to the successful integration of DTx. In addition, a study of manufacturing DTx in Egypt asserted that top management is one of the key success practices (Abdalla, 2022). While the literature is consistent on the role of top management for DTx. Aftab, Abid, Sarwar and Veneziani (2022) highlight an integrated view of environmental sustainability and innovation. Top management commitment to environmental leadership drives innovation to reduce greenhouse gas emissions to achieve low-carbon development and sustainable practices (Aftab et al., 2022).

Building on this, previous studies by Li, Yang, Yang, Zhu and Yin (2018) and Ukko, Nasiri, Saunila and Rantala (2019) suggested DTx is a leadership and management issue rather than a technical or operational issue. The study concluded that values drive leadership and management support is crucial to drive towards environmental leadership, transformational leadership, and value-driven leadership. According to Eide, Saether and Aspelund (2020), the personal motivation of leaders has an impact on the organisation's sustainability strategy, which in turn perceives greater value creation and achieves positive outcomes from their sustainability initiatives. Moreover, these leaders should possess open mindsets and creativity to enable extensive cross-sharing of knowledge and data, both internally and externally, during the DTx project.

Furthermore, Isensee, Teuteberg, Griese and Topi (2020) study in the SME context highlighted various management concepts that target environmental sustainability. The study found that managers play a crucial role in shaping employee attitudes towards sustainability by providing support and demonstrating values-based leadership. Additionally, cultural factors such as collaboration, ethics, internal capabilities, strategic orientation, and values influence employee beliefs and

attitudes. Thus, managerial influence and a positive attitude can contribute to the successful implementation of digital initiatives to achieve environmental sustainability targets. Furthermore, Ukko et al. (2019) argues that a successful digital business strategy, combined with a strong sustainability strategy, can lead not only to improved financial outcomes but also improved environmental performance.

While Horváth and Szabó (2019) acknowledge the significance of leadership, they argue that organisations may navigate potentially disruptive shifts in leadership roles to integrate AI and drive successful DTx. The emphasis on leaders with specific qualities, particularly the need for strategic thinking across complex networks, might overlook the existing capabilities of current leadership within organisations (Horváth & Szabó, 2019). In addition to these specific challenges, Holmstrom (2022) argued that many leaders struggle to effectively address the organisational challenges associated with AI integration and DTx.

While literature highlights the critical role of leadership in integrating seemingly different and complex phenomena, it recognises the potential disruption to leadership roles and challenges. Therefore, this raises a critical question: Is the leadership a key success driver or a barrier in the integration of AI and DTx for advancing environmental sustainability within the manufacturing sector?

2.3 ORGANISATIONAL READINESS

While previous studies highlighted the potential of DTx technologies, such as AI, to address environmental challenges (Chiarini, 2021; Rusch et al., 2023; Schögl et al., 2023), the successful adoption hinges on an organisation's readiness for DTx (Mikalef et al., 2019; Holopainen, Ukko, & Saunila, 2022). However, organisational resistance poses a significant barrier to technological change, according to Horváth and Szabó (2019). This corroborates with the study by Ching, Ghobakhloo, Iranmanesh, Maroufkhani and Asadi (2022) that organisational resistance is the most powerful obstacle to technological change. Moreover, DTx is a complex phenomenon that encompasses technological advancements and social-economic factors (Guandalini, 2022).

Therefore, organisational readiness is a multifaceted concept, comprising various critical sub-dimensions, including technological, organisational, cultural and human resources, strategic alignment, and financial readiness, essential for successful DTx implementation. This understanding has significant implications for organisations seeking to leverage DTx technologies such as AI and combinational DTs to drive environmental sustainability and underscores the need for a comprehensive approach to organisational readiness. As Holmstrom (2022) suggests, to fully benefit from AI and DTx, organisations must not only adopt new technologies but also adapt and simultaneously adjust organisation resources, culture and decision-making process.

Holopainen et al. (2022), stated the importance of assessing the organisation's overall readiness to leverage DTx in the context of company-wide business objectives. Holmstrom (2022) asserted that for AI integration, organisations must assess readiness along the four pillars: technology, organisational activities, boundaries, and goals. Moreover, the study by Holopainen (2022) conceptualised strategic readiness as an organisation-wide enduring state of preparedness for a comprehensive and systematic change toward digital technology implementation. Aligned with this perspective, Ching et al. (2022) argued that effectively leveraging DTx, particularly AI, for environmental sustainability necessitates a radical transformation of workforce skillsets, surpassing traditional professional (Nguyen, Duong, Van Nguyen, Zhu, & Zhou, 2022; Nimawat & Gidwani, 2022). Building on this, Holopainen et al. (2022) emphasise that beyond technology readiness, other factors come into play, such as organisational structure, leadership role shifts, management capabilities, and culture of openness to change, industry and economic situations are all critical for realising the intended business benefits from digital technology implementation. In addition, the study revealed that strategic readiness entails crucial practices for fostering, measuring, and strengthening digital operations.

Horváth and Szabó (2019) underscored the crucial role of effective change management strategies in enabling leadership to navigate disruptive shifts, address employee anxieties, and support reskilling initiatives. Building on this insight, Saldanha (2019) revealed the alarming rate of DTx failures, estimated at 70%. This stark reality highlights the limitations of prioritising technical aspects of DTx while neglecting the human element. Consequently, extending this viewpoint, it is

imperative to investigate the key success drivers related to contextual organisational readiness for AI adoption, specifically in the Gauteng manufacturing sector, to drive environmental sustainability. This research endeavours to address this blind spot, exploring the critical factors necessary for user adoption and organisational inertia mitigation, thereby providing a comprehensive understanding of AI-driven sustainability in the sector.

2.4 CULTURAL AND MINDSET SHIFTS FOR ENVIRONMENTAL

Organisations with a strong sustainability performance display a specific organisational culture (Grayson, Coulter, & Lee, 2018). The studies by Hernandez (2020) and Baggia, Maletič, Žnidaršič and Brezavšček (2019) indicate that managers significantly influence how employees perceive and embrace digital transformation within an organisation. Furthermore, the study revealed that effective management is key to successful digitalisation in the workplace. Managers who actively support and guide their teams through digital transitions can enhance employee acceptance and engagement with new technologies. This highlights the importance of managerial involvement in digital initiatives to ensure a smooth and positive transition for employees.

Isensee et al. (2020) study stated that environmental leadership, transformational leadership (Burawat, 2019), top leadership culture (Abdullahi, Mohamed, Shamsudin, Sharifuddin, & Ali, 2018), and values-related leadership are crucial to role-model behaviour, commitment, motivation, management support, and comprehensive environmental management. This perspective is supported by Kiefer, Del Río González and Carrillo-Hermosilla (2019) study that identified several factors that influence the adoption of environmental innovations in manufacturing firms. These factors include physical resources, competency and dynamic capabilities, corporate culture, and organisational learning.

Dabic, Maley, Švarc and Poček (2023) asserted that, despite the emphasis on managerial and technical aspects, integrating and adopting AI technologies through a successful digital transformation requires a significant cultural shift within organisations. Although cultivating strategic leadership skills, managing change

effectively, investing in employee development, fostering collaboration, mitigating risks, and considering ethical implications are essential, these efforts alone may not be sufficient. Indeed, without a fundamental transformation of organisational culture, the integration of AI technologies may face substantial barriers (Dabic et al., 2023). Thus, while the technical and managerial facets are critical, the cultural dimension plays an equally pivotal role in ensuring the success of digital transformation initiatives.

2.5 BUILDING A DIGITAL-READY WORKFORCE

According to Macke and Genari (2019) HRM plays a crucial role in fostering sustainability within organisations. In essence, HRM and sustainability are interdependent concepts that must be considered together to achieve organisational success. Furthermore, it involves integrating sustainable practices into the organisational culture, policies, and operations to ensure long-term viability and environmental responsibility, concluded study by Macke and Genari (2019). By integrating sustainable practices, HRM can enhance organisational flexibility and provide greater adaptability for the workforce amidst the ongoing digital transformation. Furthermore, the study by Dabic et al. (2023) highlighted that HRM is instrumental in facilitating digital transformation by harmonising organisational and employee interests. Sustainable HRM promotes digitalisation through strategic investments in employee development, ensuring individuals possess the requisite skills for thriving in the digital era.

Despite the potential benefits of digitalisation, a study by Dabic et al. (2023) revealed that the socio-political controversies surrounding digital work, such as work polarisation and non-standard employment, present significant challenges for HRM. While technology advances, many middle-skill jobs are being automated, leading to a concentration of jobs at both ends of the skill spectrum, leading to increased income inequality between highly skilled and low-skilled jobs. Nevertheless, to drive DTx and AI integration requires skills and expertise. Nair (2019) raises a major concern and highlights the significant obstacle, the shortage of skilled digital talent to drive organisations' digital transformation journeys. The talent gap will hinder the successful implementation of sustainable digital initiatives. Holmstrom (2022)

asserted that embracing AI and DTx will require the necessary skills and knowledge. Moreover, the study by Booyse and Scheepers (2023) highlighted that only highly skilled software engineers can use AI technology.

Despite the aforementioned challenges sustainable HRM systems are valuable in the digitalisation era of work. They offer potential long-term economic success in digitalisation (Dabic et al, 2023). Mariappanadar, Maurer, Kramar and Muller-Camen (2022) support this view by pointing out that HRM benefits go beyond corporate social responsibility (CSR); it not only reduces workplace harm but also holds the potential for long-term economic success in the digitalisation era.

This theme raises a question: Are there available skills and expertise to support the manufacturing sector's AI adoption and DTx to advance environmental sustainability practices?

2.6 POLICY AND REGULATION: EXTERNAL FACTOR

The economic landscape of Africa is rapidly transforming, with SA leading the charge as the continent's third-largest economy (Udeagha & Muchapondwa, 2023). However, this very progress casts a long shadow over environmental sustainability. In addition, this complex dilemma of prioritising economic growth while safeguarding the environment presents a critical challenge for SA's future.

According to Bell, Goga and Robb (2021), developing economies like SA must industrialise while reducing their environmental sustainability impact and adapting to climate change. Green industrial policy, promoting green manufacturing and low-carbon innovation, offers a potential solution for SA to achieve sustainable development.

An industrial policy to promote green manufacturing and low-carbon innovation plays an essential role (Anzolin & Lebdioui, 2021). Wang, Zhang, Ren and Shi (2024) study in China provides evidence supporting the effectiveness of green industrial policy in promoting sustainable development. Their findings suggest that both command-control policies (e.g., regulations) and market-oriented policies (e.g., financial incentives) can stimulate innovation perseverance within enterprises. Chiarini (2021)

highlighted the Italian Ministry of Economic Development launched the 'Industria 4.0 National Plan' in 2016, a government initiative to promote investment in advanced cybertechnologies among Italian companies.

While the role of government is crucial other external market forces must not be neglected. Customer demands necessitate digital transformation within supplier operations (resources and capabilities) for sustained competitiveness (Dubey et al., 2019; Bag et al., 2021b).

The study by Bag et al. (2021b) stated policy reforms are essential to incentivise renewable energy adoption and align with SDGs (Colglazier, 2015). Current frameworks often hinder widespread renewables utilisation. Targeted policy changes can address these barriers, fostering a shift towards clean energy and achieving broader sustainability goals.

While incentivising clean technology adoption through policy frameworks appears promising, some argue that such policies might create an unrealistic burden on developing nations like SA. Udeagha and Muchapondwa (2023) acknowledged policy uncertainty as a significant barrier without elaborating on potential burdens.

The efficacy of digitalisation strategies in achieving environmental sustainability hinges on robust regulatory frameworks and targeted policy initiatives. A compelling illustration of this can be found in the European Union's (EU) upcoming implementation of digital product passports, mandated by recent legislation (European Commission, 2020; Berger, Schöggel, & Baumgartner, 2022). This policy exemplifies how regulations can act as a catalyst for the adoption of sustainability-oriented DTx. Similarly, SA has established the Department of Communication and Digital Technologies Artificial Intelligence Institute of SA (AIISA) to support AI adoption (Mashishi, 2023). Dubey et al. (2020) highlight that in today's digital world, government agencies like the Department of Trade and Industry (DTI) heavily influence businesses by setting the national digital strategy that companies must follow.

By establishing supportive policy and regulatory environments, governments can empower businesses to leverage digitalisation and information technology (IT) resources, ultimately fostering a significant advancement in environmental sustainability. Therefore, to effectively promote sustainable practices, it is critical for

governments to provide support mechanisms such as subsidies, tax breaks, and financial and technical assistance concluded Malek & Desai (2019). This is consistent with the findings of Bag et al. (2021b) stated policy reforms are essential to incentivise renewable energy adoption and align with SDGs (Colglazier, 2015).

Harvath and Szabo (2019) highlight a contrasting perspective; beyond sustainability, there are other drivers for adopting AI and DTx. The other drivers behind DTx include growing competition, increased innovation capacity, customer expectations, sustainability, and business model innovation (de Sousa Jabbour, Jabbour, Foropon, & Godinho Filho, 2018b). This suggests that while competition is a primary driver, manufacturers must also consider other factors to navigate the DTx journey successfully.

Despite AI and DTx's immense potential for innovation to advance environmental sustainability, implementation must be guided by robust policies and regulations. As highlighted by the literature, does the local manufacturing sector have government support? Government intervention is crucial in fostering a supportive ecosystem that incentivises sustainable practices.

2.7 DIGITAL SUPPLY CHAIN

The evolving landscape of supply chains necessitates a paradigm shift towards enhanced digitalisation. This increased digitalisation presents a unique opportunity to revolutionise how enterprises connect, collaborate, and share information within the supply chain ecosystem (Horváth & Szabó, 2019). Despite consistent economic growth in the manufacturing industry (Egilmez, Kucukvar, & Tatari, 2013; Ezici, Egilmez, & Gedik, 2020), there is a concerning disparity between the increasing reliance on non-renewable energy sources and the stagnant adoption of renewable energies, hindering sustainable development. Previous research proved a dissonance between economic growth and environmental impact (Udeagha & Muchapondwa, 2023; Bell et al., 2021; Wang et al., 2024). In addition, previous studies have highlighted the manufacturing industry's significant contribution to greenhouse gas emissions and resource depletion (Chen, Dong, & Lin, 2020). This

implies that the slow adoption of renewables and sustainable practices in the industry exacerbates this disconnect.

The study by Ching et al. (2022) revealed that I4.0, encompassing a set of interconnected functions, promotes SM practices. These functions contribute to increased efficiency, reduced harmful emissions, and the development of new business models. While the literature provides various definitions, Bag et al. (2020) define SM as encompassing CE principles prioritising clean production processes and resource recovery to minimise environmental impact (Bag et al., 2020).

Bag et al. (2020) found that manufacturing strategies are designed to achieve sustainable development goals which are supported by Machado et al. (2021), I4.0 enabler of sustainable development. The integration of advanced manufacturing technologies has revolutionised SM. In addition, the adoption of sustainable practices within the manufacturing sector is demonstrably yielding positive economic and environmental outcomes (Schöggli et al., 2023).

Ching et al. (2022) points out that achieving SM with I4.0 might be overly ambitious. While the technology offers potential, implementing it across a complex value chain requires significant collaboration and planning, which in the absence will hinder widespread adoption.

2.8 SUSTAINABLE MANUFACTURING

Yadav et al. (2020) suggested that the rate of sustainability in developing countries is significantly poor. Furthermore, asserted that sustainability is a paramount concern in the contemporary global marketplace, and a disregard for its salient aspects can result in substantial financial losses for manufacturers. In addition, the authors highlighted sustainability as an important issue, a perspective supported by Ezici et al. (2020), who highlighted that in response to the environmental impact of industrial activities, sustainable manufacturing has become a global priority.

However, the manufacturing industries have demonstrated consistent and sustainable growth in their economic output, while the use of renewable energy has remained stagnant (Ezici et al., 2020). Building on the previous research, integrated

time series, study done in the US manufacturing sector (Egilmez et al., 2013) underscored the critical need to assess the environmental impact of various manufacturing sectors holistically. While these sectors are crucial to the economy, they also have a significant impact on the environment. Achieving 100% efficiency requires a significant reduction in greenhouse gas emissions (79%), energy use (61%), hazardous waste (80%), toxic release (75%), and water withdrawals (78%) across the board.

Yadav et al. (2020) asserted that to advance the discourse on sustainability, it is necessary to explore the enablers that drivers facilitate adoption. Despite few studies conducted, the previous quantitative study found a positive influence between digital transformation and sustainability performance in local manufacturing firms (Bag et al., 2021a). The study in South Africa examined the impact of digital technologies on sustainability, focusing on the single adoption of these technologies.

Despite the potential of AI and DTx, previous studies provided opposing views and found that the adoption of digital transformation technologies hurt sustainability (Kiel, Müller, Arnold, & Voigt, 2017; Li et al., 2020). The main argument made is that digital transformation and sustainability practices were conceived to address different purposes (de Sousa Jabbour et al., 2018b), which raises questions about whether digital transformation can coexist with enterprise sustainability efforts (Lohrmann, 2017; Osburg, 2017; Beier, Niehoff, & Xue, 2018).

While I4.0 technologies, in combination with management approaches such as lean production, can enhance competitiveness, energy-intensive manufacturing environments often face significant challenges in achieving sustainability goals. Even with advanced green production models, energy consumption remains high, and pollution levels can be severe (Ma, Ding, Liu, Ren, & Yang, 2022). Furthermore, the transition to a low emission world presents substantial risks, particularly compliance costs burden for an operating entity. Settembre-Blundo, González-Sánchez, Medina-Salgado and García-Muiña (2021) study states that the organisation risk approach is centred on fragmented operational measures, aimed at siloed mitigation of an unexpected event, financially biased.

Based on the preceding discussion, previous studies highlight the need for more research on the impact of digital transformation in advancing sustainability practices in the manufacturing sector. Savastano, Amendola, Bellini and D'Ascenzo (2019)

claimed that the debate in the literature is ongoing; there is a lack of integration between digital impact on sustainability (Jamwal, Agrawal, Sharma, Kumar, & Kumar, 2021).

2.9 DIGITAL TECHNOLOGIES

Truong (2022), DTx, specifically AI, big data, and the IoT, presents a compelling solution suite for addressing environmental sustainability challenges. These tools are effective for optimising waste management, preventing pollution, and promoting sustainable resource management. The study concluded that these tools mitigate the adverse impacts of human activities on the environment (Truong, 2022). Schögggl et al. (2023) study revealed a positive and statistically significant correlation between the implementation of a digitalisation strategy within companies and the adoption of DTx across various domains, including sustainability management.

In the study conducted in Austria by Schögggl et al. (2023) among the eight industries surveyed, the construction, electronics, and metal and machinery industries were found to be the most advanced, while the textile and food industries exhibited the lowest degree of digitalisation. Schögggl et al. (2023) identified big data analytics, AI, IoT, and blockchain as the primary DTx employed in the Austrian manufacturing sector. This study recommended future studies to explore AI's significant untapped potential for driving corporate CE and sustainability management.

Despite the hyped benefits of DTx, the vast array of potential applications and associated uncertainties, as evident in the literature leaves companies perplexed when attempting to pinpoint their specific DTx requirements. As highlighted by Schögggl et al. (2023), this casts doubt on the feasibility of successful implementation. Moreover, a study by Ngepah et al. (2024) indicated a statistically meaningful association between I4.0 adoption and a decrease in South Africa's MVA. While I4.0 promises advancements in automation and efficiency, the research indicates a negative association with MVA in the short term. This finding points towards possible challenges hindering the effectiveness of I4.0 implementation in South Africa's manufacturing sector.

Furthermore, a study in Italy revealed that AI and sustainability are not natural allies. While they may appear correlated, internationalisation reveals competing priorities, forcing difficult trade-offs (Denicolai et al., 2021). Therefore, the complex tensions between AI excellence and sustainability excellence must be explored. The assumption that they effortlessly coexist should be challenged. However, companies face challenges in defining their specific DTx requirements due to the vast array of potential applications and associated uncertainties.

Dauvergne's (2022) study of AI reveals a crucial paradox in the oil industry's adoption of intelligent automation in supply-chain logistics. While this technological advancement offers cost savings and efficiency gains, it also perpetuates a rebound effect, leading companies to reinvest in increased resource extraction and production, thereby exacerbating environmental degradation and resource depletion. Dauvergne's (2022) study underscores the urgent need for sustainable practices and responsible reinvestment strategies to mitigate the adverse consequences of technological progress in the industry.

Schögl et al. (2023) built on prior research by Chiarini, Belvedere and Grando (2020), who examined the relationship between I4.0 adoption and manufacturing strategies in Italy. While the study identified associations between I4.0 and strategies like supply chain integration, lean practices, environmental sustainability, and servitisation, it did not reveal a positive impact on companies' environmental performance (Chiarini et al., 2020). This suggests that I4.0 technologies alone may not be sufficient to drive environmental improvements, and additional factors likely play a role.

2.10 DATA-DRIVEN SUSTAINABILITY

Cleaner production (CP), increasingly critical in the energy-intensive manufacturing industry, is an effective way to achieve a CE. Ma, Zhang, Liu, Yang, Lv and Ren (2020) stated that continuous improvement of sustainability is critical for Energy-intensive industries (EIs) and improves their competitiveness. Furthermore, list EI's such as pulp and paper, steel, glass (Du, Sun, Ouyang, & Zhang, 2018), ceramics (Ros-Dosd_a, Fullana-i-Palmer, Mezquita, Masoni, & Monfort, 2018), and nonferrous

metals (Sun, Xu, Lv, Mao, & Wu, 2019a; Sun, Zhou, Lv, & Wu 2019b). Cleaner production aims for sustainable development through energy conservation, energy reduction and improved productivity and efficiency. In addition, the convergence of digital technologies and intelligent manufacturing has given rise to sustainable intelligent manufacturing. This innovative approach harnesses advanced technologies to optimise data management throughout the manufacturing process, enhancing efficiency and contributing to sustainability objectives.

To fully comprehend the concept of data-driven sustainability, it is essential to understand how data and analytics can be used to measure and improve not only environmental but also social and economic performance. The literature review suggests that data-driven approaches, combined with AI technologies, may offer significant potential for advancing environmental sustainability in the Gauteng manufacturing industry. Tseng, Bui, Lim, Fujii and Mishra (2022) highlighted Sustainable Supply Chain Management (SCCM), as a type of information flow, a holistic approach to supply chain management that emphasises sustainability. It involves creating a collaborative environment where all participants work together to achieve shared goals while considering the broader impact of their actions on the economy, society, and the environment. Furthermore, described SCCM as the strategic integration of the Triple Bottomline (TBL) into systemic business processes to enhance the long-term alignment of a firm and its Supply Chain.

However, to achieve the full potential of sustainability, companies must follow a strategic approach to implement data-driven sustainability, considering both its positive and negative effects on turnover. This requires careful planning and execution to ensure that sustainability initiatives align with overall business objectives (Esfahbodi, Zhang, Watson, & Zhang, 2017; Tseng, Chang, Lin, Wu, Chen, Xia, & Xue, 2020; Poursoltan, Mohammad, Seyedhosseini, & Jabbarzadeh, 2021; Tseng et al., 2022).

2.11 ENVIRONMENTAL SUSTAINABILITY

Environmental sustainability involves an organisation's approaches, practices, actions and programs aimed at minimising its adverse effects on the natural environment while enhancing beneficial impacts (Isensee et al., 2020).

Ezici et al. (2020) highlighted that in response to the environmental impact of industrial activities, sustainable manufacturing has become a global priority. The research findings indicated that manufacturing industries have demonstrated consistent and sustainable growth in their economic output while the use of renewable energy remained stagnant. The research, integrated time series, was based on the previous study done in the US manufacturing sector (Egilmez et al., 2013), underscoring the critical need to holistically assess the environmental impact of various manufacturing sectors. While these sectors are crucial to the economy, they also have a significant impact on the environment. Achieving 100% efficiency requires a significant reduction in greenhouse gas emissions (79%), energy use (61%), hazardous waste (80%), toxic release (75%), and water withdrawals (78%) across the board.

According to Ma et al. (2020), the journey towards sustainable, intelligent manufacturing in complex processes faces significant challenges due to the vast and diverse energy data generated at a rapid pace. The data generated in energy-intensive manufacturing is vast, diverse, and valuable, reflecting the complex and dynamic nature of these processes. However, despite technological advancements, extracting insights and root causes from such complex data remains a formidable task. Ma et al. (2022) concluded that despite advanced green production models, energy consumption will remain high with severe pollution levels. Lamb, Wiedmann, Pongratz, Andrew, Crippa, Olivier, ... and Minx (2021) support but raise different challenges. Reducing GHG emissions is a complex global challenge, with sources ranging from energy-intensive industrial activity to urban -infrastructure, land use and human behaviour.

Nevertheless, the data-driven approach offers a promising solution (Ma et al., 2020). By implementing a strong data-driven framework, manufacturers can efficiently analyse and manage their energy data. This enables intelligent manufacturing practices and promotes sustainability. Energy Intelligence Indicators are essential for

reducing costs and improving sustainability. A data-driven approach focused on data reduction is ideal for implementing sustainable intelligent manufacturing, turning challenges into opportunities for innovation and efficiency. A study by Ma et al., (2020) concluded that the integration of I4.0 and sustainability is in the very initial stages.

2.12 INVESTMENT: SUSTAINABLE DIGITAL TRANSFORMATION

To transform traditional manufacturing into sustainable manufacturing, adequate financial resources and investments are essential (Mangla, Luthra, Rich, Kumar, Rana, & Dwivedi, 2018). Top management plays a crucial role in allocating funding to support the integration of digital technologies such as AI and a combination thereof to support and enable the transformation. According to de Sousa Jabbour, Jabbour, Godinho Filho and Roubaud (2018a), the integration of I4.0 and sustainability is still in its early stages. Despite the potential for cost reduction and increased competitiveness offered by new technologies, the rapid pace of technological advancement can render investments obsolete before they generate a return on investment. This highlights the risk associated with investment in technologies in an evolving technological landscape. Such investment may not yield the expected return on investment (ROI) (Birkel, Veile, Müller, Hartmann, & Voigt, 2019).

Zhang, Veltri, Calvo-Amodio and Haapala (2021) study concluded that sustainability management in SME manufacturing is often siloed, with decision-making for environmental impact, social responsibility, and financial considerations treated separately. This perspective views environmental and social policies primarily as costs incurred to meet customer expectations and regulatory requirements. However, such a mindset restricts managers from fully grasping the interconnectedness of these sustainability pillars, ultimately hindering their ability to achieve comprehensive business sustainability within manufacturing systems. Awareness of the interdependence of these concepts is crucial for a strategic approach and for fostering a more integrated approach (Zhang et al., 2021).

Malek and Desai (2019) highlight the significant financial and technological challenges faced by emerging economies in adopting sustainable manufacturing

practices. Furthermore, Xu, Li, Sberger and Peng (2023) emphasise that inefficient investment is a significant hindrance to DTx, especially financially constrained manufacturers. Brock and Wangenheim (2019) asserted that manufacturers must assess the compatibility of their legacy manufacturing systems to ensure smooth integration with AI technology solutions.

This highlights a critical issue manufacturers may face, the substantial upfront costs and additional investment required to upgrade legacy technology to achieve readiness for DTx. As a result, the financial burden may lead to focus on the challenges of investment rather than potential long-term sustainability benefits.

Supporting this perspective, Ukko et al. (2019) revealed the negative moderating effect on financial performance due to the temporal lag between implementing sustainability initiatives. Tangible financial realisation is dependent on cost reductions, efficiency gains, and optimised business processes (Li et al., 2018). This observation aligns with Zhang et al. (2021), which highlights a siloed decision-making approach in SME manufacturing, amplifying prioritising financial considerations over environmental sustainability.

2.13 BENEFITS OF DIGITAL TRANSFORMATION

Numerous studies discussed the benefits of DTx and the associated risks that may arise from digitalisation (Chiarini, 2021; Narkhede et al., 2024). Bag et al. (2021b) highlighted a positive influence between digital transformation and sustainability performance in local manufacturing firms. Moreover, Truong's (2022) study, a holistic review of how DTx impacts the environment, revealed a high number of studies focused on pollution prevention and control, followed by waste management and handling.

According to Truong (2022), the direct environmental effects of DTx include (1) the production of digital infrastructure, (2) the energy consumption of digital infrastructure, (3) mining of the hardware to be used as digital infrastructure, (4) collection, recycling, and disposal of digital assets physical infrastructure, (5)

greenhouse emissions for the generation of power used by DTx. The direct effects identified were confirmed by Chiarini's (2021) empirical study in Italy Manufacturing.

Despite the benefits of DTx and AI adoption, however, Truong's (2022) study listed direct effects, the following indirect effects were identified and supported by Dauvergne (2022): (1) forecasting the waste generation, (2) unveiling resource waste, (3) designing more efficient waste management models. Moreover, digitalisation and networking contribute to the reduction of greenhouse gas emissions.

However, as Denicolai et al. (2021) revealed, while SME manufacturing, AI and sustainability may appear harmonised, global market growth reveals difficult trade-offs. This raises questions about the complex relationship between AI and sustainability in different contexts. To address this contradiction, Yadav et al. (2020) asserted to explore the enablers that drive sustainability adoption. As a result, as highlighted by studies by Ukko et al. (2019), managers often prioritise short-term economic performance over sustainability. The evaluation of sustainability initiatives' performance is biased towards financial gains.

2.14 HOLISTIC PERFORMANCE MEASUREMENT

The manufacturing sector, while a cornerstone of emerging economies, faces pressure to balance economic growth with environmental sustainability. As Malek and Desai (2019) highlight, emerging economies face significant financials in adopting sustainable manufacturing practices. Despite these challenges, DTx and AI technologies, with the promised immense potential of increased efficiency and innovation to advance sustainability, offer a potential solution. However, the complex interplay between DTx, sustainability initiatives, and short-term financial objectives may hinder progress. Therefore, to address these challenges, a comprehensive performance measurement framework is essential.

Previous studies underscored that the negative moderating effect of a sustainability strategy on financial performance can be attributed to the profit-oriented nature of many companies (Rantala, Ukko, Saunila, & Havukainen, 2018; Saunila, Ukko, &

Rantala, 2018). When organisations prioritise a comprehensive sustainability strategy that encompasses social, environmental, and economic factors, their focus may shift away from purely financial objectives, potentially hindering the relationship between operational capabilities and financial performance.

A holistic performance measurement framework is essential for the interconnectedness of environmental, economic, and social factors, ensuring that all relevant dimensions are evaluated. Studies by Ukko et al. (2019) indicate that managers often prioritise economic performance over sustainability, which can hinder their willingness or ability to integrate sustainability into their decision-making. This is supported by an earlier study by Baumgartner and Rauter (2017), emphasising the priority of economic gains over sustainability.

While sustainability initiatives can lead to improvements in cost reduction, efficiency, and business processes, financial benefits may not be immediately apparent. This could explain why sustainability strategies sometimes have a negative moderating effect on financial performance. The study by Ukko et al. (2019) revealed that the negative moderating effect on financial performance may be due to the temporal lag between the implementation of sustainability initiatives and the realisation of tangible cost reductions, efficiency gains, and optimised business processes (Kauffman & Walden, 2001; Ash & Burn, 2003; Li et al., 2018). As a result, the financial returns of a sustainability strategy within the context of digital transformation may not be immediately apparent.

To effectively measure the impact of sustainability initiatives, a holistic measurement approach must include quantifying environmental outcomes, such as greenhouse gas emissions reduction, energy conservation, and waste minimisation. To achieve GHG emissions, Wang, Rodrigues, Hu, Behrens and Tukker (2019) assert that manufacturers have set ambitious emission targets, in alignment with the Paris Agreement. These GHG emission targets are set to be achieved by 30% by the year 2030. Economically, requires assessing financial performance metrics, including profitability, return on investment, and cost savings.

Socially, encompasses evaluating the effects on employees, communities, and other stakeholders, including job creation, social responsibility initiatives, and community engagement. Finally, technologically it entails examining the effectiveness of digital technologies in driving sustainability efforts, such as the role of artificial intelligence

in optimising processes and reducing emissions. Previous research stated that to achieve the full potential of sustainability, manufacturers must adopt a strategic approach to implement data-driven sustainability, considering both its positive and negative effects. This requires careful planning and execution to ensure that sustainability initiatives align with overall business objectives (Esfahbodi et al., 2017; Tseng et al., 2020; Poursoltan et al., 2021; Tseng et al., 2022).

Furthermore, to maximise the benefits of sustainability strategies, businesses must carefully consider the specific context in which they operate and tailor their approaches accordingly. This involves understanding factors such as industry dynamics, regulatory requirements, stakeholder expectations, and resource availability (Ukko et al., 2019). The claim asserts that sustainability strategy is a crucial element in modern business management. It emphasises the importance of understanding the specific contexts in which such strategies yield positive outcomes.

By adopting a holistic approach to performance measurement, organisations can gain a comprehensive understanding of the impact of their digital transformation and sustainability initiatives, identify areas for improvement, and demonstrate their commitment to sustainable practices.

2.15 DIGITAL INNOVATION: SUSTAINABILITY AND RISK MANAGEMENT

In the context of environmental sustainability, compliance risks arise from non-adherence to laws, regulations, or self-imposed standards. According to Settembre-Blundo et al. (2021) study, risks can lead to legal penalties, financial losses, and reputational damage. In addition, the study stated that the organisational risk approach is centred on fragmented operational measures, aimed at siloed mitigation of an unexpected event, financially biased.

Moreover, the issue associated with this approach is that the risk is partial due to the lack of appreciation of critical events that might impact the organisations as a whole. In addition, the author asserted that in social science, risk and uncertainty pertaining to the chance of unexpected events occurring can impact human activities in unpredictable ways. This perspective is supported by Shivaani (2018).

The potential introduction of a carbon tax poses significant financial and operational implications for manufacturers, particularly heavy emitters. Jia and Lin (2020) argued that carbon tax will encourage carbon-intensive activities and shift towards more sustainable practices. This view is supported by Lamb et al. (2021), policies like carbon pricing and incentives are the key drivers of GHG emission reduction.

However, while pricing carbon may incentivise innovation and reduce environmental impact, it also raises potential increased costs for manufacturers. While the risk to manufacturers, revenue generated may be used to lower other taxes such as corporate tax, income tax, etc, (Jia & Lin, 2020; Ma et al., 2020; Wang et al., 2020).

In addition to the challenges posed by carbon tax, the rapid technological advancements present both opportunities and risks. While evolving technology possesses the potential to revolutionise industries and business practices, it also presents inherent risks. Although new technologies often lead to cost reductions and enhanced competitiveness, the rapid pace of technological progress can render investments obsolete before they yield a return (Settembre-Blundo et al., 2021).

Furthermore, despite the huge potential of AI in promoting environmental sustainability, significant risk persists. As Camacho (2024) highlights, the integration of AI technology and other DT into sustainable manufacturing introduces significant cybersecurity risks that pose a threat to the industry.

Insensee et al (2020) stated that despite the potential benefits of digitalisation for environmental sustainability, the widespread use of digital technologies could have unintended negative consequences, such as increased greenhouse gas emissions, electronic waste generation, and rebound effects. This highlights the need for a cautious and strategic approach to digitalisation that addresses these challenges and promotes sustainable practices (Hilty & Aebischer, 2015; van der Velden, 2018).

2.16 CHALLENGES OF SUSTAINABLE MANUFACTURING

Despite the potential benefits of digitalisation for environmental sustainability and overall contribution to the business strategy, the digital technologies integration and adoption can have negative consequences. Previous studies cited the downside as

increased greenhouse gas emissions, electronic waste generation, and rebound effects. This underscores the need for a sustainable approach to digitalisation that minimises these adverse impacts. (Hilty & Aebischer, 2015; van der Velden, 2018).

Birkel et al. (2019) highlighted that while new technologies usually increase competitiveness by reducing costs, the rapid rate of technology changes and emerging disruptive technologies may result in making earlier technology obsolete. Therefore, the initial upfront investment potentially be sunk costs. In addition, there is no time to amortise if new innovations follow one another rapidly. DeStefano, Johnstone, Kneller and Timmis (2024) emphasise the significant upfront costs required for complex IT infrastructure, like cloud computing and digital technologies. The need for substantial upfront capital poses a considerable barrier for many organisations.

Furthermore, the challenge of integrating AI technologies with legacy manufacturing systems adds another layer of complexity. Brook and Wagenheim (2019) revealed the importance of legacy systems compatibility with AI technologies. Holmstrom (2022) suggested that manufacturers assess the technology readiness of their technology for AI integration. This claim raises a critical question, many manufacturers may still have outdated process equipment that lacks monitoring and data transmission capabilities. This significant barrier not only complicates AI integration. However, DeStefano (2024) also argues that the nature of IT infrastructure to enable AI integration and DTx is shifting largely from sunk costs to variable costs. Mangla et al. (2018) asserts that to transform sustainable manufacturing, adequate financial resources and investments are essential.

In addition to the challenges of integrating legacy manufacturing systems, as Ukko et al. (2019) highlighted DTx extends beyond mere technological implementation, supported by Li et al. (2018). Therefore, transformation requires a comprehensive strategy that encompasses not only technological integration but also the redesign of business processes and the development of organisational capabilities. This dual emphasis on managerial and technical aspects is crucial for creating an adaptable and effective organisation in the digital era.

Furthermore, overcoming legacy and outdated manufacturing systems by investing in modernisation can introduce new challenges. New technologies usually increase competitiveness by reducing costs. As Birkel et al. (2019) highlighted, the rapid rate

of technology changes and emerging disruptive technologies may result in making earlier technology obsolete. Therefore, the initial upfront investment will potentially be sunk costs. In addition, leaving no time to amortise, particularly when new innovations emerge rapidly.

By addressing these challenges, organisations can enhance their adaptability and achieve their strategic objectives (Dabic et al., 2023).

2.17 CONCLUSION AND INSIGHT

This thematic literature review has raised the multifaceted and complex challenges facing manufacturers when integrating AI and driving DTx for environmental sustainability in the Gauteng manufacturing sector. Several key themes emerged from the thematic literature review, including digital leadership, organisational readiness, and building a digital-ready workforce; environmental sustainability, including cultural shifts, policy and regulation; and sustainable practices within supply chains and manufacturing processes.

Furthermore, the analysis highlights the pivotal role of AI and digital technologies in enhancing sustainability and managing risks. Finally, it highlights the significance of investment in supporting these initiatives, the potential benefits of digital transformation, and the necessity of holistic performance measurement to assess the overall impact of these efforts.

By understanding these interconnected factors, organisations in the Gauteng manufacturing industry can develop effective strategies to leverage digital transformation for sustainable growth and development.

In addition, by addressing these factors, the industry can harness the potential of digital technologies, such as AI to transform and create a more sustainable and resilient future. Knowledge gaps that emerged from the review include conditions necessary to drive successful integration, such as key drivers, barriers, opportunities, benefits, risks and challenges for the themes identified from the literature review. Without understanding the key drivers, AI integration will not deliver the desired environmental sustainability benefits, particularly GHG emission targets.

From the thematic literature reviewed, the following unexplored questions remain unanswered (1) key success drivers related to contextual organisational readiness for AI adoption in the manufacturing sector, (2) exploring the critical success factors necessary for user adoption and for mitigating organisational inertia in AI-driven sustainability, (3) assessing the effectiveness of green industrial policy in promoting sustainable development in South Africa, (4) benefits, challenges and risk by adopting DT technologies adoption for advancing environmental sustainability in the manufacturing sector, examine the potential impact of DT on environmental sustainability.

The manufacturing sector in Gauteng, SA, faces a critical challenge in balancing economic growth with environmental sustainability (Udeagha & Muchapondwa, 2023). The main gap this study seeks to address is the unexplored role of Artificial Intelligence (AI) in achieving sustainability goals in developing economies and the insufficient investigation into the application of AI technology to reduce greenhouse gas emissions in industries with lower levels of digitalisation. The study, building on the previous work by Schöggel (2023), proposed future research to explore the untapped potential of AI for environmental sustainability in manufacturing.

3. RESEARCH QUESTIONS

This qualitative exploratory study aimed to identify the key success drivers for the adoption of digital technologies such as AI to advance the environmental sustainability practices within the Gauteng Manufacturing sector. Specifically, the study objective was to understand the impact of DTx on environmental sustainability impact on greenhouse gas emission (GHG) reduction, waste reduction, and energy efficiency to preserve the environment from the large manufacturing sector companies based in Gauteng.

In essence, the research is exploring what makes it successful for manufacturing companies in Gauteng to adopt AI and other digital technologies to protect the environment and advance sustainable development.

Building on Rusch et al. (2023) call for future research, this proposal aimed to address a significant knowledge gap by exploring the untapped potential of Artificial Intelligence (AI) in the manufacturing industry. The thematic literature review identified several gaps, this study explores the key drivers of successful DTx in advancing environmental sustainability practices in the large manufacturing sector in Gauteng, South Africa. The research questions were formulated based on the thematic literature reviewed. Furthermore, the main research question was broken down into several specific questions to guide the research process.

The research questions (RQ#) for the study:

Research Question 1 (Organisational Capabilities): What are the key drivers for the successful adoption of DT AI in the Manufacturing sector to achieve the environmental sustainability dimension of greenhouse gas emission reduction?

In research question 1, the study seeks to explore the key drivers underlying manufacturing companies' adoptions of digital technologies, specifically AI, and the elements that contribute to their successful implementation in achieving environmental sustainability objectives, with a specific focus on greenhouse gas emissions.

Research Question 2 (Impact): How is success measured for measuring the effect of adopting DT for the environmental sustainability dimension?

Research question 2's main goal is to determine how to evaluate the success of adopting and integrating digital technologies to reduce environmental sustainability, such as greenhouse gas emissions. The question explores the metrics and indicators used to assess the environmental impact of DTx initiatives.

Research Question 3 (Opportunities and Challenges): What policy initiatives and regulatory frameworks are necessary to promote sustainable development in the South African manufacturing sector?

Research question 3's main goal is to determine what specific policies and regulations are influencing sustainable development within the South African Manufacturing sector. In addition, the question seeks to explore specific policies and regulatory frameworks that support the adoption of digital technologies, like AI, in the South African manufacturing sector to reduce greenhouse gas emissions to advance sustainable development.

Research Questions 4 (Challenges): What are the potential environmental benefits and challenges, barriers, and constraints faced by manufacturing organisations when implementing DTx for sustainability purposes?

The research question explores the positive environmental impacts of digital technologies adoption, such as AI through digital transformation, on manufacturing organisations, such as efficiency gains, waste reduction, and pollution mitigation. Furthermore, the question explores the difficulties and limitations manufacturing organisations face when implementing these technologies for sustainability, such as technological limitations, economic factors, organisational factors, and regulatory factors.

Research Question 5 (Risk): What are the potential negative effects, direct and indirect, of implementing DT such as AI for environmental sustainability?

Research question 5's main goal is to explore the potential downside of using digital technologies, specifically AI to address environmental challenges. The questions seek to identify the direct negative effects, such as increased energy consumption to

support the use of digital technologies, and indirect negative effects, such as increased production leading to environmental degradation.

4. RESEARCH METHODOLOGY

4.1 INTRODUCTION

This chapter is about the research methodology that was explored in order to answer the main research question: the drivers for successful DTx in advancing environmental sustainability for Gauteng's manufacturing industry. The research method used to answer the question was a qualitative approach to generate insights and triangulation for content analysis to generate further insights from published sources.

Literature review on manufacturing DTx impact on environmental sustainability practices is scant (Guandalini, 2022); as a result, there is significantly less understanding of the relationship between DTx and sustainability. This view is further strengthened by Kraus et al. (2021), who stated that the manufacturing and oil and gas industries are relatively new participants in the DTx journey. Due to the nascent nature of the impact of DTx on environmental sustainability, particularly in the context of South Africa's (SA) manufacturing sector, the small body of extant research is largely qualitative and exploratory and, to a lesser extent, a systematic literature review (Vuksic, Ivančić, & Vugec ,2018; Guandalini, 2022).

4.2 RESEARCH DESIGN

4.2.1 Philosophy: Interpretivism

Researchers embark on a quest for knowledge guided by two prevailing philosophical approaches: positivism and interpretivism (Creswell, 2014). These contrasting worldviews shape the role of data in research, influencing how we think about, gather, and make sense of information (Denzin & Lincoln, 2011). Positivism seeks objective truths, while interpretivism uncovers subjective meanings, reflecting fundamentally different assumptions about knowledge and reality (Schwandt, 2001).

Interpretivism has been applied as the research philosophy with the main objective of answering the main research question. The researcher had to look beyond the technical aspects of DTx and the integration of digital technologies such as AI and explore the human element and other factors that were identified through thematic literature review. This approach, interpretivism, allowed the researcher to examine how people within the industry perceive and understand DTx and environmental sustainability. By understanding the human side of DTx, key drivers for successful implementation were identified.

4.2.2 Approach: Inductive

This research was conducted using one-on-one, in-depth expert semi-interviews to gain a deeper understanding of the topic. By employing the qualitative approach, the aim was to uncover rich and nuanced insights to discover the key success drivers behind I4.0 adoption. This methodology is particularly well-suited for exploring complex and evolving phenomena like I4.0, which is best studied in its natural environment - the real-world settings of organisations and industries (Yin, 2009).

An inductive approach was utilised to unveil unforeseen drivers from raw textual data, and induction allowed the researcher to discover hidden drivers through the data. The granular detail was expected to reveal unexpected variations in how stakeholders perceive, prioritise, and implement DT for sustainability practices across Gauteng, thus building a nuanced understanding. Finally, according to Thomas (2006), induction allows us to move beyond existing literature and build knowledge grounded in the lived experiences of people within the industry. In this study, research raw data that was collected through semi-structured interviews was translated into codes, categorised and then themed, linking to the study.

4.2.3 Purpose of Research Design: Exploratory

This exploratory research design embarked on a journey to uncover the key drivers for successful Digital Transformation (DTx) implementation, tailored explicitly to environmental sustainability in the Gauteng manufacturing sector. While existing research provided valuable insights into DTx and environmental sustainability, this

study aimed to deepen our understanding of the Gauteng context. Through an exploratory approach, the researcher gathered foundational knowledge, identified key drivers and factors, and developed a comprehensive research question for future studies.

Guandalini (2022) argued that while DTx and environmental sustainability is a topic of interest for practitioners and academics. The limited empirical research and literature are at an early stage of development. Through the exploratory approach, guided by semi-structured interviews, interviewees delved into their lived experiences and shared how they relate to the three main constructs: AI integration, DTx, and environmental sustainability. Participants were able to describe the integration process, identify key drivers, challenges, opportunities, risks and benefits and evaluate the outcomes of integrating digital and environmental sustainability in driving manufacturing enterprise performance.

4.2.4 Research Strategy

The research employed a thematic analysis which identified recurring themes and patterns within qualitative data. This perfectly aligned with this research study's objective of uncovering the key drivers of DTx on environmental sustainability practices for the large manufacturing sector in Gauteng in SA. Adopting thematic analysis allowed the researcher to move beyond simply describing the data and enabled the researcher to identify the underlying patterns and recurring themes that reveal the key drivers for successful DT implementation.

4.2.5 Time Horizon

A cross-sectional study was conducted for this initial qualitative and exploration study. Cross-sectional elements provide a more practical approach for the initial investigation. It allowed for an in-depth exploration of the human element and social context surrounding sustainable DT in Gauteng's manufacturing sector within a feasible timeframe. The findings will inform future research directions and potentially pave the way for a longitudinal study focusing on specific aspects identified.

According to Guandalini (2022), the literature on DTx and environmental sustainability is still in its early stages. Kraus et al. (2021) noted that the manufacturing and oil and gas industries are relatively new to DTx. Bag et al. (2021b) study highlights DTx is still nascent in South Africa. As a result, this study is not longitudinal and does not evaluate or study changes over a period.

4.2.6 Methodological Choices

To address the research question effectively, a qualitative research methodology was employed in this study. This approach is particularly suited for gaining an in-depth understanding of the perceptions, lived experiences, and accumulated knowledge of industry participants, experts, and sustainability practitioners (Fenech, Baguant, & Ivanov, 2019). By utilising qualitative methods, the study aimed to uncover the critical drivers of successful digital transformation (DTx) in advancing environmental sustainability within Gauteng's manufacturing sector. This methodology not only facilitates a richer exploration of the complex dynamics at play but also ensures that the insights gathered reflect the nuanced realities of stakeholders directly engaged in the industry.

In addition, the methodology applied for this research was further enhanced through data triangulation with content analysis. This dual approach allows for a more comprehensive review of the phenomenon being studied, facilitating a deeper understanding of the complex dynamics involved. This approach is well suited to enable the researcher to unveil subjective meanings, explore the social context (Grabowska, Saniuk, & Gajdzik, 2022), and understand the underlying drivers. DTx is not a monolithic phenomenon; but rather a multifaceted process that is context-dependent. This perspective is aligned with Narkhede et al. (2023), who cited the applicability of DT integration as a function of the type of manufacturing production system. The understanding of how different stakeholders (policymakers, DTx and Sustainability practitioners and experts, and business leaders) in the Gauteng manufacturing sector perceive DTx and environmental sustainability is crucial.

According to Saunders and Lewis (2018), the qualitative study generates non-numeric data and uses words, to express ideas, experiences, beliefs, behaviours and motivations. A qualitative study was chosen for this initial exploratory study in

the Gauteng Manufacturing sector to answer the main research question. Quantitative research methods may not yield in-depth data as they focus on numerical analysis rather than gathering detailed information. In contrast, qualitative research methods use open-ended questions and observation to comprehensively understand the constructs and topic under investigation (Chiarini, 2021). Therefore, qualitative research was more suitable for eliciting rich data that can provide a deeper insight into the topic of interest and provide a holistic understanding of the lived experiences, challenges, and opportunities faced by industry stakeholders as they navigate DTx and environmental sustainability dimensions.

4.3 POPULATION

The research targeted large enterprises as defined by SA due to potential resource allocation and impact on the broader manufacturing sector (Bag et al., 2021b; George et al., 2021).

Additionally, the research targeted large enterprises including Multinational Corporations. Gaglio, Kraemer-Mbula and Lorenz's (2022) study highlights, in the SA context, large enterprises' resources and capabilities to drive DTx and integrate DT in manufacturing. According to de Beer (2023), approximately 11,400 manufacturing enterprises are registered for value-added tax (VAT), representing the total population. Moreover, Gauteng is the country's manufacturing hub, accounting for 40.5% of the total manufacturing industry, 43% of the workforce and 42% of sales of goods and services.

The research population for this study consisted of Gauteng manufacturers listed on the Johannesburg Stock Exchange (JSE). In particular, manufacturers that had published comprehensive integrated financial reports, with environmental, social and governance (ESG) disclosed.

To ensure a representative sample and effectively address our research question, purposive sampling technique was adopted. The selection criteria was designed to identify key participants from manufacturers who could provide meaningful insights. These criteria included:

Criteria (1), manufacturers actively implementing DTx with AI integration. Criteria (2), manufacturers that have already adopted AI, have explored or are currently exploring its potential. Criteria (3) individuals in relevant job roles, such as sustainability managers, digital transformation experts, IT directors, or AI specialist. Criteria (4) participants with experience in DTx, AI adoption, environmental sustainability and manufacturing operations. Finally, criteria (5), consulting firms that have partnered with manufacturers to provide advisory support for AI or DTx implementation efforts. While following the criterial approach can potentially lead to a more homogeneous sample, diversity within the sample can also enrich the research findings.

By adopting these criteria's, an initial target sample of 20 participants was identified. The estimated initial target is consistent with the existing literature (Hennink et al., 2017; Fofana, Bazeley, & Regnault, 2020; Guest, Namey, & Chen, 2020), which suggests that data saturation typically requires between 9 to 17 interviews. These participants possessed the relevant expertise and experience to provide valuable insights into the key drivers for AI adoption in promoting environmental sustainability in the Gauteng within the manufacturing sector. This focused approach ensured that our findings were rooted in practical experiences and diverse perspectives, enhancing the relevance and applicability of our research.

The suitability of candidates was derived prior to the interviews being scheduled through email and phone call conversations and further in the beginning of the interview where the candidates were asked to introduce themselves and share their experience working with digital projects.

4.4 UNIT OF ANALYSIS

The unit of analysis can vary from individuals, groups, and organisations to social phenomena and is determined by the research question. The unit of analysis was the manufacturing enterprises based in the Gauteng, it included the manufacturing sector; executive managers, general manager/vice-presidents, and senior managers; manufacturing digital experts; consultant senior partners, and finally, sustainability practitioners; vice-presidents and managers, experts directly or indirectly involved in DTx to achieve sustainability goals. The participant pool

encompassed individuals with varying tenures, job levels, experience and number of years ranging from 5 to 15 years implementing digital initiatives and organisational experiences of up to 30 years. In addition, majority of the participants had graduated with university engineering and chemistry degrees, the highest being doctoral degrees and MBA's. This heterogeneity was intended to generate a rich and diverse dataset, reflecting the perspectives of a broader range of participants within the organisations. This vast range allowed for valuable and unique insights from varied perspectives and personal experiences. This combination and the multi-dimensional approach reinforced the validity of the study.

4.5 SAMPLING METHOD AND SIZE

Though the target population was known as the Gauteng manufacturing industry, however, to answer the research question, the sample frame for this study was unknown to the researcher. A purposeful sampling method for selecting participants based on their expertise and experience in I4.0 adoption was utilised. The sample size consisted of 13 industry professionals and experts in DTx, environmental and sustainability experts, ensuring a diverse range of perspectives. The sample size was determined based on the principles of data saturation and theoretical saturation, ensuring that the data collected was rich and comprehensive. The sample method and size are consistent with qualitative research approaches, which prioritise depth and richness of data over sample size (Hennink & Kaiser, 2022).

The participant selection process involved identifying potential candidates through industry reports, such as recent integrated reports of listed manufacturers based in Gauteng, and professional networks such as management consultants, followed by screening based on their expertise, experience, and involvement in I4.0 adoption. Snowball sampling was also employed, with interviewees recommending colleagues who are experts and would be well suited to answer certain questions in their specific field of work, i.e. employees involved in sustainability recommending the digital experts. Selected participants were invited to participate in the study, and interviews were scheduled at a convenient time and date. An interview guide and consent form were prepared, and Microsoft teams was tested for audio recording and transcribing

to collect and analyse the data, ensuring confidentiality and rigour in the research process.

Sample companies were selected with varying profiles across five key dimensions: digital technology or I4.0 technology AI adoption, industry sector, company commitment to DT, company ownership (local or multinational), and company size (within large enterprise classification). Selecting companies with diverse profiles across these five dimensions and gender representation was because the research aimed at achieving a rich and nuanced understanding of the multifaceted landscape of I4.0 adoption in South Africa. This comprehensive approach allowed for identifying not only the factors influencing adoption but also the variations based on company characteristics and industry context (Yin, 2009).

4.6 MEASUREMENT

The study is explorative in nature. This research utilised semi-structured, in-depth interviews as an instrument. This approach facilitated the development of a comprehensive interview guide (Appendix 1) with well-defined probing questions, to ensure rich and detailed insights from industry experts. The research was complemented with open-ended questions on key themes identified from the thematic literature review, organisational readiness, leadership role factors, digital technologies, regulatory and supporting fiscal policies, perceived benefits and challenges. All the research interviews were conducted virtually and recorded. Before commencing the research, a pilot interview was conducted. This pilot interview allowed the researcher to review the data received and course-correct to ensure that questions addressed the study's objective.

4.7 DATA GATHERING PROCESS

A systematic approach was taken to gather relevant information for this study. Answering the research question required a meticulously designed data-gathering process to ensure the reliability and validity of the findings. This meticulously

designed data-gathering process laid the foundation for a robust and informative research investigation into the factors influencing DTx driven by I4.0 adoption among large enterprises in South Africa.

In-depth interviews with key stakeholders within selected companies were conducted. The steps entailed recording and management methods throughout the research. The process consisted of three key milestones:

4.7.1 Interview Guide Design

The study utilised a semi-structured interview guide developed based on the research objectives and theoretical frameworks and the interview guide consisted of open-ended questions which were designed to elicit detailed responses from participants (Patton, 2002). The questions were organised into five sections, covering topics such as I4.0 adoption experiences, challenges and opportunities, digital transformation strategies, government support and policy, and future outlook and recommendations (Creswell, 2014). The interview guide was pilot-tested with an industry expert and consultant who not only works with various manufacturing companies for digital solutions, but previously worked in manufacturing organisations. This was done to ensure clarity, relevance, and effectiveness (Braun & Clarke, 2006), and to also understand the time that needed to be allocated per interview. The final interview guide was refined based on feedback from the pilot test, ensuring that the data collected was rich, reliable, and valid and 60 minutes was allocated as the reasonable time to complete each interview.

4.7.2 Sample Preparation

An interview schedule was drawn based on the availability of the selected initial target participants. The participants were telephonically contacted, and emails were sent as a way to remind the participants to share their availability, articulate the research's purpose clearly and to show gratitude for their willingness to participate. This was then followed by an email invitation to the participants (Appendix 2), with the consent form attached (Appendix 3), before meeting virtually to conduct the interview.

4.7.3 Interviews

This research used a carefully planned interview guide to explore AI adoption and DTx. The guide was constructed around open-ended questions that encouraged detailed responses from participants. It was divided into five sections, covering aspects such as; adoption experiences, challenges, strategies, government support, and future outlook (Creswell, 2014).

The interviews were scheduled upon clearance and approval from the Gordon Institute of Business Science (GIBS) ethics committee. Based on the availability of participants, the interviews were scheduled for 60 minutes each and conducted from July to the end of August 2024. To ensure consent of the interviewee, participants sent back their signed consent letters prior to the interviews and in the interview the researcher requested further consent to audio record the session and to use the data from the interview.

4.8 ANALYSIS APPROACH

4.8.1 Data Preparation

This study employed a thematic analysis to identify patterns and themes in the interview data, guided by DT or I4.0 adoption frameworks (Braun & Clarke, 2006). Data preparation involved transcribing, cleaning, and coding using ATLAS.ti (Muhr, 2004) and Microsoft excel. The transcribing process was through the audio recording and transcribing on Microsoft team, a total of 8.27 hours was taken to conduct all interviews, with the longest interview duration being almost 62 minutes while the shortest was around 28 minutes. The transcripts had to be cleaned and errors corrected through reiterative listening of the audios while fixing the errors in the transcripts. This process took a further 35 minutes or more per interview to complete and then reading of each transcript was done before and during coding. The coding process was done using AI coding on ATLAS.ti, the platform assigned initial codes, grouped and merged similar codes. These codes were then exported into Microsoft Excel and a selection of relevant categories was done. The researcher further

conducted a thematic analysis to identify patterns and themes that answered the research questions (Edmondson & McManus, 2007; Gioia, Corley, & Hamilton, 2013).

4.8.2 Coding and Categorisation

This study used a systematic approach to analyse interview unstructured data. This entailed initial transcripts AI coding, followed by axial coding for grouping similar codes into categories. The selective coding to identify the most relevant categories (Corbin & Strauss, 2008). This process allowed this study to focus on computerised coding, which followed established guidelines and utilised a specialised software (ATLAS.ti) to manage and analyse large datasets (Zakaria & Zakaria, 2020). Through this rigorous process supported by steps outlined below, the research aimed to identify meaningful patterns and themes in the data, providing valuable insights into the topic under investigation. With this in mind, the researcher was also able to view and use quotations linked to the codes.

Thematic analysis is a widely used method for qualitative research in the behavioural sciences. It offers a flexible approach for identifying, describing, and interpreting patterns within datasets (Braun & Clark, 2006). Therefore, to effectively conduct thematic analysis, researchers must engage in a systematic process that involves:

1. **The first step, familiarisation:** To gain a deep understanding of the data, the researcher should immerse in the data from the interview transcripts.
2. **The second, coding:** Encompasses identifying and labelling key concepts or patterns within the data.
3. **The third, theme generation:** This step entails grouping related codes into broader themes that capture the underlying meaning of the data.
4. **The fourth, theme review:** Relates to themes generated, includes evaluating and refining to ensure themes accurately represent the data.
5. **The fifth, theme definition:** Involves systematically defining and naming final themes to ensure consistency and clarity in the analysis process.

By following these steps, this research study can extract valuable insights from the data and develop a comprehensive understanding of the research topic. Initially, an inductive coding approach was used, utilising recommended Atlas.ti software and AI coding tools. While AI tools can streamline the coding process, manual review and analysis using Microsoft Excel were adopted to ensure accuracy and deeper understanding. This labour-intensive approach allowed for a rigorous process that included capturing the nuances to provide greater confidence in the results. Familiarity with the data is crucial for effectively navigating the coding process and allowing the data to speak inductively.

4.8.3 Data Saturation

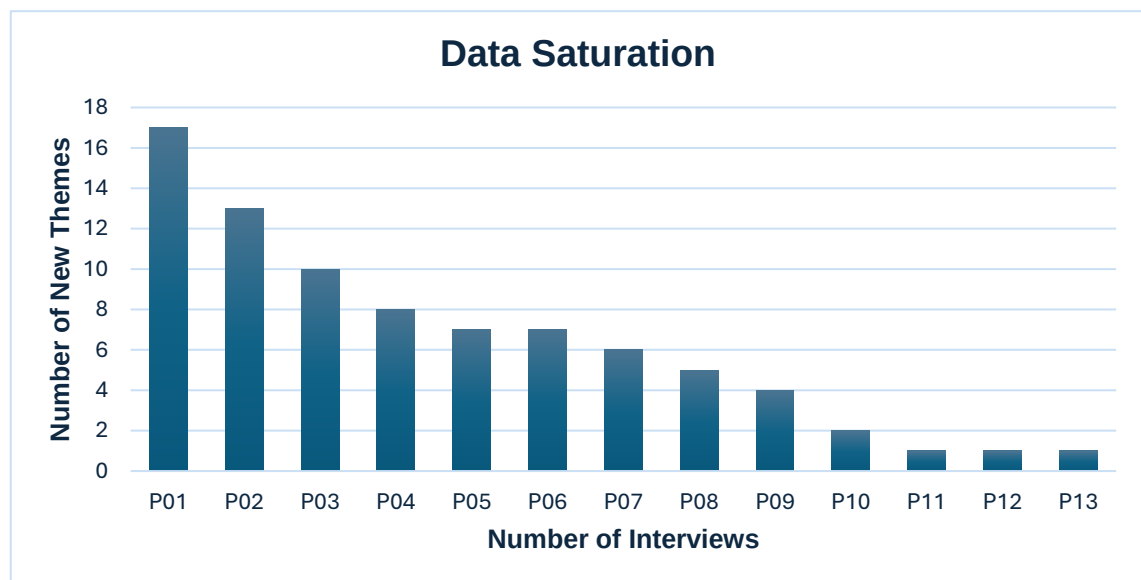


Figure 1: Data Saturation

Source: Created by Author

The graph above demonstrates the number of participants and themes generated from transcripts. From the graph, data saturation appears to have been reached after the 11th interview participant from 13 semi-structured interviews. While some participants still introduced a few new codes, the overall trend indicates that the data collection process has effectively captured the majority of categories and relevant themes, as evidenced by the diminishing number of new data arising from later interviews.

While certain participants contributed more new insights, the difference is notable. The variance might be due to depth and breadth of experience and engagement with the topic or is approaching completion. Furthermore, saturation might be reached with fewer interviews due to the homogeneity of the participants. A more homogeneous group may reach saturation faster due to shared experiences. This is consistent with the existing literature by Hennink & Kaiser (2022).

The study participants had diverse educational backgrounds, including engineering and science from undergraduate to doctoral degrees, complemented by business and leadership postgraduate degrees. Based on the Gauteng Manufacturing industry, participants, on average, had approximately 7 years of experience working on digital projects, while the average tenure is about 13 years. Participants constantly highlighted leadership alignment and support, integrated strategy as key drivers, lack of cultural aspects considerations, investment, and need for government support and incentives as barriers. Furthermore, also noted from participants is that AI is at an early stage of adoption, and shares the same risks, such as carbon tax and challenges, such as environmental regulatory compliance.

4.9 DATA VALIDITY AND RELIABILITY

This research ensures the accuracy and dependability of its findings through a range of measures (Yin, 2009). Semi-structured expert interviews provided data information rich for this exploratory study. Open-ended interviews allowed the participants the ability to share their thoughts and experiences in depth, establishing valid content while open to allow unexpected and novel knowledge to emerge (Yin, 2009; Creswell, 2014). While open-ended questions can reduce bias, it's important to acknowledge that participants may still have personal biases or motivations that could influence their responses. Techniques such as probing questions were considered and included in the interview guides. Additional considerations, such as researcher bias and generalisability, were outlined in the limitation sections below.

The questions asked were directly related to the research objectives and themes, ensuring face validity (Thomas, 2006; Yin, 2009). The study's use of theoretical

frameworks and concepts related to Digital Technology and Industry 4.0 adoption, including AI and environmental sustainability, enhanced construct validity (Bag

et al., 2020; Chiarini, 2021). To ensure inter-coder reliability, multiple coders were used, and inter-coder agreement statistics were calculated (Weston, Gandell, Beauchamp, McAlpine, Wiseman, & Beauchamp, 2001; Hwang, 2008).

Furthermore, to ensure validity and reliability, participants were asked the same full set of questions with minor tweaks or changes for those who came from consulting houses. A detailed record of the data collection, coding and analysis process has been maintained. The researcher continued with interviews until there were no new codes emerging, indicating saturation. An initial 15 interviews were scheduled but ended up stopping at 13 interviews, catering for any potential cancellations. Triangulation was also used to increase the viability and the quality of the data. By addressing data validity and reliability, this study ensures the accuracy, consistency, and generalisability of the findings, providing a robust foundation for the research conclusions.

For this exploratory study, participants were selected based on a defined criteria and with a snowball purposive sampling method adopted. The researcher's choices and the participants' referrals and homogeneity can introduce bias into the sample. To address the potential bias, participants identified represented diverse manufacturing companies in Gauteng and a data triangulation strategy was adopted to improve the data reliability and validity. Of the 13 participants, 16% were consultants, 84% were full-time manufacturing employees, and 16% of those were environmental sustainability professionals.

4.10 ETHICAL CLEARANCE

The researcher attained ethical clearance approval from the GIBS Ethics Committee in July 2024 before commencing with interviews (Appendix 4). Consent letters were sent to the participants to sign as a form of giving consent to take part in the interview and for the data obtained in the interview to be used in this research. At the beginning

of each interview, participants were further asked if they gave consent as per the consent letter and if they gave permission to continue.

4.11 RESEARCH LIMITATIONS

This qualitative research delved into the subjective experiences and perspectives of various stakeholders involved in Gauteng's manufacturing industry.

While the previous exploration identified drivers for successful DTx, it focused on an objective analysis. Qualitative research offers valuable insights by directly exploring the perceptions and experiences of those involved in the process. However, qualitative research comes with its own limitations:

- **Research scope:** While the thematic literature review identified many research gaps and unexplored problems, this study focused on AI digital technology and drivers of success for adopting AI as DT or I4.0 for advancing environmental sustainability dimension greenhouse gas emissions such as carbon dioxide.
- **Limited Generalisability:** Qualitative study findings might not directly apply to the entire Gauteng manufacturing industry, but the research attempted to address this by including diverse stakeholders and ensuring participant selection reflected the industry's composition.
- **Purposive sampling:** While purposive sampling offers the benefits of a targeted audience with lived experience, convenient to the researcher, the limitation is the findings cannot be generalised to the same extent as the findings from probability sampling.
- **Subjectivity of Data:** Qualitative data is based on personal opinions and interpretations. The research challenged this by employing rigorous data collection methods like semi-structured interviews alongside triangulation with other data sources (e.g., industry reports) to enhance the credibility of findings.
- **Researcher Bias:** The research employed transparent data analysis techniques but was unable to do any member checking, where participants review interpretations to ensure their experiences are accurately represented.

By acknowledging these limitations, the research leveraged the strengths of a qualitative approach to gain a nuanced understanding of how stakeholders perceive and experience the drivers for successful DTx in achieving environmental sustainability within Gauteng's manufacturing industry.

5. FINDINGS/ RESULTS

5.1 INTRODUCTION

The primary aim of this qualitative exploratory study was to explore the key success drivers of DTx in advancing environmental sustainability practices within the Gauteng manufacturing sector. Specifically, the study of how AI can be leveraged to support environmental sustainability in the manufacturing sector in Gauteng and what organisational internal and external drivers of success are crucial to facilitate the adoption of AI-driven sustainability solutions.

This chapter presents summarised key findings from a thematic and inductive approach, qualitative data analysis. These key findings are organised thematically based on 13 participant interviews. The chapter begins by providing a detailed profile of the interviewed participants, which sets the context for the research. Following this, it then outlines the process followed to develop the themes from the qualitative data, including the concept of data saturation and how it was achieved. Next, the chapter presents the key findings derived from the qualitative data analysis, followed by the finding's overall summary. Importantly, the research questions detailed in the body of the chapter served as an anchor for presenting the themes that emerged from the thematic data analysis. Finally, the themes derived serve as a foundation for the research narrative.

This structured approach was followed to ensure the coherence of the results, and the findings data answered the research question linked to the overall research aim.

5.2 PARTICIPANTS OVERVIEW PROFILE

Table 1 below provides an overview of the participants interviewed. To ensure participant confidentiality, the names of the participants were replaced with unique identifiers, such as P01 for participant number 1. To get additional insight into the manufacturing sector, consulting companies were included as participants. The criteria to include was based on their engagement in the manufacturing industry,

specifically, engagement aimed at driving DTx with sustainability impact. The manufacturer's representation to participate in this study initially were companies headquartered in Gauteng, with the JSE or with dual listing, with operations in Gauteng. In addition, Gauteng based companies with fully published Integrated Financial Reporting and ESG reports.

The majority of the manufacturing industry participants in this study represent Multinational Corporates (MNC) with operations in Gauteng, from sub-sectors of Food and Beverage, Non-metal minerals, Petroleum products, Chemicals, rubber and plastics. The majority, 72.73%, hold senior positions such as C-level and VP level within their organisations. The decision to assign senior leaders to drive DTx shows that the manufacturing sector values experienced leaders. This approach is likely to enhance strategic planning, focus on strategic initiatives and support effective investment decisions.

In addition, the participants in this study had a mix of science, technical and postgraduate business-related qualifications, ranging from undergraduate to doctoral degrees. Their educational backgrounds include technical disciplines like engineering and science, complemented by business and leadership postgraduate degrees. This wide range of expertise underscores the diverse and highly educated nature of the professionals who participated in this study.

On average, the participants had approximately 7 years of experience working on digital projects, while the average tenure is about 13 years. Out of the total of 13 participants interviewed, 16% were consultants, 84% were full-time manufacturing industry employees, with 16% of the manufacturing industry working as full-time environmental sustainability professionals.

Table 1: Interview Participant Profile

Participant No	Role	Tenure	Years in Digital	Experience in Digital	Qualifications
P01	Head Digital Delivery and Data Science	30 years	15 years	Chemical Process Engineering Data Science (15) years and 7 years DTx	PhD Chemical Engineering
P02	Senior Manager in Information Management	5 years	5 years	Overseeing DTx and IT portfolio management	Higher National Diploma in Electrical Engineering + MBL
P03	Group CIO	7 years	5 years	Driving digital and IT modernisation, 16 years in consulting and digital projects	MSc Metallurgical Engineering
P04	Senior Vice President for Corporate Affairs	30 years	2 years	Involved in digital initiatives since 2022	Chemical Engineering + MBL
P05	Head of Digitalisation	34 years	7 years	Leading digital team in the energy business, involved in DTx since 2017	PhD Organic Chemist. Geologist
P06	Production Manager	10 years	10 years	Transitioning towards digital technologies, using big data analytics	BSc Chemical Engineering + PGDip; MEM,

				and machine learning	
P07	Chief Information Officer	9 years	9 years	Overseeing IT and digital projects, extensive experience in consulting and digital strategy	BSc Computer Science
P08	Head of SHE Regulatory Compliance	Since July 2024	2 months	Team members use digital tools for data integration and reporting	BSc Chemical Engineering
P09	Expert Partner	3.5 years	3.5 years	Focus on DTx's in energy and natural resources, former chief digital officer	Chemical Engineering
P10	Connected Brewery Digital Lead	2.5 years	2.5 years	Overseeing connected brewery portfolio, experience in automation engineering	BSc Eng Electrical, Control & Instrumentation
P11	Partner	13 years	13 years	DTx work across different industries. The leaders in AI and Gen AI. Internal R&D for Digital use cases	BSc Chemical Engineering
P12	Manager Air Quality Department	7 years	7 years	Overseeing air quality, water emissions or environmental conditions the	Chemical engineering and Biochemistry

				compliance monitoring	
P13	Business Director	18 years	10 years	Cyber Security, AI, Machine Learning, and Advanced Analytics, with a focus on ESG and Sustainability.	BSc Actuarial + MBA

The participant's diverse educational backgrounds, tenure and experience in digital projects and the diversity within the manufacturing sector ensured a comprehensive understanding. In addition, the diversity offered deeper insights and rich perspectives and allowed for a more nuanced view of how the manufacturing industry is adopting AI and digital technologies. Therefore, varied backgrounds are crucial for understanding the key success drivers, challenges and opportunities, benefits and risks related to the adoption of AI to advance environmental sustainability in the manufacturing sector.

Having established the profile of who is providing data, the next sections delve into the process that was followed to derive the key themes from the data.

5.3 KEY THEMES – KEY SUCCESS DRIVERS EMERGED FROM THIS STUDY

Post-data analysis identified seven additional key themes, and the literature review was updated with newly emerged themes. This discovery adds to the initial six themes identified by thematic literature, bringing the total to 13 key themes. Detailed codes, categories, sub-themes and key themes are provided in Appendix 5.

5.3.1 Research Question 1 (Organisational Capabilities): What are the key drivers for the successful adoption of DT AI in the Manufacturing sector to achieve the environmental sustainability dimension of greenhouse gas emission reduction?

Research question 1, the study seeks to explore the key drivers underlying manufacturing companies' adoptions of digital technologies, specifically AI, and the elements that contribute to their successful implementation in achieving environmental sustainability objectives, with a specific focus on greenhouse gas emissions.

Theme 1: Digital Leadership Drivers

The data from the participants interviewed reveals a strong alignment and active support from top management within the organisation regarding the strategic importance of emerging technologies, particularly AI is a key driver.

P03: "We are aligned top to bottom in terms of the strategic importance or how the new tech emerging technologies as well as in particular Gen AI and AI is going to drive value for the company in terms of where we are as a company."

In addition, data analysis shows that alignment includes articulating an ambition and developing a formal organisational strategy to ensure that DTx efforts are cohesive and effective for achieving the manufacturer's strategic objectives.

P04: "From a leadership point of view, it is important to understand where AI can assist your business, but first start with the business case and the business vision."

P02: "On a high level, the leadership has targets in terms of responding to license requirements into whether it is water usage or emissions of toxic gases, the KPIs, there are legal or constraints that we need to operate within otherwise the license to operate might be revoked whether it is because of water usage or spillages or emissions."

Participant *P01* cautions that the education of the senior management is crucial to get the right sponsorship and commitment.

P01: "You require Senior management at executive levels commitment and sponsorship of digital, that's a given. Everyone will tell you that, but you have to be careful again that they know what they are talking about."

The findings are supported by external surveys from WEF Global Lighthouse and ITWeb, which emphasise leadership alignment is crucial to facilitate the strategic roadmap, including vision, value and roadmap, for the integration of AI and digital technologies:

de Boer and Torti. (2023) suggests on the 2023 WEF and McKinsey survey "To align the senior leadership team on the transformation vision, value and roadmap and reimagining business domains to deliver outstanding customer experiences and create competitive distance."

Woolley (2024) highlights in the survey from the iTweb article that "effective leadership in sustainability requires a deep understanding of the potential benefits, as well as the ability to communicate a compelling vision and inspire the entire organisation to embrace sustainable practices."

Participant *P07* cautions that it is a challenge to achieve a strong alignment and active support, and argues it takes effort and education before buy-in from top management can be secured, particularly for integrating emerging technology in manufacturing.

P07: "It really takes longer to get the management and executives on board, and it does not help that the average age of our senior managers and executives is in the early 50s."

Participant *P06* raised an opposing view, highlighting that multinational companies tend to rely on mandates or recommendations from their global headquarters. In addition, the lack of enthusiasm from local senior leaders can stifle sustainable innovation.

P06: "So I think in our case because the top or senior management looks to us to almost present a business case, especially around innovative ideas."

Unless it is something that comes cascaded from our global headquarters, in terms of our senior managers, I have not seen any of them who are very passionate about us going Digital or driving digital technologies.”

Woolley (2024) stated, “Without a strong, visible commitment from the C-suite, employees may perceive sustainability as a low-priority or optional initiative, rather than a critical component of the company’s long-term success.”

Moreover, it has emerged from the participants that South African manufacturers are lagging behind in DTx compared to global trends. In addition, the lack of leadership conviction regarding the value of DTx. Moreover, past digital initiatives’ investments focused on visibility and data lakes without clear business objectives.

P02: “It still feels a bit like we are not sure how much or if this will create value. If you look globally, the use cases are very much proven, and the value unlock for clients has been proven.”

Interview participant P07 and data from the WEF Global Lighthouse survey also support the slow progress and technology adoption of AI technologies:

P07: “In manufacturing, we are generally laggard when it comes to technology adoption, and AI is no different, and there is always the big question mark around the upfront investments versus the returns that we will get from the deployment of the technology.”

P06: “One of the things that drive lack of adoption because there is always that reluctance by the current senior leaderships to go towards something that is not really proven that will be risky for the business.”

The WEF and McKinsey survey data highlights the slow progress; 70% of companies are still stuck in “pilot purgatory”, (de Boer & Torti, 2023).

Proactive communication from top management about AI initiatives drives innovation and organisational change.

P02: “The leadership also from the executive need to also set the tone by embracing the change that is coming, but they need to do it ahead of time so that people are not disrupted in the ways of work when it actually happens.”

Summary

The findings from the theme of digital leadership, which is part of Research Question 1, highlight that leadership alignment and proactive support are key drivers of success. Additionally, a conviction demonstrated by strong commitment and sponsorship from leadership is crucial for the successful integration and adoption of AI in the manufacturing sector. However, the lack of clear value cases and leadership conviction poses significant barriers to DTx to advance environmental sustainability practices. The analysis reveals proving a compelling value case remains a major challenge. Furthermore, participants noted that senior leader's proactive championing of digital initiatives promotes innovation at lower levels. Finally, participants stressed that a cultural shift within manufacturing companies is essential to promote innovation, and technology adoption, and sustainability.

Theme 2: Organisational Readiness for DTx Drivers

The data from the participant interview reveals that effective change management must be the manufacturer's priority. This key driver is essential to facilitate the successful adoption of digital technologies, particularly AI technologies.

P02: "The leadership also from the executive need to also set the tone by embracing the change that is coming, but they need to do it ahead of time so that people are not disrupted in the ways of work when it actually happens."

Participant *P01* support the effectiveness of change management as a key driver, emphasising that all major DTx projects include change and communications experts.

P01: "What we have got now is on all of our large projects, we now have a change communication expert or a change management expert or a communication expert, and they are frequently the same person, and we have them in our large projects to help us because we just don't know."

In addition, the emerging data from the participant interviews highlight change management efforts must address the human aspects of change. This key driver is essential for realising the full potential of digital initiatives and ensuring that technical

advancements translate into meaningful organisational improvements and sustainability targets. Moreover, the analysis reveals that successful DTx requires a comprehensive approach that addresses both human and technical factors.

P13: “So the two main challenges would be adoption and then actually the readiness of the company. If you look at human behaviour, that is like the final frontier in any case. I mean, if you do not influence behaviour, nothing will happen.”

Thus, the *P01* participant supports, emphasising employee behavioural adjustment for the technical to derive full potential from the technical solutions.

P01: “So there are some human behavioural elements that need to be adjusted to accept the digital.”

P12 participant highlights employee resistance to change, specifically at an operational level, driven by digital technologies integration.

P12: “You would see pushback or, like globally, everywhere you go in a control, people first ask you who is going to take my job.”

In the 2030 Builder report, Genghini (2024) highlights that “fostering a culture of sustainability within the organisation can be a significant challenge, as it requires a shift in mindset, behaviours, and daily habits. Employees may be resistant to change, particularly if they perceive sustainable practices as an added burden or a disruption to their established workflows.”

Furthermore, participant response reveals change management efforts must be augmented by coaching, as a strategic intervention. Coaching is essential for facilitating the adoption of new digital tools and ensuring that employees are equipped to utilise them effectively. Providing guidance, support, training, and coaching can help overcome initial resistance to change and ultimately drive successful DTx.

P13 “The adoption and change management is a massive part of this and coaching as well because bearing in mind you also have a large contingent of blue-collar workers as well that needs to be trained and educated on this

and understand that it is an extension of the job and the fulfilment model replacement.”

P02: “So it is about the change management that one has to go through within the organisation to show the value of DTx creating capacity for employees to do anything else.”

Summary

The findings from the theme of organisational readiness, which is part of Research Question 1, highlight that effective change management is a significant driver for the successful adoption of AI and digital technologies. Additionally, effective leadership is essential for driving successful change management. Furthermore, participants stressed that employee behavioural adjustment is necessary to embrace technology advancements for achieving environmental emissions targets. Building on this, the analysis reveals that manufacturers must adopt coaching as a strategic intervention to support employees in navigating change and to embrace desired behaviours. Finally, effective change management must be driven by change and communication experts for the effective adoption and integration of AI for advancing environmental sustainability practices.

Theme 3: Building a Digital-Ready Workforce Drivers

It has emerged from the interview participants that there is lack of skilled digital talent, a significant barrier and may slow the pace of the digital and AI technologies adoption.

P05: “One of the issues the company faces which I would imagine that is probably true for most companies across South Africa, is a lack of talent, so we do not have data scientists. We do not have data engineers, or the country now does not have enough, and those that we do have, or the country does have are so in demand that they can do whatever they want.”

Findings supported by Participant P07.

P07: "In the context of South Africa, it is more the development of skills and properly qualified people to understand the outputs of digital solutions and to be able to work with those."

Moreover, it has emerged from the data that, the lack of digital talent challenge is further compounded by lengthy time required to develop talent.

P01: "We have got the bursary program in place with the universities now where we are paying for bursaries for data scientists and then bringing them into the company and training them, and that is fine. And the first ones are here, but that is seven years to train the individual. Four years in university and three years on the Development program."

Further analysis from the data reveals that manufacturers, have developed different strategies to address skills shortage. Accordingly, the strategies are designed to address the current and future talent needs. To address current needs and to accelerate the learning, a blend of learning strategies has been adopted; including tailored training, experiential training, continuous learning, and collaboration with external experts are approaches leveraged to accelerate the learning.

P10: "Management does provide ample training opportunities for DT."

Participant *P03* supports, emphasising mobilising Human Resources to recognise the need and to support training and development efforts.

P03: "I am working with the head of HR to advertise with her the training that we want to make available, Soft. We are in deep conversations with her in terms of her sponsoring that enablement across the organisation for Gen AI."

P04: "The one we are in the forefront of designing a curriculum so that we can send our engineers on the training." But also, you need a training department that is always on the lookout for new offerings in terms of DTx courses and development."

Furthermore, the data revealed that the challenge of employee training is dependent on financial resources or funding availability.

P07: “So there is that constraint, but there are lots of people in the business who have taken it upon themselves to skill themselves in the area and I work closely with those.”

The data analysis highlighted that companies are proactively investing in future training needs by partnering with universities through bursary schemes to develop a digital talent pool.

P04: “Whether it be the relationship with the university, as I said, we are working with Stellenbosch, but also you need a training department that is always on the lookout for new offerings in terms of DTx courses and development.”

In the WEF and McKinsey survey report de Boer and Torti (2023) stated that “the best performing capabilities are not built alone; it takes an ecosystem of strategic partnerships – with universities, innovation centres and technology partners.”

Summary

The findings from the theme of building a digital-ready workforce, part of Research Question 1, highlight that lack of digital talent, in particular data scientists for AI technology development, is a significant barrier. Moreover, the data reveals the challenge of developing digital talent and the slow pace of development. Moreover, further analysis highlights that manufacturing companies started adopting short and long-term strategies to build organisations’ digital capabilities. To address the current needs, a blended training approach is undertaken. Further analysis revealed training and development funding allocation challenges, which hamper the efforts to develop the needed capacity to implement digital technologies.

Theme 4: Sustainable DTx: Investment Drivers

From the participants’ interviews, it has emerged that the upfront costs for implementing and integrating AI far exceed the immediate benefits. These findings underscore that investment may be a significant barrier for integrating digital and AI

technologies to advance environmental sustainability. Further analysis highlighted the conversation about technology integration is often biased on financial challenges, rather than long-term benefits. The scarcity of investment is a major obstacle for advancing and achieving sustainable manufacturing.

P07: “Manufacturing is we are generally laggard when it comes to technology adoption, and AI is no different, and there is always the big question mark around the upfront investments versus the returns that we will get from the deployment of the technology and there is always a question of but what is wrong with what we are doing.”

Participant P02 supports the finding and emphasises the duality of benefits, pursuit of short-term financial objectives and environmental sustainability.

P02: “Every project, especially capital intensive, has to make sense to the shareholders both from a return perspective and the impact on the environment.”

Participant P12 further reinforces the initial finding, stating that manufacturers often start with typical questions and conversations around the investment decision, the trade-off between environmental sustainability initiatives and the financial returns on their investment.

P12: “Another one is where what we do with multivariable capital portfolio optimisation. So how do you trade off where you invest between the different ESG elements and the business requirements to get the most value.”

Participant P06 highlights an opposing view that there is capital funding available for innovation and sustainable manufacturing.

P06: “So there is a lot of Capex in terms of modernising the plant and using green technology. It is all about the return on investment, and we do not only measure return on investment in terms of the financial value that one derives. So, we also look at things like quality or if it helps us achieve our sustainability goals. It will also be something that we consider.”

Genghini (2024) suggested that “another significant barrier to achieving sustainability goals is the lack of sufficient resources and budgetary

constraints. Implementing sustainable practices often requires substantial upfront investments, whether it is in new technologies, infrastructure upgrades, or employee training and development.”

Participant *P13* cautions and raises that additional significant investment is required to modernise manufacturing companies' stranded assets. Stranded assets are outdated process equipment, lacking signalling and digital monitoring capabilities. Furthermore, these stranded assets may be a significant barrier for integrating AI and other digital technologies.

P13: “They do not have any MES system, becomes very difficult to implement the greenhouse gas system or something that tracks and monitors and reports on top of that. So, it is definitely the digital maturity of the company.”

de Boer and Torti (2023) reveal that “it is an expensive proposition: often, a resource requirement of more than \$100 million is required to successfully transform large companies.”

Participant *P09* raises an opposing view, revealing that manufacturers can adopt, innovate and retrofit approaches to the existing manufacturing equipment. In addition, the participant argues that this approach will minimise the significant additional upfront investment required. Moreover, this approach is more cost-effective for increasing the adoption of digital technologies to achieve environmental sustainability goals. Furthermore, this approach aligns with and promotes the broader trend of using digital technologies to improve sustainability practices in manufacturing.

P09: “If you look at particular matter emissions from our steam plants or our boilers, the teams really started off by saying we need to replace or upgrade all of our electrostatic precipitators, and that would have cost us billions of rands.”

Further analysis of the data revealed that strategy and funding issues. Participant *P13* highlights that manufacturers' DTx strategy, usually developed by consulting companies, is often not supported by manufacturers' financial investment or operational execution. The major gap between the strategy and execution is a

significant barrier for integration of digital technologies to advance to sustainable manufacturing within the manufacturing sector.

P13: “We have worked with various other consulting houses in the Big Four conceptually, and then when they typically work with manufacturing houses, they are very involved at a strategic level, and they typically do not get investment further than the strategic level.”

Summary

The findings from the theme of sustainable DTx investment driver, which is part of Research Question 2, highlight that the AI technology integration upfront costs often exceed the immediate benefits sought by manufacturers. Furthermore, additional investment is required to upgrade outdated infrastructure or modernise the manufacturers' operational technology for DTx readiness. However, the financial burden leads to focus on investment challenges rather than potential long-term benefits. For example, one participant noted that the manufacturing sector generally lags in technology adoption due to initial investment concerns versus immediate expected returns. Finally, there is a recognition of the need to balance short-term financial objectives with long-term environmental goals.

5.3.2 Research Question 2 (Impact): How is success measured for measuring the effect of adopting DT for the environmental sustainability dimension?

Research question 2's main goal is to determine how to evaluate the success of adopting and integrating digital technologies to reduce environmental sustainability, such as greenhouse gas emissions. The question explores the metrics and indicators used to assess the environmental impact of DTx initiatives

Theme 5: Holistic Performance Measurement

The participant's response highlights that the organisations recognised a holistic approach to measuring the value of DTx for environmental sustainability. From the

data analysed, local manufacturers measure and track a variety of value levers, including financial, environmental, and employee-related metrics, understanding the full impact of integrating digital technologies and AI and making informed investment decisions.

P13: “So, the economic viability is very important. I do not think people underestimate how stringent the businesses look at the bottom line, especially in our economic conditions.”

P04: “We ended up reflecting a potential of around 700 million Rand of EBITDA from this AI intervention.”

Moreover, the data from the interview raises significant issues. Prioritising and delivering digital and AI-enabled value in manufacturing is a major challenge. It highlights that not all opportunities will yield value. Furthermore, it states that to maximise value, it is essential to conduct a value assessment to identify the most promising options to prioritise based on their potential impact.

P09: “I think a big thing in manufacturing is that there is lots of opportunity and not all of the opportunities would give you the values. So, in order to get the value that you’re looking at, it is important to do a diagnostic and understand where the option sets sit, and then prioritise that from a value perspective.”

P10: “For instance, if you could produce some sort of use case and it is something we are looking at, using AI to monitor Carbon Dioxide (CO₂) consumption in brewing and finding a way to reduce your CO₂ consumption maximising the efficiency in terms of how much CO₂ you use per brew or how much you can recuperate from the brews. That can have a significant impact on CO₂ reductions and that is just one specific use case with CO₂ monitoring.”

Another finding from the data highlights the manufacturer’s commitment to complying with globally integrated reporting requirements. Specifically, for environmental impact, the data reveals a focus on setting and tracking 2030 emissions targets and net-zero ambitions. This includes both short-term tracking of goals and long-term planning for achieving carbon neutrality.

P12: “That drove a lot of transparency and targets like every major Manufacturing site now has specified targets for water and carbon or rather all ESG targets. As part of the financial reporting, if you look at the financial reports, it is expanded a lot to include ESG now.”

In addition, data revealed that manufacturers use measures such as emissions baseline and reduction, energy consumption, efficiency gained, waste reduction, and water usage to track the environmental impact of digital initiatives.

P12: “So having a clear value function before you even start with the developing a use case and what you typically see is even on the environmental projects, there is a value calculation through carbon tax, through water use tax, through opportunity cost and so defining that value function properly is a big unlock and in developing a use case that actually generates value for the business.”

Furthermore, analysis reveals that manufacturers track the effectiveness of digital initiatives for addressing environmental sustainability. Measures includes the adoption through scaling and usage rate, satisfaction level, and the performance of the DT.

P02: “So for every project, if you deploy the digital solution to your environment and follow the agile method, there is a business model canvas and that framework allows you to build fit-for-purpose platforms with the end user in mind and that approach almost walk towards a high possibility for adoption and success and complemented by the agile framework where the end-user become part of solution development. So, the combination of the two are enablers for success in terms of minimising this risk that we measure.”

Furthermore, data also revealed the challenges of old operations technology assets, which lack monitoring capabilities. The implementation of digital tools to enable reporting, ESG, etc, was also revealed.

P02: “So one of the projects right that we currently running is to provide visibility to what you call stranded assets. These assets are typically assets that are running without monitoring because of legacy issues. So, there is no

signalling from those assets. You cannot monitor in real time the health status of those assets.”

Summary

The findings from the theme of holistic performance measurement driver, part of Research Question 2; highlight that holistic performance measurement is crucial for assessing the full impact of DTx. In addition, data revealed not all opportunities will yield the desired outcomes. Therefore, manufacturers must prioritise and invest in high-potential AI technology-enabled use cases. Further analysis revealed manufacturers' commitment and compliance with global integrated financial reporting requirements. Finally, manufacturers' measurements and performance include measuring the effectiveness of AI integration.

5.3.3 Research Question 3 (Opportunities and Challenges): What policy initiatives and regulatory frameworks are necessary to promote sustainable development in the South African manufacturing sector?

Research question 3's main goal is to determine what specific policies and regulations are influencing sustainable development within the South African Manufacturing sector. In addition, the question seeks to explore specific policies and regulatory frameworks that support the adoption of digital technologies, like AI, in the South African manufacturing sector to reduce greenhouse gas emissions to advance sustainable development.

Theme 6: Policy and Regulation

The participant interviews highlighted that the lack of incentive provisions in the manufacturing industry is a significant barrier. Additionally, this significant gap also discourages manufacturers from investing in environmental sustainability practices. Moreover, the absence of incentives leads manufacturers to prioritise AI and digital implementation for short-term financial gains, potentially compromising long-term sustainability objectives.

P05: "I think there definitely needs to be more of an incentive provided by the government for companies to really invest in these technologies because it is not cheap in many cases you need to change your business model."

Participant *P06* reinforces the previous finding, asserting that manufacturers within the sector are compelled to make strategic decisions to move towards DTx to remain competitive and ensure long-term viability.

P06: "In my opinion, the government is not doing enough to prepare the economy for Digital, which means when companies want to move Digital, they may have to look outside the borders of South Africa, which is something that I think the government would not like."

P13: "So let us get into that because you said I'm anonymous. So, I have not found that regulation to business in South Africa has driven any adoption at a significant scale."

This finding is supported by participant *P05*, who highlighted that the government is not keen to prepare the economy for digital, citing two major reasons: the first is fear of increased unemployment, and the second is the possibility of going outside the borders to get the skills to support the implementation.

P06: "So I think from a government point of view there would not necessarily be a push where they push industries to digitalise because they may feel that would harm job prospects."

Moreover, participant *P05* stated government partnership approach is crucial for driving AI and other digital technologies adoption for advancing environmental sustainability practices. The current approach is biased towards punitive measures and not enabling.

P05: "The current setup is more of a punitive system, so if you do not comply to the law then you get punished in terms of tax and the license to operate and so forth. Whereas I think if the government would take more of a partnership approach and incentivise economies around established operational manufacturing of operations to contribute to developing new technology, new ways of working and new technology, to optimise operations."

Furthermore, the participants' responses reveal a complex relationship between businesses, government and regulatory frameworks. The data reveals that the government is expected to take more of a partnership approach with the industry. In addition, the respondents expressed scepticism about the effectiveness of current regulations, citing complexity, and challenges faced by organisations to comply with regulatory requirements.

P05: "I think that would definitely provide a bit of a multiplier effect, whereas currently, it is just you and your own efforts to comply to the law, but if there is more of a developmental type of approach that government can take, I think it will just be more effective."

P13: "So they tend to rather than looking at growth and sustaining regulation, they typically start at how do we defend the consumer, and if you start with that outlook, it makes it very difficult to drive adoption."

While regulations are intended to guide and standardise practices, their implementation often lacks a deep understating of the unique circumstances of the local manufacturing businesses and the flexibility to accommodate them.

P05: "It is not cheap in many cases you need to change your business model. You need to change the setup of your operational assets that you have, and it is an expensive exercise to go through."

Participant *P13*, supporting this finding, stated that the existing regulatory environment has not significantly influenced businesses to adopt digital technologies and AI practices directly. While regulations have increased awareness and disclosure requirements, their direct impact on driving significant adoption of sustainable practices has been limited.

P13: "So Africa's adoption rate to legislation is very low compared to the European counterparts, for example. I will give you an example. There was this thing about the Green Building Council was launched in 2017. They said every building needs to be green Building Council rated. That is like the ABC rating on your energy, and to date, less than 20% of buildings in South Africa have done that certification."

P05: “We do not only measure return on investment in terms of the financial value that one derives. So, we also look at things like quality or if it helps us achieve our sustainability goals. It will also be something that we consider.”

Finally, the participants interviewed revealed the lack of government support for the local manufacturing industry and an understanding of industry needs. In addition, both manufacturing industry businesses and the government lack of proactive engagement and collaboration to develop effective strategies to balance sustainability and profitability.

P05: “We do not get any support from the government in terms of achieving these compliance numbers.”

P13: “If someone says ESG or environmental or sustainability or even social, they just hear money going out of the door with no return because it is a government thing.”

Participant P13 supports this finding and raises a major risk of potential closures due to prohibitive costs of compliance and the need to mitigate potential business risk.

P13: “That is why you find other organisations and companies diversifying out of certain markets because of this challenge of not being able to meet those environmental targets and focus on other countries where probably the regulations are not as extensive.”

Summary

The findings gathered from the theme policy and regulation, part of Research Question 3; participants highlight, first a significant gap in government and the lack of incentives for the manufacturing sector. Second, without these incentives, manufacturers tend to prioritise short-term financial objectives from their AI and other digital technologies investments. The short-term mindset undermines AI integration for achieving long-term sustainability goals. Moreover, the findings reveal a notable disconnect between the government and the manufacturing industry. Participants expressed that due to the lack of proactive engagement, businesses feel unsupported in meeting compliance requirements. Additionally, the disconnect stifles

innovation and encourages companies to seek opportunities outside the country, where regulations may be less stringent. Finally, the need for healthy collaboration is essential between the manufacturing sector and the government to enable innovation to achieve both growth and sustainability.

Theme 7: Environmental Sustainability

The participants' response reveals that the Gauteng manufacturing sector requires a license to operate, which mandates compliance with environmental regulations, in particular minimum emissions standards and ambient air quality standards. In addition, the technologies are required for monitoring emissions, early alerts for non-compliance, and enabling the resolution process.

P02: "So, in terms of license to operate, our organisation needs to adhere to the legislative frameworks, and every so often in terms of the risk levels of organisation, we know we always measure our approach to water usage, emissions, spillages in the streams or rivers where the source of water comes from."

P04: "Well, they are different legislation that has come on board, one being the minimum emissions legislation at that we were given up to 2025 to implement throughout the organisation."

Additionally, interview analysis reveals that comprehensive emissions monitoring by manufacturers is essential for the effective environmental sustainability initiatives implementation.

P09: "The organisation has established project road maps for implementation and tracking those project developments and the other thing is the indirect measurements of emissions from different sources."

Furthermore, participants highlight the need to integrate technologies such as AI to comply with stringent environmental regulations such as minimum emissions standards and ambient air quality standards.

P08: "So, it is really taking it from cradle to grave, from the source, from industry back out to the receiving environment where the receiving"

environment is then a complex mixture of natural occurring as well as industry and other human factors that influence the air quality that all impacts us.

On the AI side that I am referring to, it was not specific to Environmental improvements, it was more on efficiency improvement, which you can argue it leads to the environmental improvements.”

Data from participants reinforces and supports the previous claim about the integration of AI and other technologies, highlighting that organisations are increasingly adopting digital technologies to achieve environmental sustainability goals while minimising costs and disruptions to operations.

Supported by participant *P04* who emphasises an alignment between strategy and technology enhances the ability to achieve sustainability goals efficiently.

P05: “So it adds also to the efficiency of environmental and sustainability programs at the end of the day.”

However, innovation and retrofitting existing equipment is more cost-effective to comply with environmental regulations. This approach aligns with the broader trend of using digital technologies to improve sustainability practices in manufacturing

P09: “If you look at particulate matter emissions from our steam plants or our boilers the teams really started off by saying we need to replace or upgrade all of our electrostatic precipitators and that would have cost us billions of rands.”

Finally, participant *P08* cautions and critically questions the approach to greenhouse gas emissions. The participant argues for a broader approach, to address greenhouse gas emissions, highlighting that solutions should encompass both industrial and natural sources to effectively tackle environmental challenges.

P08: “So, you have got natural, and then you have got human man-made greenhouse gases coming back to your DTx and consideration. Do you not agree that the solution must be focused not just on the industry, but also on naturally occurring events of greenhouse gases?”

Summary

The findings from the theme of environmental sustainability, which is part of Research Question 3; participants highlight that manufacturers in Gauteng require a license to operate, which mandates compliance with environmental regulations and minimum standards. This requirement compels manufacturers to use digital technologies firstly to implement monitoring systems and alerts for reporting and secondly to address non-compliance when targets are exceeded. Additionally, comprehensive emissions monitoring is essential to guide the effective implementation of environmental sustainability initiatives.

Furthermore, analysis reveals that AI technology has the potential to advance environmental sustainability practices. In support of this finding, participants noted that manufacturers are increasingly adopting digital technologies to achieve environmental targets. Additionally, participants mentioned that innovation retrofitting existing equipment through innovation is a more effective strategy than replacement with new process equipment. Moreover, alignment between strategy and technology significantly enhances the ability to achieve environmental targets efficiently. Finally, participants also cautioned and critically questioned the current approaches to managing greenhouse gas emissions, which focus only on industrial sectors like manufacturing. In addition, participants stressed a more comprehensive strategy that includes both industrial and natural sources for effective environmental impact

Theme 8: Sustainable Manufacturing: AI-Driven Environmental Sustainability

The participants' responses reveal the Gauteng manufacturing sector is in the early stages of integrating AI technologies for advancing environmental sustainability. In addition, the local manufacturers are adopting use cases but rather at a slow pace.

P07: "We are also pretty much at the early stages of incorporating AI into our digital strategy."

de Boer and Torti (2023) highlight that "the global manufacturing community is lagging in its adoption of Fourth Industrial Revolution (4IR) technologies."

Reinforcing this finding, participant *P11* reveals that digital sustainability low maturity is not an isolated case but rather a norm for the South Africa manufacturing sector.

P11: "So, in the South Africa context, we are very much slow and in the pilot phases. We are quite behind the global industry. So, I think there is pockets that are advanced like auto manufacturing in South Africa but the bulk of the industry, I would say, still pilot phases."

Moreover, participant *P09* believes that slow progress is due to historical investments that have not yielded any return on investment or business value.

P09: "So as South Africa, we are moving way too slow, and I do not think it is a lack of funding. I think there was a lot of inefficient spend historically, for example like dashboarding and creating massive data lake."

Participant *P03* presents a different perspective and highlights that a formal integrated business and digital strategy, along with senior management commitment and alignment, is critical for advancing the integration of AI and other digital technologies. In addition, essential infrastructure and the criteria for the use case are critical to driving the DTx agenda.

P03: "A golden use case is where we acknowledge that there will be a lot of small AI projects that will be driven, but we're just looking for the top five high profile Gen AI that are going to drive significant value, and we've selected those based on the strategy that we have put in place."

Participant *P02* supports the previous finding and adds that the early phase is supported by a number of proof of concepts (POC) undertaken within a single manufacturing company.

P02: "So I think we are still in the infancy in terms of artificial intelligence within the organisations. There are several proof concepts that we are running, especially around predictive asset maintenance in the space."

Participant *P09* raises a concern that a high number of uncoordinated POC creates silos and often lacks integration into a broader program. In addition, the outcomes of these POCs are not effectively leveraged by the organisation, becoming largely ineffective.

P09: “So people do a lot of like proof of concepts, and then they do it more on a discrete basis and then never integrated, so no one could really use it, so that's a big thing.”

Participant *P09*, in addition, raises a further complication, scaling from POC's

P09: “They just want to do proof of concepts, and then it is nice tools that they end up having that they do not really use.”

de Boer and Torti (2023) support the complication, highlighting that “Scaling is not easy – some companies falter, balking at the prospect of replicating single-factory approaches across their entire network.”

Participant *P04* reinforces that the initial success of a use case reflects a potential for scaling, highlighting the importance of adopting a systematic approach to scaling.

P04: “We have an example now of a successful project, and I am hoping that part of DTx is going from a pilot project in a plant level and scaling that to multiple plant areas.”

The WEF and McKinsey survey reports 82% of Lighthouses now design new use cases with scalability in mind from the beginning (de Boer & Torti, 2023).

Participant *P10* supports this finding and reveals a use case-driven approach to target specific environmental opportunities.

P10: “For instance, if you could Produce some sort of use case and it's something we are looking at, using AI to monitor CO2 consumption in brewing and finding a way to reduce your CO2 consumption maximising the efficiency in terms of how much CO2 you use per brew or how much you can recuperate from the brews.”

Summary

The findings from the theme Sustainable Manufacturing: AI-Driven Environmental Sustainability, part of Research Question 5, highlight that the Gauteng manufacturing

industry is at a low digital maturity. Specifically, a sector is in the early stage of integrating AI technologies for advancing environmental sustainability. From the data, slow progress is due to historical investment with no return on investment or business value.

Furthermore, data revealed there is an urgent need for a formal, integrated business and digital strategy along with strong senior management supported. Such alignment and commitment are essential for establishing the right infrastructure and well-defined use case criteria. Interestingly, the analysis highlights that there are a number of environmental sustainability initiatives underway in the form of proof of concepts. Moreover, the number of POCs are siloed and this fragmented approach may lead to ineffective integration into the broader program. Finally, the analysis revealed scaling initial success by adopting a systematic approach to drive AI technology integration from unit level to factory level, and ultimately to the enterprise level.

This comprehensive approach ensures that organisations can effectively leverage digital technologies to improve operational efficiency and promote drive sustainable practices, particularly in sectors such as manufacturing where environmental sustainability is a pressing concern.

Theme 9: Sustainability Risk Drivers

The participants' interview responses highlight the presence of significant risk for manufacturers adopting digital technologies to advance environmental sustainability. Successful DTx requires an effective risk mitigation approach. The data analysis highlights balancing investments in sustainability initiatives with the financial viability of current operations.

P03: "The biggest risk in the journey to transition is going to remain the investments that are required versus the sustainability of the current business that you are running."

Again de Boer and Torti (2023) highlighted that "it is an expensive proposition: often, a resource requirement of more than \$100 million is required to successfully transform large companies."

Moreover, the study found the risk of carbon tax introduction. The data suggests that manufacturers must be prepared for the potential financial and operational implications of such a tax, especially heavy emitters.

P06: "There is talk of a Carbon tax, which has not really been implemented as far as I know, but that is one that may have an impact."

P05: "The current setup is more of a punitive system, so if you do not comply to the law then you get punished in terms of tax and the license to operate and so forth."

Participant *P13* supports the previous finding and reveals another major business risk of potential closures and market diversification due to prohibitive compliance costs.

P13: "That is why you find other organisations and companies diversifying out of certain markets because of this challenge of not being able to meet those environmental targets and focus on other countries where probably the regulations are not as extensive."

Participant *P02* present a different perspective to the previous finding, asserting that executive-level management has a strong focus on top environmental risk management. In addition, there are clear priorities and expectations set at the top. Finally, to ensure environmental concerns are addressed effectively throughout the organisation.

P02: "So those top 10 environmental risks are being managed at the executive level because of the importance of priority, and they set the tone in terms of Nonconformance and the consequence management, and everybody in the organisation works in support of that."

The participants' responses, in addition to the previous significant risk findings, highlight cybersecurity risk. The increasing integration of AI and other digital technologies within manufacturing processes introduces cybersecurity risk.

P02: "There is also the risk of cyber security, once you move into operations and trying to roll out this new technology, in some instance how data is

classified within manufacturing environment, production data should not necessarily be exposed to the rest of the world.”

Additionally, according to participant P09, the risk could have significant environmental and operational consequences. The finding underscores the need for cybersecurity standards to be considered when implementing AI and digital technologies for advancing sustainable manufacturing.

P09: “I think it can have huge impacts on the organisation overall. I mean, cyber security is a broad topic now. It's not something that's discussed just generally in the organisation, and the reason for it is that someone can basically shut down your entire facility, which could lead to Loss of revenue for you as a shareholder.”

However, participants emphasised that the sustainability of the AI models is crucial for delivering long-term, targeted environmental sustainability benefits. In addition, the limitations and organisation AI technology knowledge is essential to mitigate undesired outcomes. To achieve and maintain improvements delivered by digital solutions sustainable, respondents argued it is vital to ensure the ongoing relevance and effectiveness of sustainability AI models.

P04: “So sustainability of the model is important. That is the one risk. The other risk is your training of your own people, if you lose skills, you are likely to get into trouble in terms of your sustained improvements.”

Participant P05 supports the finding and stated that monitoring the AI model performance must be put in place to ensure accuracy and performance are tracked.

P05: “So we can tell you how well the model is performing and what kind of benefits are being produced by that.”

Additionally, participant P04 highlighted retaining skilled personnel is crucial for advancing digital sustainability solutions to advance sustainable manufacturing.

P04: “That is the one risk. The other risk is your training of your own people, if you lose skills, you are likely to get into trouble in terms of your sustained improvements.”

Finally, the social impact of AI adoption must not be underestimated. Participants highlight employee insecurities if not addressed, will lead to low morale and potential risk of technology rejection.

P02: “So it is actually a win-win if one can manage that change, to reduce the risk of technology rejection.”

Participant P07 supports this finding, stating that overcoming initial resistance and getting the buy-in paves a way for adoption.

P07: “They say their estimates will always be better than whatever the system can come up with. It will take a lot of resistance, but engineers being engineers, once you get their buy-in and they believe in the numbers, then that's the gospel.”

Summary

The findings from the theme sustainability and risk management, which is part of Research Question 3, participants' responses reveal significant risks associated with the integration of digital technologies for advancing environmental sustainability in manufacturing. The transition to a low emission world presents substantial risks, particularly compliance costs burden for an operating entity. In addition, for scenarios where AI technology integration has enabled sustainable manufacturing, participants caution and highlight the threat of emerging cybersecurity risks for the manufacturing industry. Finally, the findings underscore a gap in addressing the social implications of DTx. Employees' resistance to change and fears about AI and digital technologies can be a major obstacle to successful implementation.

5.3.4 Research Questions 4 (Benefits and Challenges): What are the potential environmental benefits and challenges, barriers, and constraints faced by manufacturing organisations when implementing DTx for sustainability purposes?

The research question explores the positive environmental impacts of digital technologies adoption such as AI through the DTx on manufacturing organisations,

such as efficiency gains, waste reduction, pollution mitigation. Furthermore, the question explores the difficulties and limitations manufacturing organisations face when implementing these technologies for sustainability, such as technological limitations, economic factors, organisational factors, and regulatory factors.

Theme 10: Digital Sustainability: AI Digital Technologies Drivers

It has emerged from the data, reinforcing previous findings from the data analysis, that DT serves as a fundamental enabler of sustainability strategies. In this context, a clear strategy regarding emissions and environmental sustainability allows manufacturers to leverage data effectively. Additionally, the strategic alignment makes the process of achieving sustainability goals more predictable and manageable.

P05: “DT is the enabler of the strategy. So, if you have a clear strategy on where you want to go with your emissions and you know the approach to environmental sustainability.”

Building on this, it has emerged from the participant responses that the emergence of advanced measurement technologies, especially AI-powered, is a key driver in the adoption of digital technologies in manufacturing. These innovations provide accurate and real-time emissions monitoring. In addition, offer valuable data for identifying areas for specific improvement.

P04: “I see that going forward being key where you monitor your emissions on a more regular online basis, you gather data and you identify where you can improve based on the data that you are accumulating and also measuring, so definitely there is a definite need for AI to ensure that this improvement.”

P07: “Able to monitor the environmental conditions, dust in air pollution and that we use those digital technologies as well as our flow meters in the plant and sure that we have got the IoT technologies which are pretty much in our digital strategy to ensure that we are able to identify issues sooner rather than later and make sure that we optimise our production processes.”

Furthermore, the analysis highlights that these technologies extend beyond complying with environmental regulations and also promote a culture of continuous improvement and sustainability.

Moreover, another key finding is that manufacturers can leverage vast amounts of data through data analytics to unlock valuable insights. The data driven decisions and targeted improvements in sustainability practices; also promotes a culture of continuous improvement and drives more effective sustainability initiatives.

P05: “You can understand what in your environment has influenced that data point and therefore you can make much more informed decisions longer term with regards to certain actions that you take and how effective they are in reducing emissions and improving sustainability.

We have our digital vision for the energy business it is a formula, it is DQ IQ and the three ‘D’s stand for data defining destiny, and the three ‘I’s stand for inside inspiring innovation. I think everything that I’ve been speaking about points to that, it is all about the data and about the insights and how you innovate when you have that.”

Finally, participants emphasise that as organisations become more adept at utilising data, they can better predict production scenarios and adapt and refine their sustainability strategies over time, ensuring ongoing progress toward their environmental goals.

P03: “I think at predicting what one decision that we make for production purposes to create what emission and therefore how to get that information to the engineer’s hand at the right time, not after the fact is where we still need to go.”

Summary

The findings from the theme Digital Sustainability: AI and technologies, which is part of Research Question 4; reveal that digital technologies, AI in particular, is a key enabler of sustainability strategies in the manufacturing sector. Furthermore, participants responses highlight the emergence of advanced measurement

technologies, especially AI-powered, is a key driver behind the adoption of digital technologies in manufacturing.

Additionally, manufacturers can leverage vast amounts of data through data analytics, discovering valuable insights, that improve both operational efficiency and environmental performance. Finally, the participants emphasise that as manufacturers become more adept at utilising data, can better predict production scenarios. Furthermore, over time adapt and refine their sustainability strategies while ensuring continuous progress toward environmental goals.

Theme 11: Benefits of DTx for Environmental Sustainability

It has emerged from the interview responses that DTx through the adoption of AI and other digital technologies, is crucial for enhancing environmental sustainability. However, balancing the trade-offs between environmental sustainability targets and manufacturing firm profitability remains a significant obstacle for the manufacturing industry.

P08: "It is a major issue balancing these two because again, clients or manufacturing houses will see immediately that you are asking me costs and where is the benefits in going green."

de Boer and Torti (2023) highlight that "use cases have averaged between two and three times the return on investment within three years and between four and five times the return on investment within five years."

Participant *P13* highlights that there is a significant upside to striking this balance, emphasising a strong business case for sustainable manufacturing. Moreover, participant claim there is a growing demand for products made from low carbon sources, particularly in the European market, manufacturers can capitalise on this trend.

P13: "They keep the greenhouse gas emissions very low, and they are able to sell their product in the European market at a 30% markup compared to competitors based on the product's rating."

Reinforcing this perspective, the participant also stresses that financial objectives and operational improvement benefits are prioritised over environmental sustainability targets. The prioritisation highlights while there is a potential for AI technology to advance sustainability practices recognition, manufacturers often focus on achieving financial and operational gains.

P13: “So they pop down the goals and everything, and it just stops because the operations guys are not very keen on moving that direction. But we found that if you put the plant manager, then you say, look, you are going to run 20% more productive if we do these things, then they are very happy to adopt and drive.”

Adding a different perspective, participant *P12* argues optimising for value in manufacturing is a complex matter. The use of AI technology and data analytics can help find an optimal solution that maximises business value. This highlights that leveraging advanced technologies can facilitate a more integrated approach to enhance both profitability and environmental sustainability.

P12: “I think if you talk about that value and how to optimise for value, typically it is quite a complex to understand how the different Manufacturing parameters impact this carbon, water, yields and waste with it. That is where digital or advanced analytics, or AI, can help to figure out the right value function and then to solve for the highest value potential.”

This argument is further supported by participant *P07*, who emphasises that there is a need to consult multiple stakeholders to align on the overall benefits and value impact for the company. However, this inclusive approach can be costly and create additional complexity.

P07: “So you need to select those processes that will yield the most benefits for you as a company and acknowledge that it is not going to be quick.”

Building on this participant 3 highlights that to maximise business value, it is crucial to scale the adoption of AI and other digital technologies across the enterprise. This emphasises scaling AI technology use cases serves as a key element in achieving sustainable manufacturing at an enterprise level.

P04: “So I am hoping that there will be an adoption of the scaling process to other areas of our business to get more benefits across multiple plants.”

Further analysis from participant responses reveals that ESG is part of the business strategy and drives the overall integrated reporting compliance requirements, particularly for listed manufacturers. The benefits of the adoption of AI for environmental sustainability should be linked to ESG initiatives.

P12: “So when you talk about value function, we look at the direct benefits and the direct ESG impact.”

Genghini (2024) in the 2030 Builders report revealed that “one key strategy is to adopt a holistic, systems-based approach to sustainability. This involves aligning sustainability goals with the company’s overall business strategy and ensuring that environmental considerations are integrated into decision-making processes across all departments and functions.”

In contrast, participant *P06* presents a different view, highlighting that achieving environmental impact is often a byproduct and indirect benefit of adopting AI and other digital technologies in the manufacturing sector. This perspective reveals that while manufacturing may not prioritise environmental outcomes, the integration of the technology can lead to unintended positive effects on sustainability.

P06: “Digital would improve processes, and in a way, it will have a positive impact on greenhouse emissions and our carbon footprint, because we will now be more efficient, and I think companies would adopt digital ways of working, not necessarily with environmental goals as the main focus.”

Finally, it emerged from the data that there is a growing market demand for sustainable products; manufacturing companies must consider not only the costs but also the business opportunities of implementing digital sustainability initiatives, and potential overall benefits.

P13: “So there are only two ways for a business: I need to increase my revenue, meaning my profitability, or I need to reduce costs. So definitely, one thing people miss is that there are definite initiatives within the European market and in the Western market to drive sustainability, and they are willing

to pay a premium for products manufactured in South Africa or in Africa to get these green products.”

Summary

The findings from the theme benefits of DTx for environmental sustainability drivers, part of Research Question 4, participants’ responses reveal that firstly, the adoption of AI and other digital technologies is identified as a key driver for achieving environmental sustainability within manufacturing. However, a significant challenge highlights the need to balance environmental sustainability targets with profitability objectives. In light of this, there are market growth opportunities and new value pools for products made from low-carbon sources, particularly in European markets.

Yet optimising for value is complex; leveraging AI and advanced analytics can help find a solution that maximises business value. However, this complexity is compounded by the need to consult multiple stakeholders to align on the overall benefits of sustainability initiatives. Furthermore, ESG considerations are becoming increasingly integral to business strategies, particularly for listed manufacturers. Interestingly, data analysis, noted that achieving environmental impact may often be indirect benefits of adopting digital technologies.

Theme 12: Challenges in Implementing AI for Sustainable Manufacturing

The participants’ responses highlight that stranded assets pose a significant challenge for manufacturing companies. Stranded assets are outdated process equipment lacking signalling and digital monitoring capabilities. In addition, they often require substantial investments to modernise and integrate with modern manufacturing systems, in particular the Manufacturing Execution System (MES).

P13: “So you would get a lot of sites still having PLCs, they have implemented in the early 2000s, and they do not have scanners, they don't have any MES system, becomes very difficult to implement the greenhouse gas system or something that tracks and monitors and reports on top of that. So, it is definitely the digital maturity of the company.”

Building on these high costs, participants' responses highlight the high costs related to complex IT infrastructure such as cloud computing, digital technologies and technical development. Manufacturers face technology challenges when introducing new digital technologies like AI to evolve into sustainable manufacturing.

For instance, participant *P13* notes that achieving carbon neutrality requires a significant upfront investment.

P13: "Then the difficulty comes with managing the costs and, the goals. So, I want to be net-zero by 2050 costs a lot of money."

Furthermore, participant *P10* adds to this finding and notes that while there are environmental benefits to be derived from adopting the combination of AI and other digital technologies, the huge upfront costs can be a major obstacle.

P10: "I know the people at global are working on a lot of the AI stuff, that is one of their big challenges to introduce efficiencies because, yes, there is an environmental impact, but also that aside, there are massive costs involved in using cloud computing."

The organisation's strategy of piloting new technologies before rolling them out on a larger scale is a wise approach. However, participant *P06* stressed the steep learning curve and pressure from the key stakeholders to integrate and implement technologies swiftly may compound the challenges.

P06: "So the approach is always to pilot it first, get some learnings, tweak it a bit, and then take it into the different countries or markets that they are in."

Conversely, participant *P02* points out that:

P02: "So there is pressure from the stakeholders for us to move fast while the asset and the operation that we run are not there yet. That is one of the challenges, and we need to look at opportunities to make the same product in an environmentally friendly manner."

Genghini. (2024) stated that "The pursuit of sustainability is not just an internal challenge for companies; it is also heavily influenced by external factors and stakeholder expectations. Increasingly, companies are facing growing pressure from consumers, investors, regulators, and the general public to

demonstrate their commitment to sustainability and environmental responsibility.”

In addition, it is crucial to recognise that pilot use case must consider market-specific challenges, including varying skill levels, infrastructure availability, and data readiness, which can impact success of the environmental sustainability initiatives.

P02: “The skill set in some instances is also a challenge, we need to move at pace to get the value of these technologies that are new.”

P06: “So I think digital infrastructure is one thing that is a constraint and skills as well, so that is what is delaying this transition in emerging markets because it is almost like waiting for a developed markets to perfect it before we adopt it because we rely on them on a lot of things in terms of our manufacturing spare parts and equipment.”

Furthermore, it is crucial that new technologies seamlessly integrate into existing systems to achieve sustainable value. Respondents revealed that many solutions fall short of delivering business value due to the lack of alignment with actual business needs or poor integration.

Participant *P09* emphasises this point by stating that:

P09: “Some of the big challenges are that people buy technology solutions and do not try to solve a business problem. So, it never ends up achieving the business value because technology is always so exciting to have, but it does not really, solve anything, that is the one big thing.”

Moreover, another critical aspect to address is change management and adoption. Transitioning to new technologies often involves significant changes in workflow, which can be met with resistance from employees. The company’s readiness, especially to modernise the outdated system, poses a substantial barrier to effective implementation.

Participant *P12* supports this concern by highlighting a common challenge in digital use cases, particularly those focused on environmental sustainability. *P12* states that the lack of a clearly defined value function can hinder the development of effective solutions that generate tangible benefits for the business.

P12: “What we see often time in the Digital use cases is that the value function is not properly defined.”

Participant *P09* raises another interesting angle; in addition to the challenge of change management, without a clear data strategy, it will be difficult to integrate AI and other digital technologies to achieve desired outcomes. Furthermore, data analysis highlights the critical role that data plays in powering successful AI technology implementation. Without a solid data foundation, manufacturers may struggle to leverage AI and other digital technologies effectively.

As participant *P09* notes, without a clear data strategy, adoption and integration of AI and digital technologies will be hard to achieve the desired outcome.

P09: “Most companies do not really have good data, and they do not know how to get good data to solve some of these solutions. So, kind of having a good strategy around data is important.”

Finally, the participants' responses highlight significant implementation challenges within manufacturing companies, particularly the lack of systems integration. Moreover, this critical finding reveals without proper integration, the full potential of AI for advancing environmental sustainability cannot be realised.

P09: “Second thing is a lot of technologies are not integrated into the overall systems in the company.”

Participant *P09*, in addition to the previous claim, emphasises that

P09: “So if you do not do that, getting sustainable, scalable value from it is very hard. So, people do a lot of like proof of concepts, and then they do it more on a discrete basis and then never integrated, so no one could really use it, so that is a big thing.”

Summary

The findings from the theme Challenges in Implementing AI for Sustainable Manufacturing, part of Research Question 4, participants' responses reveal; firstly, identified stranded assets challenge, outdated process equipment that lacks

monitoring and data transmission capabilities. This significant barrier, complicates the asset integration with modern manufacturing technology, making it harder to integrate with AI and other digital technologies. This obstacle makes it difficult to track and report on greenhouse gas emissions effectively. Moreover, this highlights the digital maturity of companies as a critical factor in their sustainability efforts.

Building on this, participants highlighted the significant upfront costs required for complex IT infrastructure, like cloud computing and digital technologies. The need for substantial upfront poses a considerable barrier for many organisations.

Linking to the previous finding challenge, participants' response points out a strategy of piloting new technologies before broader implementation. Further analysis reveals this approach can be complicated by a steep learning curve and pressure from stakeholders to integrate and implement technologies quickly. Moreover, the pressure can lead to decisions that may not align with the company's current capabilities.

Additionally, another significant finding is that for AI technology integration to generate sustainable value, an effective systems integration is needed. From analysis, it has emerged that many solutions fail to deliver value due to poor systems integration.

Furthermore, the challenge of change management must not be underestimated. Adoption of AI technologies to advance sustainable practices often involves significant changes to manufacturers. Changes can be met with resistance from employees. Finally, the analysis revealed that a clear data strategy is a key driver for the successful integration of AI and digital technologies. Without a clear strategy and a solid data foundation, manufacturers may struggle to leverage the full potential of AI technologies.

5.3.5 Research Question 5 (Risk): The potential negative effects, direct and indirect, of implementing DT such as AI for environmental sustainability?

Research question 5's main goal is to explore the potential downside of using digital technologies, specifically AI to address environmental challenges. The questions seek to identify the direct negative effects, such as increased energy consumption to

support the use of digital technologies and indirect negative effects such as increased production leading to environmental degradation.

Theme 13: Digital Sustainability: Risk of AI Technology Adoption

The data from the interview participants reveals digital technologies, particularly AI technologies, may contribute to greenhouse gas emissions and potentially have an impact on the environment. In addition, from analysis, the participants highlighted that the potential impact may not be considered by manufacturers when deciding to adopt AI technologies.

P12: “But what is the indirect impact, like running servers and cloud solutions and all of that? I think that part has not been built into that value functions yet.”

Genghini (2024) reported that “AI systems demand substantial energy for operation and model training, contributing to greenhouse gas emissions. As AI usage expands, it’s crucial to prevent increased energy consumption and emissions. Balancing AI growth with environmental sustainability is paramount.”

Participant *P10* believes it is difficult to calculate the environmental impact and somewhat intangible impact on the environment from the manufacturer’s perspective. However, there is a negative impact from cloud aggregators like Amazon cloud services.

P10: “I mean, from an environmental perspective, it is not something that will be tangible; you will not be able to calculate it easily. But of course, it is going to be a negative impact on the environment, it is maybe something we might not be able to quantify because we do a lot of the work AWS, which is a shared cloud resource.

I know the people at global are working on a lot of the AI stuff, that is one of their big challenges to introduce efficiencies because yes, there is an environmental impact.”

Genghini (2024) highlighted the 2030 Builders report that “without a clear and well-defined system for measuring and tracking sustainability performance, companies may struggle to demonstrate the tangible benefits of their efforts, making it difficult to justify the necessary investments and secure ongoing support from stakeholders.”

Furthermore, from data analysis, participant *P10* does not support the notion that digital technologies and infrastructure have an impact on the environment. Specifically, it highlights that only AI technology has an impact on the environment due to the high energy consumption and cooling needed, driven by cloud computing power.

P10: “But I think overall from just the digital adoption perspective, if you rule AI out, I do not think there is a negative environmental impact, but actually a net positive impact if you consider you are not using natural resources and energy.”

Participant *P02* supports this view and emphasises that platforms or cloud-hosted infrastructure minimise the environmental impact.

P02: “DTx with a platform hosted in the cloud minimises the environmental impact and because you were using hardware and locally centralising, allows you to scale as in when the demand comes up. So, it talks in direct contradiction of this. Maybe in other areas in other industries, as I have mentioned, there would be those recycling challenges of the product that they constructed.”

Summary

The findings from the theme risk of AI technology adoption, which is part of Research Question 5, highlights digital technologies, AI in particular, have the potential to advance environmental sustainability practices. Additionally, the integration and adoption require environmental impact careful consideration. Moreover, participants highlight that the adoption of AI technology is the major contributor, potentially the only source, of greenhouse gases, directly impacting the environment. Furthermore, participants note that the manufacturing industry tends to neglect the environmental

sustainability impact in the sustainability digital initiatives value case. Finally, building on the previous finding, the analysis notes the difficulty in quantifying the indirect environmental impacts of AI adoption, leading to value case assessment gaps.

5.4 Overall Sentiments

The sentiment analysis conducted in an exploratory qualitative study reveals a generally positive outlook regarding AI and DTx's role in advancing environmental sustainability. Overall sentiment, the temperature measured during data collection and analysis is positive and forward-looking, although there were cautious considerations regarding investments, challenges, and related risks. This reflects the potential benefits of DTx while recognising the complexities involved.

Sentiment regarding leadership alignment is positive. Top management appears to be proactive and committed to aligning digital and AI initiatives with sustainability goals. This strong leadership support is crucial for driving successful transformation efforts.

The sentiment surrounding strategy appears to be pragmatic, stakeholders acknowledged the importance of integrating sustainability and digital strategy into the core business strategy. This integrated approach recognises the alignment with the overall long-term business objectives, ensuring strategies are realistic and achievable. While positive sentiment for leadership is revealed, organisational readiness and workforce indicate cautious sentiment. Effective change management, cultural aspects and employee support were cited as overlooked.

There is a positive sentiment regarding the impact of AI and digital technologies on sustainability. Participants believe these technologies can significantly contribute to sustainability goals, particularly in areas like emission reductions and efficiency improvements. This reflects a strong belief in the transformative potential of technology. While the overall sentiment is optimistic, there is a cautious sentiment regarding cybersecurity risks. Stakeholders express a need for proper governance and continuous assessment of these risks to ensure that the benefits of digital transformation do not come at the expense of security.

Sentiment around management buy-in is mixed, with some expressing caution due to financial constraints. The need to maintain AI models and ensure ongoing investment in technology is highlighted as a potential challenge that could hinder progress.

6. DISCUSSIONS OF RESULTS

6.1 INTRODUCTION

This chapter aims to discuss the key success drivers of DTx on advancing environmental sustainability practices within the Gauteng manufacturing sector. Specifically, how AI can be leveraged to support sustainability programs and identify internal and external organisational success drivers, which are crucial to facilitate the adoption of AI-driven sustainability solutions.

This study has uncovered seven additional key themes through thematic analysis. The insightful discovery provides deep and rich insight and findings that stretch our understanding by expanding upon the initial six themes identified in the literature review. Overall, the study has 13 key themes which will be discussed and used as an enriched framework to surface the key drivers of a successful AI adoption to advance manufacturing environmental sustainability.

Following the research questions–theme structure established in the previous findings chapter, this chapter discusses the findings in detail. The study findings will be compared and contrasted to existing literature in order to extend the body of knowledge.

In conclusion, this chapter discusses identified findings in detail and contributes valuable insights into key drivers of success for AI adoption through DTx for advancing manufacturing sustainability practices.

6.2 DISCUSSION: RESEARCH QUESTION 1

Research Question 1 (Organisational Capabilities): What are the key drivers for the successful adoption of DT AI in the Manufacturing sector to achieve the environmental sustainability dimension of greenhouse gas emission reduction?

The first research question explored the key drivers underlying manufacturing companies' adoptions of digital technologies, specifically AI, and the elements that contribute to their successful implementation in achieving environmental sustainability objectives, with a specific focus on greenhouse gas emissions.

Despite the promise of DTx for a sustainable future and enterprise long-term benefits, a significant knowledge gap exists regarding the drivers of success for effective implementation and adoption of AI-driven environmental sustainability solutions in the manufacturing sector, particularly in the context of Gauteng, South Africa. Building on the call for future research by Schöggel et al. (2023), which proposed future research to explore the underutilised potential of AI and further detail drivers and barriers of DTx implementation for achieving environmental sustainability in different contexts.

The discussion of research question 1 starts with the theme of digital leadership drivers for AI adoption.

6.2.1 Theme 1: Digital Leadership Drivers

The study found that leadership alignment and proactive support are key drivers of success when adopting and integrating AI for environmental sustainability. The data suggest that leadership is crucial to define the vision and overall integrated business strategy, including a digital strategy to support the overall DTx, which includes AI integration. This finding was expected and consistent with the literature reviewed related to DTx. The study finding is supported by a study by Gaffley and Pelser (2021) which revealed CEOs and C-Suite Executive Teams must lead digital strategies; reinforced by Abdalla (2022), leadership and strategy are key elements that contribute to the successful integration of DTx. Moreover, Aftab et al. (2022) highlight that top management's commitment to environmental leadership drives innovation to reduce greenhouse gas emissions to achieve low-carbon development and achieve sustainable practices.

Despite leadership's key role as a driver, getting leadership alignment and conviction is a significant challenge. The data seem to suggest that securing leadership buy-in and conviction requires a more proactive approach. The education, compelling

business case, and leadership change management are essential. For example, a participant stated:

P12: "You require Senior management at executive levels commitment and sponsorship of digital, that is a given. Everyone will tell you that, but you have to be careful again that they know what they are talking about, that they understand when they say we want digital, and ask you why you not doing digital in this company, that they actually know what they are talking about".

This finding was not expected and extends the existing literature. Horváth and Szabó (2019) acknowledged the significance of leadership in DTx. The study stressed while the primary focus is the need for leaders with specific qualities and capabilities, particularly strategic thinking across complex networks, the existing capabilities of the current leadership within organisations might be overlooked (Horváth & Szabó, 2019). In addition, the study argued that organisations will likely navigate potentially disruptive shifts in leadership roles. However, the new finding highlights the challenges involved in securing leadership alignment and conviction, even in companies with capable leaders. Many leaders struggle to effectively address the organisational challenges associated with AI integration and DTx (Holmstrom, 2022). Moreover, Malek and Desai (2019) study found that the lack of top management support and negative attitudes towards sustainability significantly hinder the adoption of AI and DTx for environmental sustainability.

Furthermore, participants noted that senior leader's proactive championing of digital initiatives promotes innovation at lower levels. This finding supports the existing literature by Eide et al. (2020), that the personal motivation of leaders has an impact on the organisation's sustainability strategy. This motivation leads to greater value creation and positive outcomes from sustainability initiatives. Additionally, the study by Isensee et al. (2020) highlights the importance of managerial influence and the need to shape employee attitudes for successful DTx to achieve environmental sustainability targets. However, data analysis identified for global manufacturers, leadership lacks passion for innovative ideas unless mandated by global headquarters. This finding contradicts the existing literature presented above.

Furthermore, this study also found that a cultural shift within manufacturing companies is essential to promote innovation, technology adoption, and sustainability. This suggests that leadership play a pivotal role in identifying cultural shifts. Specifically influencing the reshaping of the organisational culture to support the vision for successful DTx and AI adoption for sustainability, to reduce GHG. This expected finding supports the existing literature. Isensee et al. (2020), conducted in the manufacturing SME context, concluded managerial influence and a positive attitude can contribute to the successful implementation of digital initiatives to achieve environmental sustainability targets. Furthermore, fostering a culture that values sustainability and embracing DTx enhances operational efficiency and environmental performance (Isensee et al., 2020).

Table 2: Theme 1. Digital Leadership Drivers Findings

Key Findings	Implications	Challenges
Leadership is a key driver: - defines the vision and overall integrated business strategy, - supports the overall DTx including AI integration	Supports Literature: - CEOs and C-Suite Executive Teams must lead digital strategies. - leadership and strategy are key elements for the successful integration of DTx.	Getting leadership alignment and conviction
Organisations will likely navigate potentially disruptive shifts in leadership roles	Extends Literature: leaders with specific qualities and capabilities, particularly strategic thinking across complex networks, the existing capabilities of the current leadership within organisations	Securing leadership alignment and conviction, even in companies with capable leaders
Senior leader's proactive championing of digital initiatives promotes innovation at lower levels	Supports Literature: The personal motivation of leaders:	Global manufacturers and local leadership lack of passion for

	- impacts organisation's sustainability strategy, - leads to greater value creation and positive outcomes from sustainability initiatives - managerial influence, shaping employee attitudes for successful DTx to achieve environmental sustainability targets	driving innovation, unless mandated from global headquarters
Cultural shift is essential to promote: - innovation - technology adoption - sustainability	Supports Literature: managerial influence and a positive attitude can contribute to the successful implementation of digital initiatives to achieve environmental sustainability targets.	Adoption and overcoming organisational inertia

6.2.2 Theme 2: Organisational Readiness for DTx Drivers

Holopainen et al. (2022), stated the importance of assessing the organisation's overall readiness to leverage DTx in the context of company-wide business objectives. As highlighted by Holmstrom (2022), this process is complex and ongoing, requiring significant organisational adjustments across various dimensions, including resource allocation, employees, cultural shifts, and decision-making. Despite DT and AI technologies' potential to address environmental challenges (Chiarini, 2021; Rusch et al., 2023; Schögggl et al., 2023), the successful adoption hinges on an organisation's readiness (Davenport, 2018; Mikalef et al., 2019; Holopainen et al., 2022). Realising the benefits requires a proactive and strategic approach to effectively navigate the complexities of DTx AI adoption to reduce GHG emissions.

The data analysed revealed that effective change management is a significant driver for the successful adoption of AI and digital technologies. This study has found that

change management and communication are often overlooked for digital sustainability initiatives. This suggests that technology is often the main priority, and people aspects may not be considered by manufacturers, particularly when adopting AI technologies for the DTx journey. This contrasts with previous studies by Ching et al. (2022) and Holmstrom (2022), who argued that leveraging DTx, particularly AI, for environmental sustainability necessitates a radical transformation of workforce skillsets, surpassing traditional professional (Nimawat & Gidwani, 2022; Nguyen et al., 2022).

While existing literature addresses effective and systematic management (Ching et al., 2022) which requires effective leadership to drive change (Horváth & Szabó, 2019). However, it lacks clarity regarding the specific strategies for AI adoption and digital transformation change management, particularly for environmental GHG emission. The finding seems to suggest change management initiatives, often driven at the project level, may not be sufficiently supported by existing change approaches, especially when combined with disruptive technologies such as AI and DTx requirements and environmental sustainability GHG emissions. This observation corroborates with Guandalini (2022), who emphasised DTX for sustainability is a complex and multidimensional concept.

Moreover, Saldanha's (2019) alarming finding that 70% of DTx fail highlights the limitation of prioritising technical aspects over human factors. This challenges the effectiveness of the existing change management approaches for AI adoption and overall DTX for sustainability.

Furthermore, data analysis identifies that a cultural shift within manufacturing companies is essential to promote innovation and technology adoption to enhance sustainability at lower levels. This study has found that beyond effective change management, coaching is essential to adjusting a large contingent of blue-collar workers. The data suggest that manufacturers should integrate coaching as a strategic intervention to support employees in navigating change and embracing desired behaviours. Interestingly, while the extant literature reviewed addresses employee anxiety and reskilling (Horváth & Szabó, 2019), it largely overlooks the role of coaching in this context. This finding challenges the existing literature by Holopainen et al. (2022), which emphasises that organisational factors, including the

culture of openness to change, are critical for realising the benefits of digital technology implementation.

Table 3: Theme 2. Organisational readiness for DTx drivers Findings

Key Findings	Implications	Challenges
Effective change management: - change management and communication are often overlooked for digital sustainability initiatives. - technology is the main priority and people aspects are not considered.	Contradict Literature: - radical transformation of workforce skillsets, - role of effective leadership to drive change - specific strategies for AI adoption and digital transformation change management.	Change management: - driven at the project initiative level - not supported by a comprehensive change strategy optimal for disruptive technologies such as AI and DTx requirements
Cultural shift is essential to promote: - innovation - technology adoption to enhance sustainability at lower levels. Coaching is essential to adjust: - a large contingent of blue-collar workers.	Contradicts Literature: - the role of coaching - organisational factors, including the culture of openness to change are critical for realising the benefits of digital technology implementation.	Employee coaching is often overlooked. AI fundamentally going to change employees' work

- integrate coaching as a strategic intervention to support employees navigate change and embracing desired behaviours		
--	--	--

6.2.3 Theme 3: Building a Digital-Ready Workforce Drivers

The study has found that there is a significant lack of digital talent. This finding is consistent with the finding by Nair (2019) that the existing digital talent gap continues to pose a significant challenge to achieving successful DTx. Malek and Desai (2019) study revealed that the lack of technical skills is a significant barrier for AI and DTx. This suggests that the manufacturing sector has a significant shortage of individuals with the skills and expertise needed to develop and integrate AI solutions to address environmental sustainability. In particular, data science skills and expertise talent shortage. In addition, a study by Booyse and Scheepers (2023) highlighted that only highly skilled software engineers can use AI technology. This finding aligns with the study by Johnson, Jain, Brennan-Tonetta, Swartz, Silver, Paolini, ... and Hill (2021), which highlights that many companies struggle to realise the full potential of AI technology advances due to various barriers, including skill shortage.

Furthermore, this study found that the problem is further compounded by the slow and long development cycle required to cultivate the necessary skills. This finding was not expected and aligns with existing literature on digital skills development for DTx. For Industry 4.0 a study by Ustundag, Cevikcan and Karacay (2018) emphasised the importance of prioritising talent development by identifying valuable skills for now and in the future. In addition, business needs, industry trends, and global economic landscape-specific needs should be considered. This suggests that manufacturing companies should be proactive in developing digital skills rather than reactive. Companies must adapt to the rapid changes brought by Industry 4.0 (Ustundag et al., 2018). This is contrary to the study's finding that the development cycle is slow and takes time.

Building on this, the study by Dabic et al. (2023) highlighted that human resource management (HRM) is instrumental in facilitating DTx and sustainable HRM promotes digitalisation through strategic investment. This data suggests that effective HRM should streamline the skill development process and align with business-changing needs and the DTx strategy.

Moreover, the study found that manufacturing companies started adopting short and long-term strategies to build organisations digital capabilities. To address the current needs, a blended training approach is undertaken to address the current needs. This finding was expected and consistent with the existing literature, which concluded that companies through strategic workforce planning, should assess current and future needs (Ustundag et al., 2018).

Furthermore, training and development funding allocation challenges hamper efforts to develop the needed capacity to implement digital technologies. This finding was not expected and contradicts Mariappanadar et al. (2022) findings that HRM offers long-term economic success in the digital era, beyond CSR.

Table 4: Theme 3. Building a digital-ready workforce drivers Findings

Key Findings	Implications	Challenges
Lack of digital talent: - shortage of skills and expertise to develop and integrate AI solutions to address environmental sustainability. - data scientist skills and expertise talent shortage	Supports Literature: - only highly skilled software engineers can use AI technology. - companies struggle to realise the full potential of AI technology advances due to skill shortages. - prioritise talent development by identifying valuable skills for now and in the future. - be proactive in developing digital skills rather than reactive.	Employee development: slow and long development cycle required to cultivate the necessary skills.

	- adapt to the rapid changes brought by Industry 4.0. - development cycle is slow and takes time	
Effective HRM should: - streamline the skill development process, - align with business changing needs and DTx strategy.	Extends Literature: HRM offers long-term economic success in the digital era, beyond CSR.	Training and development funding allocation challenges, hamper the efforts to develop the needed capacity to implement digital technologies.
Short and long-term strategies to build organisations digital capabilities.	Supports Literature: - a blended training approach is undertaken to address the current needs. - companies through strategic workforce planning, should assess current and future needs.	Digital talent and skills availability to advance AI adoption

6.2.4 Theme 4: Sustainable DTx: Investment Drivers

This study found that the AI technology integration upfront costs often exceed the immediate benefits sought by manufacturers. Moreover, this study introduces a significant challenge: additional investment is required to upgrade outdated infrastructure or modernise the manufacturer's operational technology for DTx readiness. This is supported by Brock and Wangenheim (2019) who asserted that manufacturers must assess the compatibility of their legacy manufacturing systems to ensure a smooth integration with AI technology solutions. This suggests in many cases, the initial investment might be higher than the initial investment estimated for AI technology integration for sustainability initiatives. Additionally, higher than

expected initial capital outlay is due to existing operational technology's low digital maturity. This finding highlights a critical issue, additional investment to upgrade technology to achieve readiness for DTx. According to Malek and Desai (2019) emerging economies face significant challenges in adopting manufacturing sustainable practices due to limited financial resources and technological capabilities. Inefficient investment is a significant hindrance to DTx, especially financially constrained manufacturers (Xu et al., 2023).

Furthermore, the study found that the manufacturing sector generally lags in technology adoption due to initial investment concerns versus immediate expected returns uncertainties. As a result, the financial burden may lead to focus on the challenges of investment rather than potential long-term benefits. This observation validates the conclusions drawn in a study in the SME manufacturing sustainability management context, which highlights that the decision-making approach is often siloed, with financial considerations treated separately (Zhang et al., 2021). Thus, manufacturers may prioritise short-term financial objectives over long-term environmental sustainability goals, hindering sustainable practices. The data identifies the tension between pursuing sustainable practices and maintaining financial performance.

This finding highlights the current literature's emphasis on balancing short-term financial objectives with long-term environmental goals. Supporting this perspective Ukko et al. (2019) revealed that the negative moderating effect on financial performance can be attributed to the temporal lag between the implementation of sustainability initiatives and the realisation of tangible cost reductions, efficiency gains, and optimised business processes (Li et al., 2018).

While the expected finding extends and supports the existing literature. The study introduces a specific challenge related to the hidden costs of AI integration. This entails costs to upgrade legacy infrastructure and modernise low-maturity operational technologies. This extends the existing literature and provides insights of the financial implication of AI adoption for environmental sustainability. Also, the study supports the findings of Brook and Wagenheim (2019) which emphasise the importance of legacy systems compatibility with AI technologies.

The study aligns with Malek and Desai (2019) and highlights a major challenge faced by emerging economies in adopting AI for advancing sustainability practices. Finally, the study supports the importance of efficient investment, insufficient investment can hinder AI adoption and risk reaching GHG emissions targets (Xu et al., (2023).

However, the study challenges the assumption of adequate financial resources for advancing sustainable practices. The observation contradicts the findings of Mangla et al. (2018), who argued that to transform traditional manufacturing to sustainable manufacturing, adequate financial resources and investments are essential.

Finally, the finding of high initial costs and return on investment reinforces the trade-off between short-term financial performance and long-term environmental sustainability. Supporting this perspective Ukko et al. (2019) revealed that the negative moderating effect on financial performance can be attributed to the temporal lag between the implementation of sustainability initiatives and the realisation of tangible cost reductions, efficiency gains, and optimised business processes (Li et al., 2018).

Table 5: Theme 4. Sustainable DTx: Investment Drivers Findings

Key Findings	Implications	Challenges
The AI technology integration upfront costs often exceed the immediate benefits	Supports Literature: - hidden costs of AI integration - balancing short-term financial objectives with long-term environmental goals. - efficient investment is a key driver Extends Literature: - top management plays a crucial role in allocating funding to support the integration of digital technologies. Contradict Literature:	Investment required to upgrade outdated or modernise the manufacturer's operational technology for DTx readiness which might be higher than the initial investment

	- To transform traditional to sustainable manufacturing, adequate financial resources and investments are essential.	
Manufacturing sector generally lags in technology adoption due to initial investment concerns versus immediate expected returns.	Contradicts Literature: - Emerging economies challenge of adopting sustainable practices - Siloed decision-making short-term financial objectives versus long-term sustainability. Negative moderating effects on financial performance due to temporal lag between the implementation of sustainability initiatives	The financial burden may lead to a focus on the challenges of investment rather than potential long-term benefits

Research Question 1 Summary: Framework

Figure 2 below depicts a developing framework (point 1) for key success drivers of DTX and AI adoption in advancing environmental sustainability in the Gauteng manufacturing industry. Specifically, the framework highlights internal drivers' strong leadership, organisational readiness, skilled workforce and investment in AI adoption and sustainability to reduce GHG emissions are key drivers. To achieve GHG emission targets, leadership must set a clear vision and define an integrated business and digital strategy supported by cultural shifts and effective change management.

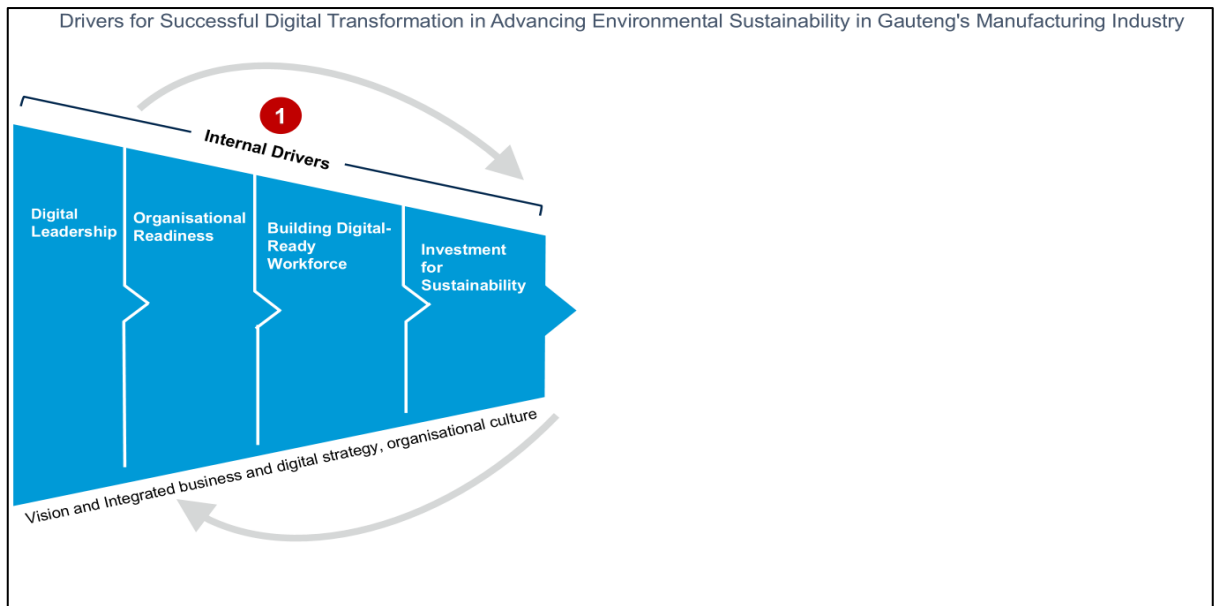


Figure 2: Research Question 1 Summary Framework

Source: Created by Author

The findings emphasise the pivotal role of strong leadership alignment and supportive organisational culture in driving successful DTx initiatives. Leaders must champion digital transformation and create an environment that fosters innovation and experimentation.

By aligning strategic goals with sustainability objectives and empowering employees to embrace new technologies, organisations can accelerate the adoption of AI-driven solutions that contribute to significant reductions in greenhouse gas emissions.

6.3 Research Question 2 (Impact): How is success measured for measuring the effect of adopting DT for the environmental sustainability dimension?

Research question 2's main goal is to determine how to evaluate the success of adopting and integrating digital technologies to reduce environmental sustainability, such as greenhouse gas emissions. The question explores the metrics and indicators used to assess the environmental impact of DTx initiatives

6.3.1 Theme 5: Holistic Performance Measurement

The study highlighted the importance of holistic performance measurement for assessing the full impact of DTx and AI adoption for GHG emissions reduction. The implications are manufacturers must consider a strategic approach, balance trade-offs and define comprehensive environmental strategies meaning both positive and negative effects are considered.

This study found that the manufacturers use AI and other DTs for environmental monitoring and improvement. This suggests that manufacturers leverage DT to monitor and enhance environmental and operational performance. The majority of participants stated they have adopted key performance indicators to measure GHG emissions such as carbon footprint. Manufacturers need to adopt comprehensive performance measurements that accurately assess the full impact of DTx, particularly in the context of AI adoption, both positive and negative effects. This finding aligns with a study by Isensee et al. (2020) which suggested that environmental sustainability includes the strategies, methods, actions and initiatives of an organisation to minimise its adverse effects while enhancing its beneficial impact on the natural environment.

In addition, the study found that manufacturers have set ambitious emissions reduction targets in alignment with the Paris Agreement (Wang et al., 2019). A participant highlighted that their company has set to reduce emissions by 30% by the year 2030. This suggests manufacturers are assessing the AI and other technologies adopted to achieve the targets. Okorie, Russell, Cherrington, Fisher and Charnley (2023) argued manufacturers must view DTx beyond technology adoption, but also as an opportunity to invest in intangible assets, supply chain, and sustainability practices.

Moreover, the study found that manufacturers recognise the need to balance economic growth with environmental sustainability. This suggests that manufacturers need to balance short-term and long-term economic benefits. Previous research stated that to achieve the full potential of sustainability, manufacturers must adopt a strategic approach to implement data-driven sustainability, considering both its positive and negative effects. This requires careful planning and execution to ensure that sustainability initiatives align with overall business objectives (Esfahbodi et al., 2017; Tseng et al., 2020; Poursoltan et al., 2021; Tseng et al., 2022).

The study's findings are consistent with existing literature and provide additional evidence in the context of AI adoption. The study extends the existing literature and reinforces the need for manufacturers to integrate sustainability into their core strategies (Truong, 2022; Tseng et al., 2022; Ma, Huang, Liu, Kong, Yin, & Chen 2023). Additionally, the previous findings by Zhang et al. (2021) suggested that awareness of the interdependence of the sustainability pillars is crucial for a strategic approach and for fostering a more integrated approach.

Previous studies revealed that while sustainability initiatives can lead to cost reduction, efficiency, and business process improvements, the financial benefits may not be immediately apparent. This could explain why sustainability strategies sometimes have a negative moderating effect on financial performance, supporting a study by Ukko et al. (2019) which revealed that the negative moderating effect on financial performance can be attributed to the temporal lag between the implementation of sustainability initiatives and the realisation of tangible cost reductions, efficiency gains, and optimised business processes (Kauffman & Walden, 2001; Ash & Burn, 2003; Li et al., 2018).

The study findings are consistent with the existing literature and provide additional empirical evidence, particularly in the context of AI adoption for the manufacturing sector.

Further analysis studies found that manufacturers are committed to compliance with global integrated financial reporting requirements. This suggests that manufacturing is reporting and disclosing their environmental credentials, targets and performance. For example, the majority of the participants of this study, further analysis on manufacturers Integrated Financial Reporting mandated by their listing requirements, confirmed reporting. This finding is consistent with the literature and supports the study by Ukko et al. (2019) which concluded that to effectively measure the impact of sustainability initiatives, a holistic approach is necessary. This involves quantifying environmental outcomes, such as greenhouse gas emissions reduction, energy conservation, and waste minimisation.

Finally, the study found that manufacturers' measurements and performance include measuring the effectiveness of AI integration. This finding suggests that manufacturing must measure the effectiveness of AI integration, its adoption by employees and its impact on sustainability initiatives. The implication is that

manufacturers need to consider beyond comprehensive approaches to measuring AI and also measure the adoption thereof.

This unexpected finding aligns with previous research by Ukko et al. (2019) for full potential manufacturers must follow a strategic approach. It contradicts studies that state that careful planning and execution of initiatives align with overall business objectives (Esfahbodi et al., 2017; Tseng et al., 2020; Poursoltan et al., 2021; Tseng et al., 2022).

Table 6: Theme 5. Holistic Performance Measurement Findings

Key Findings	Implications	Challenges
Holistic performance measurement is crucial for assessing the full impact of DTx.	Support Literature: Environmental sustainability includes: - the strategies, - methods, - measures, - initiatives of an organisation to reduce its adverse effects while enhancing its beneficial impact on the natural environment. Extends Literature: - Manufacturers must consider strategic approach, balance trade-offs and define comprehensive environmental strategies meaning both positive and negative effects are considered. - Reinforces the need for manufacturers to integrate sustainability into their core strategies. Awareness of the	Balancing trade-offs

	interdependence of the sustainability pillars is crucial for strategic approach and for fostering a more integrated approach.	
Manufacturers are committed to compliance with global integrated financial reporting requirements.	Extends Literature: to effectively measure the impact of sustainability initiatives, a holistic approach is necessary. This involves quantifying environmental outcomes, such as greenhouse gas emissions reduction, energy conservation, and waste minimisation.	
Manufacturers measurements and performance includes measuring the effectiveness of AI integration	Manufacturers need to consider beyond comprehensive approaches to measuring AI and measure the adoption thereof. Support literature: for full potential: - manufacturers must follow a strategic approach. Contradict literature: careful planning and execution of initiatives align with overall business objectives.	
Manufacturers use AI and other DT for environmental monitoring and improvement	Support literature: Environmental sustainability encompasses strategies and measurement	

Manufacturers have set ambitious emissions reduction targets	Support literature: Policy on 2030 sustainability targets	
--	---	--

Research Question 2 Summary: Framework

Figure 3 below depicts a developing framework (point 2), adding holistic performance measurement as a key success driver of DTX and AI adoption for advancing environmental sustainability. To achieve GHG emission targets, manufacturers must effectively measure the impact of sustainability initiatives. This entails quantifying environmental outcomes, such as greenhouse gas emissions reduction, energy conservation, and waste minimisation.

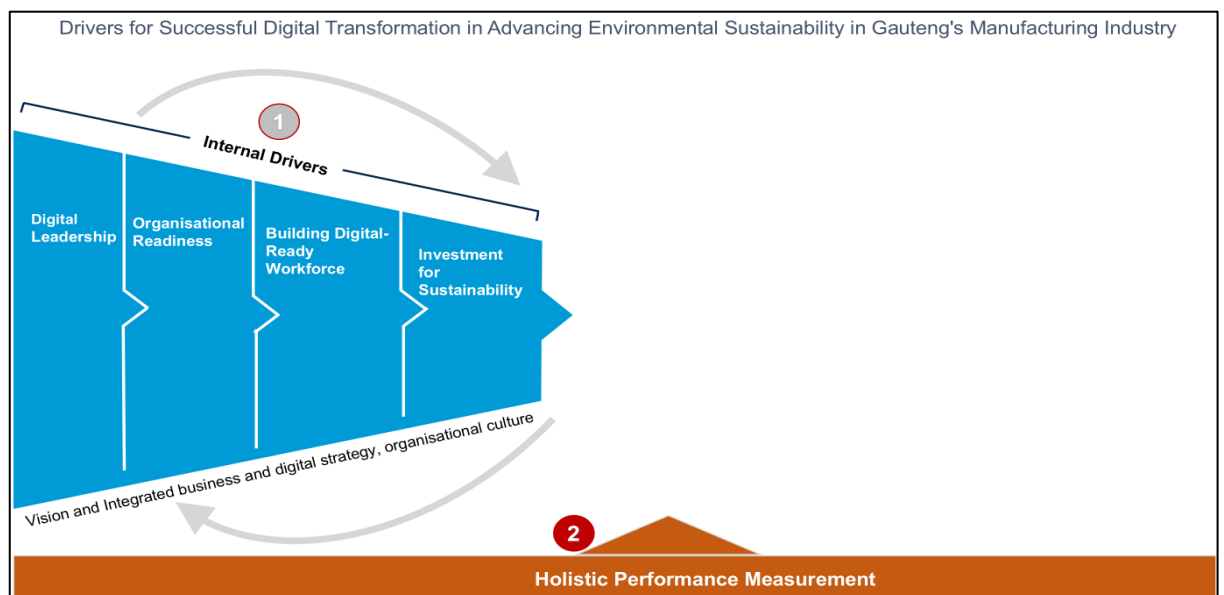


Figure 3: Research Question 2 Summary Framework

Source: Created by Author

To effectively measure the environmental impact of AI-driven digital transformation in the manufacturing sector, a comprehensive approach is necessary. Firstly, identifying key performance indicators (KPIs) is crucial.

These KPIs should encompass both direct environmental impacts, such as greenhouse gas emissions, energy and water consumption, and waste generation, as well as indirect impacts, including the supply chain's environmental footprint and product lifecycle assessments. Secondly, a robust measurement framework should be established.

This involves establishing a baseline measurement to benchmark future performance, implementing efficient data collection systems to monitor relevant KPIs, and leveraging AI-powered analytics to extract valuable insights from large datasets. By combining these elements, researchers and practitioners can accurately assess the environmental benefits of AI-driven initiatives and make informed decisions to drive sustainable manufacturing practices.

6.4 Research Question 3 (Opportunities and Challenges): What policy initiatives and regulatory frameworks are necessary to promote sustainable development in the South African manufacturing sector?

Research question 3's main goal is to determine what specific policies and regulations are influencing sustainable development within the South African Manufacturing sector. In addition, the question seeks to explore specific policies and regulatory frameworks that support the adoption of digital technologies, like AI, in the South African manufacturing sector to reduce greenhouse gas emissions to advance sustainable development.

6.4.1 Theme 6: Policy and Regulation

According to Bell et al. (2021), developing economies like SA must industrialise while reducing their environmental sustainability impact. Green industrial policy, promoting green manufacturing and low-carbon innovation, offers a potential solution for SA to achieve sustainable development.

This study found that the lack of incentives for the manufacturing sector is a significant challenge, it underscores a critical barrier to promoting green manufacturing and low-carbon innovation. Anzolin and Lebdioui (2021) argued that

an effective industrial policy is essential for promoting sustainability initiatives. Additionally, Wang et al. (2024) provide evidence from China demonstrating the effectiveness of green industrial policy in promoting sustainable development. This policy exemplifies how regulations can act as a catalyst for the adoption of sustainability-oriented DTX. As highlighted by Malek and Desai (2019), the lack of government support poses significant barriers and hinders the development of environmental sustainability. Therefore, to effectively promote sustainable practices, it is critical for governments to provide support mechanisms such as subsidies, tax breaks, and financial and technical assistance (Malek & Desai, 2019).

This unexpected finding contradicts existing literature. Dubey et al. (2020) highlighted that in today's digital world, government agencies like the DTI heavily influence businesses by setting the national digital strategy that companies must follow. Similarly, Chiarini (2021) highlights the Italian Ministry of Economic Development 'Industria 4.0 National Plan', launched in 2016, which aims to promote investment in advanced cybertechnologies among Italian companies.

Furthermore, this study introduces critical issues: due to the lack of incentives, manufacturers tend to prioritise short-term financial objectives from their AI and other digital technologies investments. The data suggests that a short-term mindset undermines AI integration for achieving long-term sustainability goals. This finding reinforces the previous theme of investment, the driver finding that the current literature emphasises balancing short-term financial objectives with long-term environmental goals.

This finding supports the study by Ukko et al. (2019) which revealed that the negative moderating effect on financial performance can be attributed to the temporal lag between the implementation of sustainability initiatives and the realisation of tangible cost reductions, efficiency gains, and optimised business processes (Li et al., 2018).

Moreover, this study found that there is a notable disconnect between the government and the manufacturing industry. Participants expressed that due to the lack of proactive engagement, manufacturers feel unsupported in meeting compliance requirements. This suggests that the lack of collaboration may lead to policy uncertainty. This aligns with the literature; a study by Udeagha and Muchapondwa (2023) acknowledged policy uncertainty as a significant barrier without elaborating on potential burdens.

The observation that supportive policy and regulation can empower businesses to leverage digitalisation for environmental sustainability is consistent with the work of (Berger et al., 2022). The study suggests that targeted policy changes can significantly advance environmental sustainability by focusing on a supportive environment for manufacturers.

This is consistent with the findings of Bag et al. (2021b) that policy reforms are essential to incentivise renewable energy adoption and align with SDGs (Colglazier, 2015). Current frameworks often hinder widespread renewables utilisation. Targeted policy changes can address these barriers, foster a shift towards clean energy and achieving broader sustainability goals.

The study raises a critical viewpoint. It found that the competitive landscape is the primary driver of digital transformation in the manufacturing industry. For example, participants expressed scepticism about the role of legislation in driving digital transformation for the manufacturing sector. This suggests that manufacturers who fail to adapt to the digital age risk being outcompeted by those who embrace new technologies and processes.

This finding aligns with a study by Harvoth and Szabo (2019), which highlighted the driving force behind DTx: growing competition, increased innovation capacity, customer expectations, sustainability, and business model innovation (de Sousa Jabbour et al., 2018b). This suggests that while competition is a primary driver, manufacturers must also consider other factors to successfully navigate the DTx journey.

While this study's findings focus primarily on competition, it considers the role of other aspects, such as innovation capacity and sustainability. Its findings extend the existing literature and provide additional empirical evidence to support DTx, particularly AI integration.

However, the study findings contradict those of Chiarini (2021), who highlighted that government policies may promote investment in advanced cybertechnologies for manufacturers.

Table 7: Theme 6. Policy and Regulation

Key Findings	Implications	Challenges
Green industrial policy: - promoting green manufacturing - low-carbon innovation, - offers a potential solution for SA to achieve sustainable development. Due to lack of incentives: - prioritise short-term financial objectives from their AI and other digital technologies investments, which undermines AI integration for achieving long-term sustainability goals	Supports Literature: - an effective industrial policy is essential for promoting sustainability initiatives. - Regulations can act as a catalyst for the adoption of sustainability-oriented DTx. Contradict Literature: - in today's digital world, government agencies influence businesses. - government support in the form of tax breaks, subsidies, financial and technical assistance.	The lack of incentives underscores a critical barrier to promoting green manufacturing and low-carbon innovation.
There is a notable disconnect between the government and the manufacturing industry.	Extends Literature: - policy uncertainty as a barrier. - supportive policy and regulations can empower businesses to leverage digitalisation for environmental sustainability - targeted policy changes can advance environmental sustainability - policy reforms are essential to incentivise renewable energy adoption and align with SDGs	Current frameworks often hinder widespread renewables utilisation.

The competitive landscape is the primary driver of digital transformation in the manufacturing industry	Support Literature: Manufacturers primarily focus on competition, and must also consider the role of other drivers, such as innovation capacity, sustainability, customer expectations, and business model innovation Contradicts Literature: Government support to promote manufacturing sector investment in digital technology adoption	

6.4.2 Theme 7: Environmental Sustainability

In the context of environmental sustainability, compliance risks arise from non-adherence to laws, regulations, or self-imposed standards.

The study has found that the manufacturing sector requires a license to operate which mandates compliance with environmental regulations and minimum standards. This suggests that manufacturing must implement monitoring systems. Additionally, comprehensive emissions monitoring is essential to guide the effective implementation of environmental sustainability initiatives. Finally, manufacturers must implement alerts and address non-compliance to targets. This aligns with the study by Ezici et al. (2020) who concluded that there is a critical need to holistically assess the environmental impact. The study extends the existing literature and supports previous research by Settembre-Blundo et al. (2021), risks of not complying can lead to financial losses, legal penalties, and reputational damage. Manufacturers confirmed carbon dioxide (CO₂), nitrogen oxide (NO_x), and Sulphur Dioxide (SO_x) as the primary GHG emissions. Additionally, water usage and electricity are critical inputs in manufacturing processes. While waste and water return to systems contribute to direct and indirect environmental impacts.

These findings highlight that merely adopting green technologies does not automatically reduce energy consumption or lower pollution. Additionally, data suggest that while manufacturers can improve sustainable practices, there are still significant environmental challenges to be addressed. The finding, though expected, is that the existing literature refers to compliance with regulatory requirements and is scant on the license to operate. This finding extends the work of Ma et al. (2022), which concluded that despite advanced green production models, energy consumption will remain high with severe pollution levels.

Furthermore, the study found that AI technology can potentially advance environmental sustainability practices. In support of this finding, participants noted that manufacturers are increasingly adopting digital technologies to achieve environmental targets. This finding was expected and validates a claim from Schöggel et al. (2023), AI possesses significant potential for driving CE and sustainability management.

Finally, participants also cautioned and critically questioned the current approaches to managing greenhouse gas emissions, which focus only on industrial sectors like manufacturing. In addition, participants stressed a more comprehensive strategy that includes both industrial and natural sources for effective environmental impact management. This finding is unexpected, challenging the notion that the manufacturing industry is the only source of GHG emissions. This finding supports existing literature by Lamb et al. (2021) that reducing GHG emissions is a complex global challenge, ranging from energy-intensive industrial activity to urban-infrastructure, land use and human behaviour.

Table 8: Theme 7. Environmental Sustainability

Key Findings	Implications	Challenges
Manufacturing operating license: - Requires a license to operate	Supports Literature: - the critical need to holistically assess the environmental impact.	Environmental challenges to be addressed

- must implement monitoring systems. - must implement alerts and address non-compliance with targets	- the license to operate.	
Merely adopting green technologies does not automatically reduce energy consumption or lower pollution.	Despite advanced green production models, energy consumption will remain high with severe pollution levels.	Economic growth leading to an increase in GHG emissions
AI technology has the potential to advance environmental sustainability practices. Manufacturers are increasingly adopting digital technologies to achieve environmental targets.	Supports Literature: AI possesses significant potential for driving CE and sustainability management.	Slow adoption rate
A comprehensive strategy that includes both industrial and natural sources for effective environmental impact management.	Supports Literature: - trends and drivers of global GHG emissions and sources	

6.4.3 Theme 8: Sustainable Manufacturing: AI-Driven Environmental Sustainability

This study found that the manufacturing industry is at a low digital maturity, specifically a sector that is in the early stage of integrating AI technologies for advancing environmental sustainability. This finding is expected and validates Schöggl et al. (2023) findings that AI possesses significant potential for driving CE and sustainability management. It also extends the literature that the integration of

Industry 4.0 and sustainability is still in its early stages (de Sousa Jabbour et al., 2018a).

Additionally, analysis indicates that the low maturity and slow progress are exacerbated by historical investment with no return on investment or business value. This finding highlights a critical issue: return on investment from implemented use cases or solutions. For example, participants noted the implementation of big data infrastructure and a dashboard to visualise data. This suggests that the manufacturers face pressure to justify investments and emphasise that return on investment (ROI) is crucial. While this finding contradicts the literature on transforming traditional manufacturing into sustainable manufacturing, adequate financial resources and investments in essential (Mangla et al., 2018) also extends the work of Birkel et al. (2019), highlighting the risk associated with technological obsolescence in the context of innovation may erode value.

Furthermore, the study found that there is an urgent need for a formal, integrated business and digital strategy along with strong senior management support. Such alignment and commitment are essential for establishing the right infrastructure and a well-defined use case criterion. This suggests that the lack of alignment and commitment from senior management is a significant impediment to effective business and digital strategy. This finding was expected and is consistent with the literature. Gaffley and Pelser (2021) revealed that CEOs and C-Suite Executive Teams must lead digital strategies; leadership and strategy are key elements that contribute to the successful integration of DTx (Abdalla, 2022). Moreover, the findings provide additional empirical evidence to support the interplay between leadership alignment and successful digital strategies.

Interestingly, the study found that manufacturers are running various environmental sustainability initiatives in the form of proof of concepts. Moreover, the number of siloed POCs and this fragmented approach may lead to ineffective integration into the broader program. This unexpected finding extends literature awareness of the interdependence of the concepts which is crucial for a strategic approach and fostering a more integrated approach (Esfahbodi et al., 2017; Tseng et al., 2020; Poursoltan et al., 2021; Zhang et al., 2021; Tseng et al., 2022). These studies highlight rigorous planning to ensure sustainability initiatives align with overall business objectives.

Finally, the study found that scaling initial success by adopting a systematic approach to drive AI technology integration from the unit level to factory level, and ultimately to the enterprise level. This suggests that a comprehensive approach ensures that organisations can effectively leverage digital technologies to improve operational efficiency and drive sustainable practices, particularly in sectors such as manufacturing where environmental sustainability is a pressing concern.

This finding was not expected and aligned with several works, environmental sustainability encompasses the strategies, processes, measures, and initiatives (Isensee et al., 2020). Ukko et al. (2019) extends that for full potential, manufacturers must follow a strategic approach; which contradicts other studies that careful planning and execution of initiatives align with overall business objectives (Esfahbodi et al., 2017; Tseng et al., 2020; Poursoltan et al., 2021; Tseng et al., 2022).

Table 9: Theme 8. Sustainable Manufacturing: AI-Driven Environmental Sustainability

Key Findings	Implications	Challenges
Manufacturing industry is at a low digital maturity, specifically a sector in the early stage of integrating AI technologies for advancing environmental sustainability	Extends Literature: AI possesses potential for driving CE and sustainability management. - the integration of Industry 4.0 and sustainability is still in its early stages. - the risk associated with technological obsolescence in the context of innovation may erode value. Contradict Literature: to transform traditional to sustainable manufacturing, adequate financial resources and investments required	Return on investment from implemented use cases or solution

Urgent need for a formal, integrated business and digital strategy along with strong senior management support.	Supports Literature: CEOs and C-Suite Executive Teams must lead digital strategies; leadership and strategy are key elements that contribute to the successful integration of DTx	Lack of alignment and commitment from senior management is a significant impediment to effective business and digital strategy
Manufacturers are running various environmental sustainability initiatives in the form of proof of concept.	Extends Literature: Awareness of the interdependence of the concepts is crucial for a strategic approach and for fostering a more integrated approach. Rigorous planning to ensure sustainability initiatives align with overall business objectives	The number of POCs are siloed and this fragmented approach may lead to ineffective integration into the broader program.
Scaling initial success: adopt a systematic approach to drive AI technology integration from unit level to factory level, and ultimately to the enterprise level: - organisations can effectively leverage digital technologies to improve operational efficiency - drive sustainable practices	Contradicts Literature: Environmental sustainability involves the strategies, processes, measures, and initiatives: - follow a strategic approach aligned with overall business objectives. - works of careful planning and execution of initiatives align with overall business objectives.	Many uncoordinated AI proof of concepts are not scalable

6.4.4 Theme 9: Sustainability Risk Drivers

This study found significant risks associated with the integration of digital technologies for advancing environmental sustainability in manufacturing. This suggests that the rapid pace of technology development may render implemented technologies obsolete. This finding was expected and aligns with the study by Settembre-Blundo et al. (2021), which finds that the rapid pace of technological progress can render investments obsolete before they yield a return. Therefore, it supports the existing literature.

The transition to a low emission world presents substantial risks, particularly compliance costs burden for an operating entity. This suggests that manufacturers often see environmental sustainability as a cost. For example, data from participants identified that manufacturing sees compliance costs as a financial burden with no returns. This finding aligns with Settembre-Blundo et al. (2021) study that the organisation risk approach is centred on fragmented operational measures, aimed at siloed mitigation of an unexpected event, financially biased.

Moreover, the study found the risk of carbon tax introduction. This suggests that manufacturers must be prepared for potential financial and operational implications of such a tax, especially heavy emitters. Jia and Lin (2020) argued carbon tax will encourage carbon-intensive activities and shift towards more sustainable practices. This view is supported by Lamb et al. (2021), policies like carbon pricing and incentives are the key drivers of GHG emission reduction. While pricing carbon may incentivise innovation and reduce environmental impact, revenue generated may be used to lower other taxes such as corporate tax, income tax and etc (Jia & Lin, 2020; Ma et al., 2020; Wang et al., 2020).

In addition, this study found that for scenarios where AI technology integration and other DTs are adopted for sustainable manufacturing, there is a significant threat of emerging cybersecurity risks for the manufacturing industry. This finding implies that DTx and AI integration increases the risk of cyber-attacks. Despite the huge potential of AI in promoting environmental sustainability, significant risk persists (Camacho, 2024).

For manufacturers, this might lead to serious consequences due to unauthorised manipulation of the process control parameters. For example, participants cited cyber security as a broad topic also a threat that poses the greatest risk to the overall organisation. This suggests that manufacturers must adopt a governance and risk framework to guide the DTx and AI technology integration for sustainable manufacturing. Robust cybersecurity measures are essential to protect manufacturing operations from potential threats. Furthermore, conducting thorough risk assessments can help identify potential vulnerabilities and enable the implementation of effective mitigation strategies.

Consistent with prior studies, this finding supports existing literature. A previous study by Saeed, Altamimi, Alkayyal, Alshehri and Alabbad (2023) highlighted that cybersecurity is an essential component of DTx and AI technology integration. In addition, organisations must prioritise cybersecurity measures to ensure successful transformation without disruption to manufacturing (Moller, 2023). In contrast, a study by Camacho (2024) concluded that AI has a multifaceted role, highlighting its dual role as both an enabler of DTx AI-powered and a potent tool for managing organisational cyber defence systems.

Finally, the study found that addressing the social implications of DTx is overlooked and significant. This suggest that manufacturers prioritise AI integration and technology aspects and overlooking human related aspects. Implication: Employees' resistance to change and fears about AI and digital technologies can be a major obstacle to successful implementation.

Table 10: Theme 9. Sustainability Risk Drivers

Key Findings	Implications	Challenges
Significant risks associated with the integration of digital technologies: the rapid pace of technology development may render implemented technologies obsolete.	Support Literature: - the rapid pace of technological progress can render investments obsolete before they yield a return. - Carbon tax considerations	Rendering investments obsolete before generating a return on investment

A significant threat of emerging cybersecurity risks for the manufacturing industry.	Supports Literature: - cybersecurity an essential component of DTx and AI technology integration - Cybersecurity measures - AI as a potent cyber defense tool	Manufacturers often see environmental sustainability as a cost
Addressing the social implications of DTx is overlooked: - prioritising AI integration and technology aspects and overlooking human related aspects.	Employees' resistance to change and fears about AI and digital technologies can be a major obstacle to successful implementation.	Employee impact and support

Research Question 3 Summary: Framework

Figure 4 below depicts a developing framework (point 3), adding external drivers' policy and regulation, environmental sustainability, and sustainability risk. This entails government policy, strategic partnerships, environmental minimum standards, and risk associated with sustainability.

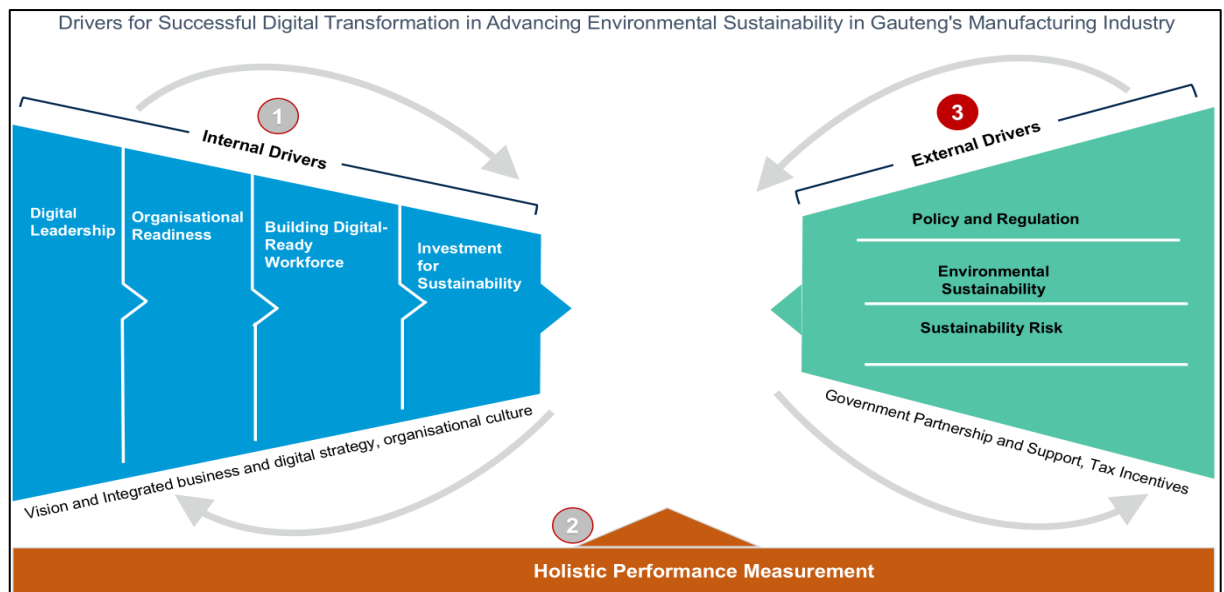


Figure 4: Research Question 3 Summary Framework

Source: Created by Author

The disconnect between government and industry expectations in the Gauteng manufacturing sector, a comprehensive Green Manufacturing Incentive Program is proposed. This program aims to incentivise AI adoption and sustainable practices by offering a range of financial and non-financial benefits to eligible manufacturing companies. Key components of this program include:

Firstly, tax incentives as tax credits for investments in AI and sustainable technologies, research and development tax deductions, and accelerated depreciation for green assets. Secondly, financial support, in the form of grants, subsidies, and low-interest loans to support the adoption of energy-efficient technologies and sustainable practices. Finally, regulatory framework, by streamlining permitting processes and developing clear and consistent regulations.

By implementing such a program, the government can create a favourable environment for manufacturing companies to adopt AI-driven solutions and reduce greenhouse gas emissions, ultimately contributing to the sustainability goals of the region.

6.5 Research Questions 4 (Benefits and Challenges): What are the potential environmental benefits and challenges, barriers, and constraints faced by manufacturing organisations when implementing DTx for sustainability purposes?

The research question explores the positive environmental impacts of digital technologies adoption, such as AI through the DTx on manufacturing organisations, such as efficiency gains, waste reduction, pollution mitigation. Furthermore, the question explores the difficulties and limitations manufacturing organisations face when implementing these technologies for sustainability, such as technological limitations, economic factors, organisational factors, and regulatory factors.

6.5.1 Theme 10: Digital Sustainability: AI Digital Technologies Drivers

This study found that AI is a key enabler of sustainability strategies in the manufacturing sector. This finding suggests that AI technology can help manufacturers to achieve their environmental targets. The findings align with the existing literature on the role of AI in advancing environmental sustainability in manufacturing. Troung (2022) similarly concluded DTx, specifically AI, big data, and the IoT, offer a compelling solution for addressing environmental sustainability challenges. The study's findings directly support Schöggel et al. (2023) argument that AI has significant untapped potential for driving environmental sustainability. By demonstrating AI technology's potential to improve process efficiency, reduce waste, reduce emissions and promote low-carbon production, the study provides empirical evidence to reinforce Schöggel et al. (2023) claims.

The majority of the participants stated that AI adoption is at an early stage of adoption. This corroborates with study by de Sousa Jabbour et al. (2018a) that the manufacturing sector is lagging behind, and at an early stage of AI adoption. However, participant P05 stated AI has been integrated for nearly five years.

P05: "So I would say we are across the continuum in some areas we already have been using AI models for probably five years in operations"

The participant highlights that the use case includes environmental reporting, predictive maintenance, packaging line optimisation and other production-related use cases such as yield and energy consumption.

WEF and McKinsey established a global lighthouse to enable the global manufacturing community to accelerate the adoption of 4IR technologies. Table 11 below by de Boer and Torti (2023) provides detailed use cases from other emerging economies. To date, over 200 use cases have been completed, tracked and reported, of which 20 are sustainability-related use cases (de Boer & Torti, 2023). Interestingly, multinational corporations with manufacturing sites in South Africa, and some in Gauteng use cases are included in the top 20 sustainability use cases reported. Building on this, the findings provide empirical evidence and validate claims by Schöggli et al. (2023). While these global use cases are promising, the local manufacturing landscape in South Africa presents unique challenges and opportunities. To unlock the full potential of AI for advancing sustainable practices, a comprehensive understanding of the key drivers for successful AI adoption and DTx is essential. To effectively assess the potential AI and DTx for manufacturing sustainability, a comparative analysis of multinational corporations with a local presence can provide valuable insights into best practices and identify potential barriers to adoption. This analysis can be complemented by case studies with successful implementations and can highlight the potential for broader adoption within the local manufacturing sector.

Table 11: Global Lighthouse Projects

Company	Use Case	Results
Johnson & Johnson	Implemented AI algorithms for process control, IIoT-based intelligent cleaning, and digital twins	47% reduction in material waste, 26% decrease in GHG emissions, 23% reduction in energy consumption
Mondelēz	Mondelēz Beijing implemented 38 Fourth Industrial Revolution use cases, such as an AI-powered dough-making	29% reduction in food waste, and water utility intake, 34% decrease in energy-related

	lights-off workshop and gas consumption optimisation by machine learning.	consumption, 29% reduction in GHG emissions
Schneider Electric	Developed an E2E closed-loop system with CO2 tracking and AI-based predictive monitoring	59% reduction in energy consumption, 61% decrease in CO2 emissions, 57% cut in water consumption, 64% reduction in waste generation
Siemens	Implemented a digital energy management system and AI-based automation for waste handling	24% reduction in unit product energy consumption, 48% reduction in production waste, 44% decrease in GHG emissions on mechanical products

Source: WEF and McKinsey (2023)

While the study findings provided empirical evidence of the potential of AI integration to drive sustainability in the manufacturing sector, it is essential to recognise the complexities and trade-offs involved. Denicolai et al. (2021) argued that while AI and sustainability may appear correlated, manufacturers' global market growth reveals competing priorities, forcing difficult trade-offs. Additionally, data from analysis raised that manufacturing sector AI integration can be hindered by factors such as first, availability of data strategy and data quality (Ma et al., 2022; Tseng et al., 2022); second, existing legacy infrastructure and operational technology low digital maturity (Birkel et al., 2019); third, skills and digital talent availability (Mariappanadar et al., 2022; Dabic et al., 2023); fourth, ethical considerations (Booyse & Scheepers, 2023).

Furthermore, study found that the emergence of advanced measurement technologies, especially AI-powered, is a key driver behind the adoption of digital technologies in manufacturing. Additionally, this study found that manufacturers can leverage vast amounts of data through data analytics, discovering valuable insights, that improve both operational efficiency and environmental performance.

Interestingly, linked to previous findings, this study found that as manufacturers become more adept at utilising data, they can better predict production scenarios and adapt and refine their sustainability strategies. The combined findings suggest the importance of data-driven decision making in manufacturing for achieving both operational and environmental goals. Ma et al. (2023) stressed that an innovative approach harnesses advanced technologies to optimise data management and improve efficiency and sustainability in manufacturing.

This finding aligns with the existing literature and the consensus gives credibility to this finding. Ma et al. (2020) stated continuous improvement of manufacturing sustainability is crucial and also improves their competitiveness. Furthermore, the study's findings extend the literature. The convergence of digital technologies and intelligent manufacturing has given rise to sustainable intelligent manufacturing (Ma et al., 2020).

The study finding that AI is a key enabler of sustainability strategies in the manufacturing sector adds to the literature on AI adoption for greenhouse gas emissions reduction. This validates the study by Schöggel et al. (2023) that AI has significant untapped potential for driving environmental sustainability.

Table 12: Theme 10. Digital Sustainability: AI Digital Technologies drivers

Key Findings	Implications	Challenges
AI is a key enabler of sustainability strategies in the manufacturing sector.	Adds literature AI key enabler of environmental sustainability Support Literature: DTx, specifically AI, big data, and the IoT, offer a compelling solution for addressing environmental sustainability challenges.	- lack of data strategy and data quality - current infrastructure and outdated operational technology - skills and digital talent availability

		- ethical and social considerations
Manufacturers use advanced measurement technologies to leverage vast amounts of data through data analytics.	Support Literature: Innovative approach: - harnesses advanced technologies to optimise data management, - improves efficiency and sustainability in manufacturing. Continuous improvement of manufacturing sustainability is crucial and improves their competitiveness. Extends Literature: the convergence of digital technologies and intelligent manufacturing has given rise to sustainable intelligent manufacturing	Data readiness and lack of clear data strategy

6.5.2 Theme 11: Benefits of DTx for Environmental Sustainability

The previous theme found that the adoption of AI and other digital technologies is identified as a key driver for achieving environmental sustainability within manufacturing. Truong's (2022) study listed the following indirect effects of DTx and AI integration, aligned with findings by Dauvergne (2022): (1) forecasting waste generation, (2) unveiling resource waste, (3) designing more efficient waste management models, digitalisation and networking contribute to the reduction of greenhouse gas emissions. This aligns with and supports this study's finding that achieving GHG emissions reduction may often be an indirect benefit of adopting digital technologies. This consensus of findings strengthens the credibility of the current study's findings.

However, this study highlights a critical challenge: the need to balance environmental sustainability targets with profitability objectives. For example, data revealed there are market growth opportunities and new value pools for products made from low-carbon sources, particularly in European markets. While the study findings provided empirical evidence of the potential of AI integration to drive sustainability in the manufacturing sector, it is essential to recognise the complexities and trade-offs involved.

These unexpected findings contradict the previous research. As Denicolai et al. (2021) revealed that SME manufacturing, AI and sustainability may appear harmonised, global market growth reveals difficult trade-offs. This raises questions about AI and sustainability in existing literature in different contexts. The controversy lies in reconciling differing perspectives and understanding the underlying drivers. This controversial finding aligns with a previous study by Yadav et al. (2020) who asserted that to advance the discourse on sustainability, it is necessary to explore the enablers that drivers facilitate adoption.

Moreover, this study found that optimising value is complex; leveraging AI and advanced analytics can help find a solution that maximises business value. This suggests that manufacturers need a more integrated approach to leverage sustainability potential. In addition, a strategic approach that balances impact on profitability. Building on the previous finding, the study found that not all opportunities will yield the desired outcomes; manufacturers must prioritise and invest in high-potential AI technology-enabled use cases. This suggests that manufacturers must be strategic when deciding on AI investment for sustainability. By focusing on high-potential use cases, manufacturers can maximise the benefits. This implies that while AI has the potential to drive sustainable manufacturing and unlock value, the effectiveness of AI solutions can differ significantly based on the context. Studies by Ukko et al. (2019) highlight that managers often prioritise short-term economic performance over sustainability. This suggests that when evaluating sustainability initiatives performance is biased towards financial gains.

The study extends the existing literature and provides empirical evidence to support the value case. It aligns with Bag et al. (2021a) findings, which demonstrated a positive influence between digital transformation and sustainability performance in local manufacturing firms. While the study's finding extends the existing literature,

also reinforces the main argument made by de Sousa Jabbour et al. (2018b) that digital transformation and sustainability practices were conceived to address different purposes. This raises questions about whether digital transformation can coexist with enterprise sustainability efforts (Osburg, 2017; Lohrmann, 2017; Beier et al., 2018).

The study's findings have significant implications for manufacturers seeking to achieve both sustainability and business value. By leveraging AI and other digital technologies, manufacturers can develop more integrated strategies that address the complexities of balancing environmental and business financial objectives.

Finally, this study identifies a critical challenge; complexity compounded by the need to consult multiple stakeholders to align on the overall benefits of sustainability initiatives. This suggests that pursuing sustainability and other key organisational objectives, such as financial short-term gains, is a complex process. To address this complexity, manufacturers need an effective stakeholder management approach. This finding, though unexpected aligns with the existing literature and provides additional empirical evidence in the context of AI integration for sustainability. Ukko et al. (2019) similarly emphasised that stakeholder involvement and incorporating the perspectives of various stakeholders, including employees, customers, suppliers, and the community is essential. Additionally, to maximise the benefits of sustainability strategies, businesses must carefully consider the specific context in which they operate and tailor their approaches (Ukko et al., 2019).

Table 13: Theme 11. Benefits of DTx for Environmental Sustainability

Key Findings	Implications	Challenges
The adoption of AI and other digital technologies is identified as a key driver for achieving environmental sustainability within manufacturing.	Supports Literature: Indirect effects of DTx and AI integration Contradict Literature: AI and sustainability global market growth reveals: - competing priorities,	The need to balance environmental sustainability targets with profitability objectives.

	- forcing difficult trade-offs.	
Optimising for value is complex; leveraging AI and advanced analytics can help find a solution that maximises business value.	Support Literature: - a positive influence between digital transformation and sustainability performance - digital transformation and sustainability practices were conceived to address different purposes.	Complexity is compounded, multiple stakeholders' overall benefits of sustainability initiatives alignment.
Achieving environmental impact may often be an indirect benefit of adopting digital technologies.	Support Literature: stakeholder involvement and incorporating the perspectives of various stakeholders, To maximise the benefits of sustainability strategies, businesses must carefully consider the specific context in which they operate and tailor their approaches accordingly	Complex stakeholder alignment and buy-in
Not all opportunities will yield desired outcomes, manufacturers must prioritise and invest in high-potential AI technology-enabled use cases	Extends Literature: managers often prioritise short-term economic performance over sustainability.	Identifying high potential value use cases. Short-term economic focus over sustainability

6.5.3 Theme 12: Challenges in Implementing AI for Sustainable Manufacturing

This study identified the stranded assets challenge and found that manufacturers still have outdated process equipment that lacks monitoring and data transmission capabilities. This significant barrier not only complicates AI integration but also other foundational digital technologies such as big data analytics. Additionally, this complication makes it difficult to implement effective environmental monitoring to track and report on greenhouse gas emissions effectively. The findings extend the

literature and raise additional challenges, such as outdated manufacturing equipment needed for AI integration. According to de Sousa Jabbour et al. (2018a) the integration of Industry 4.0 and sustainability is still in its early stages.

The implication is that manufacturers must assess the operational technology readiness and digital maturity as a critical driver for their sustainability efforts. This suggests that manufacturers must first invest to replace or modernise the current outdated manufacturing equipment that lacks the necessary data transmission to enable process monitoring. This corroborates with Brook and Wagenheim (2019) who revealed the importance of legacy systems' compatibility with AI technologies. Second, to enable data-driven operations and sustainability. The study finding challenges the existing literature, specifically the assumptions about adequate financial resources and investment, particularly for AI integration. The finding extends the literature by Mangla et al. (2018), which concluded that to transform sustainable manufacturing, adequate financial resources and investments are essential.

Building on this, this study found the significant upfront costs required for complex IT infrastructure, like cloud computing and digital technologies. The need for substantial upfront poses a considerable barrier for many organisations. This finding builds on the previous finding and focuses on the foundational infrastructure required to integrate AI technology for sustainability.

This expected finding aligns with the existing literature and provides additional empirical evidence to support the technology's adequate financial and investment literature. The study findings extend previous research by Mangla et al. (2018), which concluded that transformation to sustainable manufacturing, adequate financial resources and investments in essential. Additionally, top management plays a crucial role in allocating funding to support the integration of digital technologies such as AI and a combination thereof to support and enable the transformation.

Linking to the previous finding challenge, participants' response points out a strategy of piloting new technologies before broader implementation. Birkel et al. (2019) highlighted that while new technologies usually increase competitiveness by reducing costs, the rapid rate of technology changes and emerging disruptive technologies may result in making earlier technology obsolete. Therefore, the initial upfront investment potentially be sunk costs. In addition, there is no time to amortise if new innovations follow one another rapidly.

Moreover, the study found that the pressure can lead to decisions that may not align with the company's current capabilities. Supporting this finding, this study found that due to pressure from stakeholders, compounded and complicated by a steep learning curve to integrate and implement technologies quickly. This suggests that manufacturers need to understand the complexities and challenges faced when integrating AI and digital technologies for environmental sustainability. Additionally, emphasises the need for careful consideration of stakeholders aligned to ensure that sustainability initiatives are effective and aligned with overall company objectives. The study finding extends the existing literature and provides additional empirical evidence, thus credibility to the study findings. Ukko et al. (2019) similarly emphasised stakeholder involvement and incorporating the perspectives of various stakeholders for sustainability initiatives.

Additionally, another significant study found that AI technology integration generates sustainable value, and an effective systems integration is needed. This suggests that for manufacturers to integrate AI technology successfully, effective system integration must be in place. The implication is that without system integration it may be difficult to integrate AI technology to leverage data and drive sustainable manufacturing. This expected finding provides additional empirical evidence to support technology readiness. The study extends the existing literature that organisational readiness is crucial for successful DTx implementation (Mikalef et al., 2019; Gaffley & Pelsler 2021; Holopainen, 2022; Narkhede et al., 2024).

Furthermore, the study found that change management must not be underestimated. AI technologies adoption to advance sustainable practices often involves significant changes to manufacturers. Additionally, changes can be met with resistance from employees. This suggests that transformation to sustainable manufacturing through DTx and AI integration must go beyond technological aspects but also consider first, leadership skills and shifts, second, cultural shifts, third, employee impact, behaviour adjustment and development, and finally, ethical considerations. This finding was expected and provides additional empirical evidence in the context of AI technology adoption. The study's finding extends to the existing literature on effective change management for digital technology adoption. It contributes to a study by Dabic et al. (2023) who concluded that without a fundamental transformation of organisational culture, the integration of AI technologies may face substantial barriers.

Finally, this study found that a clear data strategy is a key driver for the successful integration of AI and digital technologies. This finding suggests that without a clear strategy and a solid data foundation, manufacturers may struggle to leverage the full potential of AI technologies. The implication is that manufacturers must define enterprise-level data strategy to support data-driven operations and enable manufacturing DTx and AI integration. This expected finding reinforces the role of data as a critical foundation for DTx, in particular AI integration to drive compliance to environmental sustainability. The study finding aligns with the literature by Schöggli et al. (2023), which identified big data analytics, AI, IoT, and blockchain as the primary DTx employed in the manufacturing sector.

The study extends the literature and reinforces the findings of the previous research. Ukko et al. (2019) similarly emphasised that to fully comprehend data-driven sustainability, it is essential to understand how data and analytics can be used to measure and improve environmental, social, and economic performance.

Table 14: Theme 11. Benefits of DTx for Environmental Sustainability

Key Findings	Implications	Challenges
Manufacturers outdated process equipment that lacks monitoring and data transmission capabilities: - making it harder to integrate with AI and other digital technologies. - makes it difficult to track and report on greenhouse gas emissions effectively.	Extends Literature: the integration of Industry 4.0 and sustainability is still in its early stages. - operational technology readiness and digital maturity - invest to replace or modernise the current outdated manufacturing equipment - enable data-driven operations and sustainability.	Stranded assets

Digital maturity of companies is a critical factor in their sustainability efforts.		
The need for substantial upfront costs poses a considerable barrier for many organisations.	Extends literature: sustainable manufacturing adequate financial resources and investments New technologies increase competitiveness by reducing costs the rapid rate of technology changes and emerging disruptive technologies may result in making earlier technology absolute	Financial burden and huge capital outlay
AI technology integration to generate sustainable value, an effective systems integration is needed.	Extends Literature: AI system integration challenges for leveraging data organisational readiness for successful DTx implementation	Value case complexity
Change management must not be underestimated. AI technologies adoption to advance sustainable practices often involves significant changes to manufacturers. Changes can be met with resistance from employees.	Contradicts Literature: organisational culture transformation	
A clear data strategy is a key driver for the successful integration of AI and digital technologies. Without a clear strategy and a solid data	Support Literature: enterprise-level data strategy to support data-driven operations and enable manufacturing DTx and AI integration	Data readiness and lack of data strategy to support DTx and AI integration

foundation, manufacturers may struggle to leverage the full potential of AI technologies fully.	- big data analytics, AI, IoT, and blockchain are the primary DTX employed in the manufacturing sector. - to fully comprehend data-driven sustainability, it is essential to understand how data and analytics can be used to measure and improve environmental, social, and economic performance.	
---	---	--

Research Question 4 Summary: Framework

Figure 5 below depicts a developing framework (point 4), adding the benefits, opportunities, and challenges associated with the integration of AI for environmental sustainability.

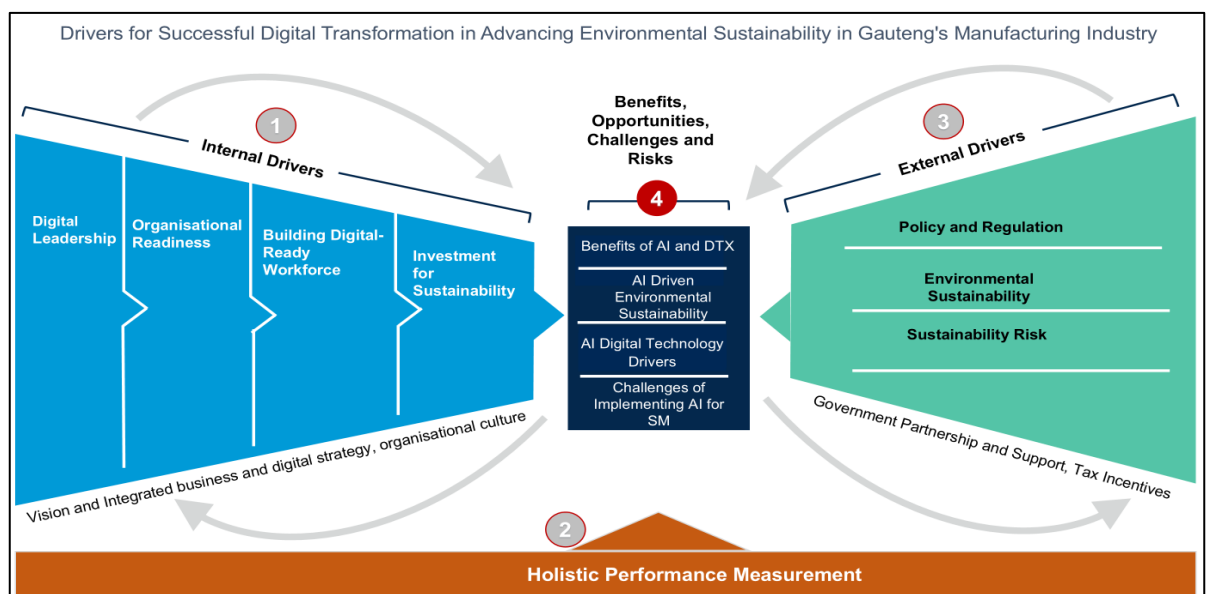


Figure 5: Research Question 4 Summary Framework

Source: Created by Author

While the research provides a comprehensive overview of the challenges and opportunities associated with AI adoption in manufacturing, a more focused analysis

of the direct environmental impacts and technological limitations could further strengthen the findings.

For instance, a detailed exploration of specific AI applications, such as predictive maintenance and energy optimisation, could quantify the potential environmental benefits more precisely. Additionally, a deeper dive into the technical barriers, such as data quality and algorithm complexity, would provide valuable insights for policymakers and industry practitioners

Cybersecurity remains a critical concern. This risk highlights the potential for cyberattacks to disrupt AI-powered systems and hinder emissions reduction efforts. The protection of sensitive data and critical infrastructure from cyberattacks is essential to ensure the continued operation of AI-powered systems

Technology obsolescence: This risk emphasises the need to stay updated with the latest technological advancements to maintain the effectiveness of AI-driven solutions.

6.6 Research Question 5 (Risk): The potential negative effects, direct and indirect, of implementing DT such as AI for environmental sustainability?

Research question 5's main goal is to explore the potential downside of using digital technologies, specifically AI to address environmental challenges. The questions seek to identify the direct negative effects, such as increased energy consumption to support the use of digital technologies, and indirect negative effects, such as increased production leading to environmental degradation.

6.6.1 Theme 13: Digital Sustainability: Risk of AI Technology Adoption

This study found that AI has the potential to advance environmental sustainability practices. Additionally, the integration and adoption of AI require careful consideration of environmental impact.

This study raises significant risk, AI technology is the major contributor, potentially the only source directly impacting the environment. These findings highlight that

while AI has the potential to drive sustainability, the technology has associated risks. The implication is that manufacturers must understand the environmental effects related to AI and other digital technologies. This finding was expected, though came from few participants and aligns with the existing literature. While this study's finding contradicts the existing literature, however it does also support the previous research. An empirical study by Truong (2022), concluded that DT's direct environmental effects as (1) the production of digital infrastructure, (2) the energy consumption of digital infrastructure, (3) the mining of the hardware to be used as digital infrastructure, (4) collection, recycling, and disposal of digital assets physical infrastructure, (5) greenhouse emissions for the generation of power used by DTx. These findings were confirmed by Chiarini's (2021) empirical study, the effects of DT and AI adoption.

The study's findings are controversial, firstly because the reconciliation of AI technology solutions is the sole source of environmental impact. Secondly, the narrow view of the effects of AI technology integration into manufacturing. Dauvergne (2022) highlights a paradox in AI integration, which perpetuates a rebound effect, leading to increased resource extraction and production, thereby exacerbating environmental degradation and resource depletion.

The implications from the findings underscore the necessity for a nuanced understanding of AI's environmental impact. From the data analysis, the interview participant suggested a comprehensive business case to include the environmental impact. Additionally, the study found that the manufacturing industry tends to neglect the environmental sustainability impact in the sustainability digital initiatives value case. This consensus of the findings provides credibility to the study's findings. Dauvergne (2022) study underscores the urgent need for sustainable practices and responsible reinvestment strategies to mitigate the adverse consequences of technological progress in the industry.

Building on the previous finding, this study found that manufacturers have difficulty in quantifying the indirect environmental impacts of AI adoption. This finding suggests that manufacturers lack an understanding of the AI integration impact on the environment. The implication is that manufacturers need to recognise that to effectively measure the impact of sustainability initiatives, a holistic approach is necessary. This involves quantifying environmental outcomes, such as greenhouse

gas emissions reduction across the ecosystem to mitigate the adverse consequences of technological progress in the industry. This finding seems to contradict the previous finding by Troung (2022) on the direct and indirect effects of AI integration. The findings reinforce Dauvergne (2022) study, which concludes the urgent need for sustainable practices. In green production models, energy consumption remains high, and pollution levels can be severe (Ma et al., 2022).

Table 15: Theme 13. Digital Sustainability: Risk of AI technology adoption

Key Findings	Implications	Challenges
Manufacturing industry tends to neglect the environmental sustainability impact in the sustainability digital initiatives value case	Contradict Literature: the direct environmental effects as: - the production of digital infrastructure, - the energy consumption of digital infrastructure, - mining of the hardware to be used as digital infrastructure, - collection, recycling, and disposal of digital assets physical infrastructure, - greenhouse emissions for the generation of power used by DTx.	AI technology is the major contributor directly impacting the environment.
Manufacturers have difficulty quantifying the indirect environmental impacts of AI adoption. This may lead to value assessment gaps.	Contradict literature: the direct and indirect effects of AI integration. Urgent need for sustainable practices; while green production models, energy consumption remains high, and pollution levels can be severe.	Quantifying environmental outcomes and impact of AI Complex value case and well-defined value logic

Research Question 5 Summary: Framework

Figure 6 below, depicts a developing framework (point 5), adding a final risk, AI adoption risk. This identifies the negative environmental effects of AI adoption to address manufacturing greenhouse gas emissions.

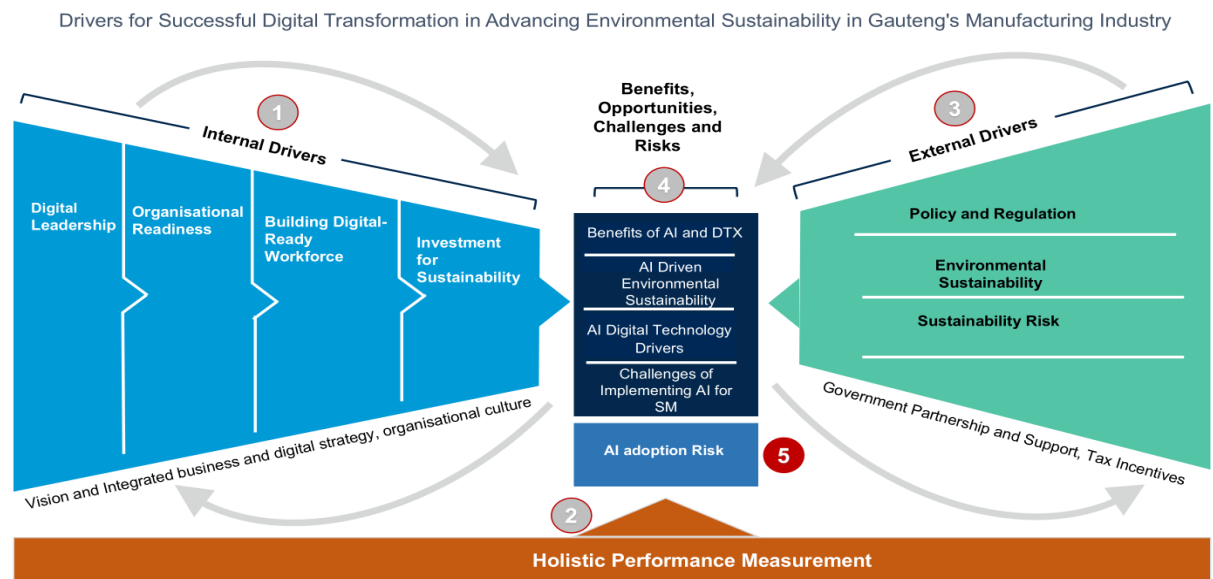


Figure 6: Research Question 5 Summary Framework

Source: Created by Author

Environmental trade-offs: This risk acknowledges the potential for AI-driven technologies to increase energy consumption and generate electronic waste, which could negatively impact the environment.

By proactively addressing these risks in questions 4 and 5, manufacturers can harness AI's full potential to drive significant reductions in greenhouse gas emissions while ensuring the long-term sustainability of their operations.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 INTRODUCTION

The concern for environmental sustainability and the huge potential of AI powered by digital transformation curiosity was behind this study.

This chapter will conclude the research by summarising the key research findings in relation to the research aims and questions. Additionally, will demonstrate the value and contribution to theory and practice. Finally, this chapter will conclude by reviewing the study limitations and proposing future research opportunities and directions.

To answer the research question; to explore key drivers of digital transformation to advance manufacturing sector environmental sustainability, a holistic approach must be undertaken, including barriers, challenges, opportunities and risks.

7.2 RESEARCH FINDINGS

DT has undoubtedly revolutionised how businesses operate, resulting in unprecedented progress in promoting sustainability (Holmstrom, 2022). Furthermore, AI technology is a key driver of DTx for today's organisations. This is due to several factors: first, decision-making power combined with large, big data analytics (Holmstrom, 2022); second, cognitive abilities resembling those of humans (Huang & Rust, 2018). The manufacturing industry resources, and intricate production processes drive significant energy consumption. Consequently, it presents unique environmental sustainability challenges (Kraus et al., 2021). To address this challenge, DTx is proposed as a transformative solution to revolutionise capital-intensive manufacturing assets to advance environmental sustainability (Junior et al., 2018; Dubey et al., 2019; Li et al., 2020; Ardito et al., 2021).

Guandalini (2022) identified a critical gap in integrating environmental sustainability considerations within DTx. Nevertheless, without a clear understanding of the

relationship between these concepts, businesses, organisations, and policymakers may struggle to make informed decisions regarding DTx investments. Consequently, this lack of clarity could lead to missed opportunities to leverage technology for sustainability goals or unintended negative environmental consequences.

Despite the promise of DTx for a sustainable future and enterprise long-term benefits, a significant knowledge gap exists regarding the drivers of success for effective implementation and adoption of AI-driven environmental sustainability solutions in the manufacturing sector, particularly in the context of Gauteng, South Africa. Building on the calls for future research by Rusch et al. (2023) and Schöggli et al. (2023) which proposed future research to explore the underutilised potential of AI and further detail drivers and barriers of DTx implementation for achieving environmental sustainability in different contexts. In addition, building on the drivers and barriers study by Veile et al. (2020), this study aimed to investigate how AI can be leveraged to support environmental sustainability in the Gauteng manufacturing sector. Specifically, to explore organisational key drivers of success crucial to facilitate the adoption of AI-driven sustainability solutions to reduce GHG emissions.

Yadav et al. (2020), highlighted that there is a significant gap in sustainability practices in developing countries. Therefore, this could lead to substantial financial consequences and boycotts from increasingly environmentally conscious consumers.

This research is crucial for addressing the current shortcomings in meeting the needs of manufacturing industries in the digital era, where digital transformation and AI are essential for achieving environmental sustainability goals.

By exploring this knowledge gap, this study can contribute to the development of effective strategies for promoting environmental sustainability practices and reducing the ecological footprint of the manufacturing sector in South Africa.

This study aimed to address a significant knowledge gap identified by Schöggli et al. (2023) by exploring the untapped potential of AI in the manufacturing industry. Specifically, this exploratory study aimed to explore the key success drivers of digital transformation in advancing sustainability practices for the manufacturing sector in Gauteng, with a particular focus on AI technology adoption to reduce greenhouse gas emissions. This qualitative research study answered the overall research

question through five sub-questions and the findings are presented here and summarised in Appendix 6.

To answer this research question, this study uncovered eight key drivers for the successful integration of AI technologies for sustainability, defined along both internal and external drivers. **Firstly, internal drivers:** (1) digital leadership, (2) organisational readiness, (3) building a digital-ready workforce, (4) sustainable investment drivers, (5) holistic performance measurement. **Secondly, external drivers,** (6) policy and regulation, (7) environmental sustainability, (8) AI-driven sustainable manufacturing.

Thirdly, benefits, opportunities, challenges and risks: (9) sustainability risk, (10) AI technology drivers, (11) benefits of DTx for environmental sustainability, (12) challenges for implementing AI for sustainable manufacturing and finally, (13) risk of AI technology adoption.

The study found AI adoption has the potential to advance environmental sustainability practices within the Gauteng manufacturing sector. The study provides empirical evidence supporting the previous assertion that AI has underutilised potential. However, the results indicate that AI adoption by manufacturers is still in a nascent stage, with numerous use cases underway. In terms of environmental sustainability, the study found that the benefits are primarily both direct and indirect. For instance, the AI integration by manufacturers is targeted primarily to efficiency gains, energy consumption optimisation, and predictive maintenance resulting in greenhouse reduction and less wastage.

In addition, the results show a consensus that AI has the potential to advance sustainability practices in the manufacturing sector. This adds to previous research conclusions by Schöggli et al. (2023) and Rusch et al. (2023) that improved efficiency and energy demand optimisation have resulted in a significant decline in GHG emissions.

Moreover, findings confirmed that for a successful AI-driven DTx to advance manufacturing environmental sustainability practices, there are significant hurdles to overcome and associated risks to be mitigated, outlined below per research question (RQ) and theme:

Research Question 1

Theme 1: Digital Leadership Driver

While the study found that top leadership alignment and support secured, however, it is noteworthy that securing consistent alignment and conviction, even for capable leaders, remains a challenge. As Holmstrom (2022) noted, AI-driven transformation differs significantly from other DT integrations; this finding supports Horváth and Szabó (2019), that leadership will navigate disruptive shifts. In addition, this study's results revealed that senior leaders play a pivotal role in fostering enterprise-wide innovation by actively championing DT initiatives such as AI at lower levels. Furthermore, the motivation and commitment not only drive cultural shifts but also empower the organisation to embrace innovative practices, creating a more dynamic and responsive organisation. This is consistent with conclusions by Horváth and Szabó (2019) that transforming manufacturers will likely navigate potentially disruptive shifts in leadership roles.

In conclusion, the study provides valuable insights into the challenges and strategies associated with transforming as a digital leader within the manufacturing sector. The findings highlight the critical importance of leadership alignment, support and conviction. Additionally, leadership commitment and conviction for driving AI integration, personal leadership motivation for sustainability (Eide et al., 2020), environmental leadership for GHG emissions ambition (Aftab, 2022), leading organisational cultural shift (Horváth and Szabó, 2019) for successful DTx to advance environmental sustainability. By highlighting the critical role of strong leadership in setting a clear vision and targets, defining an integrated strategy, and driving enterprise-wide innovation to advance sustainability practices to achieve GHG emissions targets.

The study supports existing literature. Aftab et al. (2022) highlight that top management commitment to environmental leadership drives innovation to reduce GHG emissions, achieve low-carbon development and advance sustainable practices.

The research contributes to the existing body of knowledge by presenting empirical data on the key drivers and leadership challenges for integrating environmental sustainability and DTx, especially AI adoption in the context of the manufacturing

sector. This research offers valuable insights for manufacturers seeking to leverage DTx and AI adoption to achieve environmental sustainability targets.

Theme 2: Organisational Readiness Driver

While effective change management is a significant driver for the successful integration of AI technology, the results indicate that change management and communication are often overlooked for digital sustainability initiatives. In addition, results show that human aspects are often overlooked. Furthermore, the results noted that beyond effective change management, employee coaching is a necessity. For change management, the results are in contrast to previous studies by Ching et al. (2022), who argued that effectively leveraging DTx, particularly AI, for environmental sustainability necessitates a radical transformation of workforce skillsets, surpassing traditional professional (Nguyen et al., 2022; Nimawat & Gidwani, 2022). Moreover, as Holmstrom (2022) noted, DTx goes beyond the implementation of DT and implies deeper enterprise-wide change. In addition, organisations must be aware of DTx risks and challenges associated with the mobilisation of AI technologies for new ends for which success rates are low. Furthermore, the finding contradicts Holopainen et al. (2022), that organisational factors and embracing the culture of change are essential for realising the benefits of AI and DTx technology implementation.

In conclusion, the study provides valuable insights into the challenges and strategies associated with organisational readiness for AI integration within the manufacturing sector. The findings challenge the existing approaches to change management for integrated environmental sustainability and AI integration. Building on the previous finding, the research introduces another challenge; blue-white-collar employee coaching is often overlooked.

The theme of organisational readiness findings contributes to the existing body of knowledge by offering empirical evidence of the challenges and strategies associated with organisational readiness. Findings highlight contradictions with existing literature, employee cultural shifts, change management, and lower-level coaching.

Theme 3: Building Digital-ready Workforce Driver

The study results indicate there is a significant lack of digital talent, especially data science and sustainability IT experts. Johnson et al. (2021) highlight that companies may struggle to realise the full potential of AI technology advances due to skill shortages. Veile et al. 2018 highlight the opposing view that there is no evidence that barriers such as lack of expertise significantly hinder organisational readiness for the integration of DTs.

Furthermore, findings show that the shortage of individuals with skill and expertise is exacerbated by the slow and long development cycle required to cultivate the necessary skills. Mariappanadar et al. (2022) asserted effective HRM can go beyond CSR and offer long-term economic success in the digital era. To address the issues, the study results specify manufacturers adopted short and long-term strategies to build organisations' digital capabilities. The skills gap and long development cycle can slow the pace of AI adoption and innovation and limit the potential of achieving GHG emissions.

Finally, theme results noted that while manufacturers are investing in training and development, funding allocation challenges may hamper the efforts to create capacity to adopt AI for reducing GHG emissions.

The findings support Ustundag et al.'s (2018) conclusions that it is crucial to prioritise talent development by identifying valuable skills for now and the future. However, the results raise interesting dissonance and contradict existing literature.

In conclusion, the results from the theme of building a digital-ready workforce key driver provide valuable insights into the challenges and approaches associated with building digital capabilities within the manufacturing sector. In addition, the theme makes a significant contribution by providing empirical evidence to support claims of the lack of digital skills and expertise. In addition, the lack of environmental sustainability- IT skills and expertise to translate sustainability into technology solutions was highlighted as a challenge. The findings are inconsistent with Veile et al. (2018), who concluded without evidence that the lack of skills and expertise is not a barrier to organisation AI readiness for sustainability.

The theme contributes to the existing body of knowledge by offering empirical data, contradictions and challenges associated with building digital capabilities for integrated environmental sustainability and DTx. Furthermore, it highlights the importance of addressing the digital talent shortage through targeted training and development, while recognising the potential limitations and challenges involved.

Theme 4: Sustainable DTx Investment Driver

The theme results show that the AI technology integration and DTx upfront costs often exceed the immediate benefits sought by manufacturers. Moreover, an additional investment is required to upgrade outdated infrastructure or modernise the manufacturer's operational technology for DTx readiness. The results cited higher than expected capital outlay is due to the low digital maturity level of the manufacturing technology. It has been noted in this study that the manufacturing sector generally lags in technology adoption due to initial investment concerns versus immediate expected returns. This aligns with Brock and Wangheim (2019) assertions that manufacturers must evaluate the compatibility of legacy operational systems. Malek and Desai (2019) raised a significant challenge facing the manufacturing sector in emerging economies, limited financial resources and technological capabilities for advancing sustainability.

Finally, the theme results show that consequently, manufacturers may prioritise short-term financial objectives over long-term environmental goals. As highlighted by Li et al. (2018) it takes time to translate sustainability efforts into financial benefits and operational efficiencies. Ukko et al. (2019) suggest that a lag in achieving financial benefits from sustainability initiatives may explain why previous studies found a negative correlation between sustainability and financial performance.

This theme, sustainable DTx investment drivers, makes several contributions to this study. Firstly, the results challenge the assumption that adequate financial resources are sufficient for advancing sustainable practices. This contradicts the findings of Mangla et al. (2018), who argued that transformation to sustainable manufacturing, adequate financial resources and investments in essential, without articulating adequate resources. Secondly, building on the contradiction above, the theme results introduce additional investment requirements needed to modernise

manufacturers' existing operational infrastructure. Thirdly, the theme provides empirical evidence to support claims that emerging technologies are challenged with limited financial resources and technological capabilities.

In conclusion, the study provides valuable insights into the challenges faced by the manufacturing sector. The findings highlight that the low digital maturity makes the investment required to drive DTx a financial burden for the manufacturers. The study contributes to the existing body of knowledge by providing empirical evidence on the DTx and AI integration investment challenges in the context of the manufacturing sector for meeting GHG emissions ambitions.

Research Question 2

Theme 5: Holistic Performance Measurement

The results demonstrate that holistic performance management is crucial for assessing the full impact of DTx. In addition, the results indicate that the majority of manufacturers have set 2030 ambition of 30% GHG emissions targets, aligned to the Paris Agreement (Wang et al. 2019). Research revealed that the manufacturing sector has adopted key performance indicators (KPI) as a framework to measure GHG emissions performance.

The framework adopted enables integrated reporting required to comply with listing requirements. Moreover, the results show that manufacturers recognise the need to balance economic growth with sustainability goals. This contradicts research studies that careful planning and execution of initiatives align with overall business objectives (Esfahbodi et al., 2017; Tseng et al., 2020; Poursoltan et al., 2021; Tseng et al., 2022),

Furthermore, results confirmed that manufacturers' measurements and performance include tracking the effectiveness of AI integration. These findings are consistent with the literature and support the study by Ukko et al. (2019), which concluded that a holistic approach is essential to measure the impact of sustainability initiatives. This entails quantifying environmental benefits like GHG emissions reduction, energy conservation, and waste minimisation.

This theme, holistic performance measurement, makes several contributions to this study. Firstly, it provides empirical evidence by confirming that the manufacturing sector has set 2030 ambitions to contribute to 2030 SDG's. Secondly, environmental monitoring and KPIs measurement are adopted to track the performance against the target. Also, that the measurements encompass financial, operational and environmental through integrated reporting. Thirdly, empirical evidence on the need to balance economic growth and environmental GHG emissions targets. Fourthly, challenges and contradicts that advancing environmental sustainability practices may not yield financial benefits.

In conclusion, the theme of holistic performance measurement study provides valuable insights and empirical evidence in the context of AI adoption in the manufacturing sector. Overall, the study supports the existing literature while also contradicting several studies that financial objectives may not be realised and initiatives align with overall business objectives (Esfahbodi et al., 2017; Tseng et al., 2020; Poursoltan et al., 2021; Tseng et al., 2022).

Research Question 3

Theme 6: Policy and Regulation

The results indicate that the lack of incentives to fund the manufacturing sectors' DTx for sustainability is a significant challenge. Furthermore, the findings show that due to the lack of incentives, manufacturers tend to prioritise short-term financial objectives. Moreover, the results indicate that there is a notable disconnect between the government and the manufacturing industry. Furthermore, the results show that the competitive landscape is the primary driver of DTx in the manufacturing sector. The results contradict the study by Anzolin and Lebdioui (2021), who argued that industrial policy is essential for promoting sustainability initiatives; the effectiveness of green industrial policy in promoting sustainable development (Wang et al., 2024).

While the results support the existing theory (Harvath & Szabo, 2019), the driving force behind DTx is growing competition, increased innovation capacity, customer expectations, sustainability, and business model innovation (de Sousa Jabbour et al., 2018b). However, the theme results contradict findings by Chiarini (2021),

highlighting that government intervention through policies may incentivise increased investment in advanced cybertechnologies for manufacturers.

The existing literature on DT has consistently highlighted that government regulations, specifically that provide assistance and incentives (Chiarini, 2021), for shaping production technologies (DeStafeno et al., 2024), play a significant role in stimulating the adoption (Lutfi, Alsyouf, Almaiah, Alrawad, Abdo, Al-Khasawneh, ... & Saad, 2022).

This theme, policy and regulation drivers, makes several contributions to this study, firstly, it makes a key finding that there is a lack of government incentives for local manufacturers to invest in sustainable practices by adopting AI and DTx for meeting sustainability and GHG emissions. Secondly, there is a lack of collaborative strategic relationships between the government and the manufacturing industry. This disconnect may explain the lack of understanding of the industry's needs and investment. Participants highlighted that government environmental targets lack deep input and a deep understanding of the manufacturing industry. Thirdly, the theme results show contradictions with existing studies, industrial policy to support manufacturers (Anzolin & Lebdioui, 2021); incentives to fund investment (Chiarini, 2021; DeStafano, 2024).

This study provides valuable insights and a more nuanced understanding of the challenges and drivers of DTx in the manufacturing sector. In particular, the results emphasise the role of government incentives and the disconnect between the industry and government. By contradicting existing literature (Chiarini, 2021; DeStafano et al., 2024), the study highlights inconsistencies in government policies. This study contributes further evidence to the literature on the effects of tax incentives on investment. Furthermore, it offers valuable recommendations for policymakers and industry leaders.

Theme 7: Environmental Sustainability

The results indicate that manufacturers require a license to operate, which mandates compliance with environmental regulations and minimum standards. Additionally, findings show that comprehensive emissions monitoring is essential to guide the

effective implementation of environmental sustainability initiatives. Findings confirmed that the manufacturer's GHG emissions are primarily carbon-related emissions, nitrogen oxide (NO_x), and Sulphur Dioxide (SO_x). Furthermore, the results demonstrated that AI technology has the potential to advance environmental sustainability practices. This finding validates a claim from Schögggl et al. (2023), that AI possesses significant potential for driving CE and sustainability management. Furthermore, the findings align with the study by Ezici et al. (2020), that to assess the environmental impact, a comprehensive approach is essential.

The theme, environmental sustainability drivers, contributes to this study; firstly, it provides empirical evidence of the regulatory requirements and license to operate which mandates minimum emissions standards. In addition, manufacturers have established comprehensive environmental monitoring to guide effective emissions reduction programs. Secondly, they provided empirical evidence of Gauteng's manufacturers' GHG emissions mix. Thirdly, empirical evidence that manufacturers use AI technologies and results demonstrated it has an impact on reducing GHG emissions.

In conclusion, the theme findings provide valuable insights and provide empirical evidence, comprehensive emissions monitoring, and the potential of AI for manufacturing sustainability. Overall, the study supports and adds to the existing literature by Settembre-Blundo et al. (2021) and Schögggl et al. (2023) that AI possesses significant potential for sustainability management.

Theme 8: Sustainable Manufacturing: AI-Driven Environmental Sustainability

The results show that the manufacturing industry is at an early stage of integrating AI technologies for advancing environmental sustainability. Additionally, findings indicate that the low maturity and slow progress are exacerbated by historical investment with no return on investment or business value. Furthermore, the findings revealed that there is an urgent need for a formal, integrated business and digital strategy along with strong senior management support. Moreover, the results indicate that manufacturers are running siloed experimental projects to improve sustainability. Finally, results recommend that scaling initial AI success requires a strategic framework that drives enterprise-wide adoption.

The theme sustainable manufacturing: AI-driven environmental sustainability driver, makes several contributions. The findings align with several works, environmental sustainability strategies, processes, measures, and initiatives (Isensee et al., 2020). Ukko et al. (2019) extend that for full potential manufacturers must follow a strategic approach and contradict works that investment in sustainability may not result in financial gains (Esfahbodi et al. 2017; Tseng et al. 2020; Poursoltan et al. 2021; Tseng et al. 2022).

In conclusion, the study provides valuable insights and empirical evidence of the manufacturer's low digital maturity. Overall, the study supports and adds to the existing literature.

Theme 9: Sustainability Risk Drivers

The results indicate that the integration of AI introduces several risks to the manufacturing industry. In particular, the cost burden for a transition to a low-emissions environment. Moreover, despite the potential benefits of AI, the findings show that there is an emerging threat of cybersecurity associated with DTx and AI integration. Furthermore, the risk of the introduction of the carbon tax. Finally, results showed that the social impact of AI adoption is often overlooked.

The theme results, sustainability risk drivers, make several contributions to this study. Main risk (1) highlights the potential carbon tax introduction and provides empirical evidence to support claims of policy uncertainty and pressure on manufacturers. Jia and Lin (2020) argued that carbon tax will promote a shift towards sustainable practices; (2) cost burden to transition to a low-emissions world, and (3) increased cybersecurity risk due to DTx and AI technology integration. This is consistent with prior studies by Saeed et al. (2023), that cybersecurity is a critical part of DTx and AI technology integration. Finally, the theme findings provide empirical evidence to support the increased concern of AI's social implications.

In conclusion, the study provides valuable insights and provides empirical evidence of potential risks associated with AI-powered DTx. The theme findings support the existing literature. Saeed et al. (2023) cybersecurity and DTx; In contrast, a study by

Camacho (2024) concluded that AI has a dual role as both an enabler of DTx AI-powered and a powerful cyber defence system.

Research Question 4

Theme 10: Digital Sustainability: AI Digital Technologies Drivers

Despite the majority of the participants confirming that AI adoption and DTx are at an early stage for manufacturing, aligned with a study by de Sousa Jabbour et al. (2018a) the manufacturing sector is lagging behind. The results show that AI is a key enabler of sustainability strategies in the manufacturing sector. This finding answers a future research call by Schöggel et al. (2023) that AI has significant untapped potential for driving environmental sustainability. Furthermore, findings indicate that the emergence of advanced measurement technologies, especially AI-powered, is a key driver behind the adoption of digital technologies in manufacturing. Finally, the results show that manufacturers derive insights by leveraging data through big data analytics.

The theme findings make several contributions to this study. Firstly, AI is a key manufacturing sector enabler for advancing environmental sustainability practices aimed at reducing GHG emissions. This supports conclusions from a study by Ma et al. (2023), which stressed that advanced technologies improve efficiency and sustainability in manufacturing.

This theme makes several major contributions. First, it answers the previous research gap, that AI has untapped potential to address manufacturing environmental sustainability. Second, results provide empirical evidence that the manufacturing sector uses AI and other DT technologies to transform manufacturing and advance environmental sustainability. Third, the results provide evidence to support claims that AI and DTx have the potential to promote sustainable manufacturing.

In conclusion, this finding provides insights into data-driven manufacturing and sustainability. Consistent with previous studies, it supports existing literature integration of digital technologies power sustainable, intelligent manufacturing (Ma et al., 2020); and existing literature that AI has significant potential to address

environmental sustainability (Schöggl et al., 2023). Finally, while the study's finding extends the existing literature, also challenges an argument made by de Sousa Jabbour et al. (2018b) that DTx and sustainability practices were conceived to address different purposes.

Theme 11: Benefits of DTx for Environmental Sustainability

The previous theme results showed that the adoption of AI is a key driver for achieving environmental sustainability within manufacturing. Truong (2022) listed the following indirect effects of DTx and AI integration, supported by Dauvergne (2022): (1) forecasting waste generation, (2) unveiling resource waste, (3) designing more efficient waste management models, (4) reduction of greenhouse gas emissions. The participants emphasised the use case as practical applications in manufacturing, including improving operational efficiency, optimising energy consumption, predictive maintenance and improving throughput. Dauvergne's (2022) study on AI revealed that increased throughput perpetuates the rebound effect. Ma et al. (2022) support and challenge that green technologies do not automatically reduce energy consumption; therefore pollution will remain high.

This theme's results raise a challenge: the need to balance environmental sustainability with profitability. Moreover, the results indicate that optimising value is complex. Building on this finding, the results show that not all opportunities will yield the desired outcomes. Finally, the results indicate a further complication in aligning multiple stakeholders on the overall benefits of sustainability initiatives.

This theme, the benefits of DTx for environmental sustainability drivers, makes several significant contributions to this study. Firstly, the results provide empirical evidence of the AI practical applications, and the outcomes claims made by manufacturers, direct and indirect benefits. While positive results, the challenges of the findings by existing literature are notable. Dauvergne (2022) increased throughput perpetuates the rebound effect. Ma et al. (2022) deploying green technologies does not equate to reduced energy consumption or reduced pollution levels.

Secondly, results provide empirical evidence on the difficulty quantifying the benefits of integration of DT, AI and environmental sustainability. Moreover, it supports growing claims that the difficulty making trade-offs between environmental sustainability and short-term financial objectives for manufacturers in emerging economies. Thirdly, empirical evidence is that not all opportunities will deliver desired outcomes, supporting previous claims about complex value cases and difficulty quantifying. Finally, multiple and complex stakeholder alignment with the overall business objectives and integrated sustainability and business benefits.

In conclusion, this theme's results provide practical insights and guidance for manufacturers; the results show how AI and analytics can be harnessed for sustainability while striving for profitability. The findings support and extend existing literature through several contributions outlined above.

Theme 12: Challenges in Implementing AI for Sustainable Manufacturing

The results show that manufacturers still have outdated process equipment that lacks monitoring and data transmission capabilities, referred to as stranded assets. Moreover, the findings show that there are significant upfront costs required for complex IT infrastructure, like cloud computing and digital technologies to enable AI adoption. In addition, the results indicate that the pressure to adopt AI technology can lead to decisions that may not align with the company's current capabilities. Furthermore, findings from the results show that while AI technology integration has the potential to generate sustainable value, an effective systems integration is needed.

Nevertheless, the results indicate that change management must not be underestimated. AI technologies adoption to advance sustainable practices often involves significant changes to manufacturers. Additionally, changes can be met with resistance from employees. The findings contribute to a study by Dabic et al. (2023) that without the transformation of organisational culture, the integration of AI technologies may be hindered.

Finally, this study found that a clear data strategy is a key driver for the successful integration of AI and digital technologies. The study finding aligns with the literature

by Schöggl et al. (2023) which identified big data analytics, AI, IoT, and blockchain as the primary DTx technologies. Similarly, Ukko et al. (2019) emphasised it is essential to understand how data analytics can be leveraged to improve sustainability.

This theme, challenges in implementing AI for sustainable manufacturing, makes several contributions to this study. Firstly, it identifies outdated manufacturing operational technologies and equipment that lack monitoring and data signalling capabilities. Secondly, the results provide empirical evidence for upfront costs for technology adoption supporting claims of the high investment required to integrate AI technologies for existing traditional manufacturers. Thirdly, results show evidence that effective system integration is essential to get the full potential of AI adoption and DTx to reduce GHG emissions. Finally, results provide evidence that a clear data strategy supported by quality data assurance is essential for the integration of AI and DTx to transform into sustainable manufacturing.

In conclusion, these findings provide practical insights and empirical evidence on the challenges faced by manufacturers when adopting AI-powered DTx. The findings underscore the necessity for a nuanced understanding of AI's environmental impact and the study supports the existing literature.

Research Question 5

Theme 13: Digital Sustainability: Risk of AI Technology Adoption

While AI has the potential to advance environmental sustainability practices, the integration and adoption require environmental impact careful consideration. The results show that AI technology is the major contributor, potentially the only source directly impacting the environment. Furthermore, the results indicate that manufacturers have difficulty in quantifying the indirect environmental impacts of AI adoption. Finally, the results show that the manufacturing industry tends to neglect the environmental sustainability impact in the sustainability digital initiatives value case.

The theme finding contradicts the literature. Truong's (2022) study concluded, confirmed by Chiarini's (2021) empirical study, that DTs have direct negative

environmental effects as (1) the production of digital infrastructure, (2) the energy consumption of digital infrastructure, (3) mining of the hardware to be used as digital infrastructure, (4) collection, recycling, and disposal of digital assets physical infrastructure, (5) greenhouse emissions for the generation of power used by DTx.

Dauvergne (2022) states that AI integration leads to rebound effects and, consequently, environmental degradation.

The theme results make contributions. Manufacturers view that unawareness of the negative effects of AI and other DTs on the environmental impact. This provides empirical evidence of lack of awareness and understanding. Moreover, manufacturers find it difficult to quantify the environmental impact in the value case.

In conclusion, the findings provide practical insights and emphasise the need for a deeper understanding of AI environmental implications. The manufacturers must adopt a comprehensive value because that caters for environmental impact. Dauvergne (2022) asserted responsible reinvestment strategies to address the negative environmental impact of technological progress in the industry.

7.4 PROPOSED FRAMEWORK

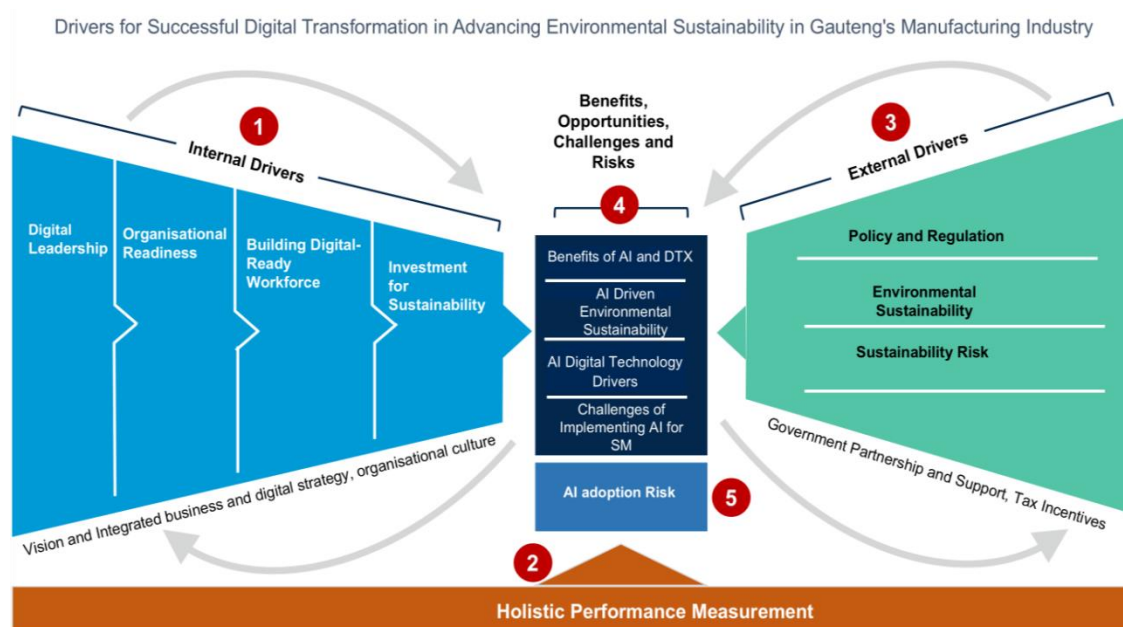


Figure 7: Proposed Framework

Source: Created by Author

The above comprehensive framework developed was based on empirical analysis. It offers a nuanced understanding of the key drivers behind successful digital transformation in Gauteng's manufacturing industry, particularly in the context of environmental sustainability. It highlights the interdependence of internal and external forces, as well as the potential benefits, opportunities, risks, and challenges associated with the integration of AI and DTx in manufacturing.

Key Themes:

Table 16: Internal drivers

Theme	Description
Leadership and Vision	Strong leadership, a clear vision, and integrated business and digital strategy are essential for guiding digital transformation and integrating environmental sustainability goals.
Organisational readiness	A committed leadership to lead effective change management and help organisations navigate disruptive change is essential. Ensure organisational readiness and adjustments to support technology adoption. Additionally, employee supportive culture, is crucial for successful AI and digital technology adoption.
Digital-ready workforce	Investing in a skilled workforce with digital expertise is vital for the effective implementation and utilisation of digital technologies.
Investment and funding	Significant financial investment is required to acquire and implement digital technologies and sustainable practices.

Holistic performance measurement	A comprehensive approach that considers both business and environmental goals is necessary for successful outcomes.
----------------------------------	---

Table 17: External drivers

Theme	Description
Policy and regulation	A supportive regulatory environment, coupled with government partnerships, can significantly accelerate digital transformation and sustainability initiatives.
Environmental Sustainability	Regulatory requirements, manufacturers' mandates and compliance requirements. Risk associated with non-compliance.
Sustainability Risk	The cost required to successfully integrate AI technologies and other required technology infrastructure such as cloud computing, etc. Moreover, the emerging cybersecurity threat requires a robust risk and governance framework to guide AI integration.

Table 18: Benefits, Opportunities, Challenges and Risk

Theme	Description
Benefits of AI and DTx	Benefits of AI and DTx for sustainability
AI-driven sustainability	AI potential to advance manufacturers' sustainability.
AI-driven technology	AI opportunities, industry digital maturity, that is AI adoption, including associated challenges.

Challenges of implementing AI for SM	Challenges manufacturers face when adopting AI
AI technology adoption risk	Direct or indirect negative impact of AI and other digital technologies

Conclusion:

This model underscores the complex nature of digital transformation and its potential to drive environmental sustainability in Gauteng's manufacturing industry. By understanding and addressing the key themes and insights presented, organisations can position themselves for success in this transformative journey

7.3 PRACTICAL IMPLICATIONS FOR BUSINESS

Firstly, and most importantly, this study confirmed that the adoption of AI technology for environmental sustainability has the potential to advance manufacturing sustainable practices. For manufacturers considering the adoption of AI for GHG emission reduction, managers need to be aware of the key internal organisational drivers and be willing to embark on multiple, continuous and simultaneous organisation changes along the journey. The leadership alignment and conviction emerged from the interview participants stressed the importance of leadership, to drive enterprise-wide transformation. The data also revealed that organisations will navigate disruptive leadership shifts. Managers to invest in leadership development programs to prepare leaders to facilitate disruptive change and drive effective change management. Training to include leaders' digital literacy, innovation through managing AI and DT technologies, and soft skills such as facilitating mindset and behaviour shift.

Managers need to be aware that committed and strong leadership play a pivotal role in leading enterprise-wide innovation and change. It is recommended that leaders recognise the leadership shifts required to lead and successfully navigate the

organisation through change. The following steps are recommended to ensure successful AI integration and DTX: Firstly, strong leadership must define a clear vision for driving AI adoption and driving in alignment with sustainability goals. Secondly, define a comprehensive strategy, which entails integrating business, sustainability goals, and digital supported by a clear data strategy. Thirdly, initiatives should be prioritised and sufficient funding to support AI integration and manufacturing infrastructure modernisation should be allocated.

Secondly, managers must assess the readiness of the organisation before the start of the transformation. Managers must evaluate the current organisation's AI readiness and identify areas of improvement. Implement effective change management and interventions to support employees, including coaching interventions to mitigate resistance to change. In this regard, Holmstrom (2022) makes us aware that AI has human-like capabilities, including learning, perceiving, knowing, acting, reasoning and communicating. Booyse and Scheepers (2023) highlight the importance of understanding SA regulatory requirements, specifically for cases where AI may lead to job losses.

Thirdly, managers should adjust their Human Resource Management strategies for building a digital-ready workforce. Specifically, managers must identify the skills and expertise needed to deliver the vision and integrated strategy. Collaborate within the industry to collaborate with the government for tax incentives and university to create a curriculum to address current and future skills requirements. Consider setting up an internal or industry-level digital academy to provide the skills and expertise required by the industry. Fourthly, managers must develop an implementation roadmap from the integrated strategy and vision, determine funding needs and allocate resources for supporting investment in AI and DTx to address manufacturing's low digital maturity and modernise the outdated manufacturing equipment and technology.

Finally, managers must be aware of the need to implement a comprehensive measurement system to measure the impact of AI and DTx on manufacturers. First, by establishing key performance indicators to measure the environmental impact of AI initiatives. Second, review and adjust existing value case that quantifies the economic, environmental, direct and indirect benefits of AI adoption for environmental sustainability.

Managers need to engage and re-establish partnerships with the government at the company level and industry level. They should prioritise requests for government support in the form of tax incentives and subsidies for investing in sustainable manufacturing.

Finally, managers need to be aware of the challenges and risks associated with AI technologies. Managers develop a robust and comprehensive risk framework to mitigate potential risks associated with sustainability, such as carbon tax introduction and compliance, and AI technology adoption, such as cybersecurity risks and the negative environmental impact of AI and DT to manufacturing.

7.4 PRACTICAL IMPLICATIONS FOR POLICY AND REGULATION

Previous studies revealed that government support through incentives and tax breaks can promote the manufacturing industry. Additionally, Udeagha and Muchapondwa (2023) posit that policy uncertainty is a significant barrier. Bag et al. (2021b) emphasise that policy reforms are essential to foster a shift towards achieving broader sustainability goals.

For the manufacturing industry to promote sustainable practices and reduce environmental impact through AI and DTx, it is recommended that the government implement the following interventions: First, establish a strategic partnership with policymakers, businesses, industry, and academia. Secondly, develop targeted policies and thirdly, promote AI adoption and DTx. Dubey et al. (2020) highlight that in today's digital world, government agencies heavily influence businesses by setting the national digital strategy that companies must follow. Below are recommended steps to improve collaboration and create support for the manufacturing sector:

First step: Strategic Partnership

Industry to collaborate and engage government with the main objective of forming a public and private partnership designed to foster collaboration between various stakeholders, including academic institutions, industry experts, and policymakers, to

gain insight and align on unique challenges and opportunities facing the manufacturing industry.

Second Step: Develop targeted policies

Research and conduct international benchmarks with best practices. Draft targeted consistent regulations supported by clear policies to address manufacturers challenges and leverage opportunities. Translate policies into specific policy incentives designed to promote long-term-investments for sustainability initiatives.

The government, through relevant departments, could design and implement tailored incentives and tax breaks or credits (Table 19) to promote investment in sustainability technologies to reduce manufacturers' environmental impact.

Develop a policy measurement system to measure the effectiveness including quantitative analysis, such as cost-benefit analysis or impact assessments, to strengthen the policy recommendations.

Table 19: Policy – Tax Incentives

Policy	Action
Tax Incentives	• Conduct an international benchmark, successful international models can provide insights (UK, emerging economies China, Italy). • Design specifically tailored tax incentives or credits for investments in sustainable practices enabled through AI and other DT technologies for GHG emissions reduction pollution control equipment (Chiarini, 2021). For example, China established and supported Italian manufacturers.

Government and policymakers should provide financial support through grants and subsidies (Table 20) for projects focused on environmental sustainability. This will

encourage manufacturing to prioritise environmental sustainability goals. Policymakers need to establish clear and supportive regulatory frameworks that promote the adoption of sustainable practices, to ensure alignment with the needs and priorities of the manufacturing industry. DeStefano et al. (2024) study showed that the policy increased investment in IT infrastructure and capital.

Table 20: Policy – Subsidies and Grants

Policy	Action
Subsidies and Grants	Allocate funds to support projects that reduce emissions. Provide matching grants to promote private sector investment in sustainable practices. DeStefano et al. (2024) policy exemplifies how regulations can act as a catalyst for the adoption of sustainability-oriented DTx

Third Step: Promoting Sustainable Manufacturing

SA has established the Department of Communication and Digital Technologies Artificial Intelligence Institute of SA (AIISA) to support AI adoption (Mashishi, 2023). It is recommended that AIISA jointly work with the Department of Trade and Industry with manufacturers to expand the scope of AIISA. Furthermore, establish localised version institutions such as WEF Global Lighthouse to support the local manufacturing community and accelerate the adoption of AI and DT for promoting sustainability

Forming a strategic partnership and integrating the works of the aforementioned departments will lead to comprehensive policy measures grounded in the industry requirements. Government can foster a supportive and favourable environment for manufacturers to invest in sustainable practices and drive innovation. This dual approach will not only contribute significantly to environmental sustainability but will enhance the competitiveness of the manufacturing industry.

7.5 THEORETICAL IMPLICATIONS

Despite the promise of DTx for a sustainable future and enterprise long-term benefits, the literature showed a significant knowledge gap exists regarding the drivers of success for effective implementation and adoption of AI-driven environmental sustainability solutions in the manufacturing sector, particularly in the context of Gauteng, South Africa. Following the recommendation for further study by Schöggl et al. (2023), which proposed future research explore the underutilised potential of AI; and further detail drivers and barriers of DTx implementation (Veile et al., 2020) for achieving environmental sustainability in different contexts.

This study aimed to investigate how AI can be leveraged to support environmental sustainability in the manufacturing sector in Gauteng and what organisational internal and external factors drivers of success are crucial to facilitate the adoption of AI-driven sustainability solutions.

The results showed that AI adoption and DTx has significant potential to advance the manufacturing sector's sustainability practices. The findings provide empirical evidence supporting Schöggl et al. (2023) assertions that underutilised AI has the potential to advance manufacturing sustainable practices. This study contributes to the existing body of knowledge on AI and DTx for environmental sustainability. Given that the current integrated AI and environmental sustainability literature is at nascent stage, this study fills a critical gap by offering practical insights and a framework for implementation. Furthermore, this study contributes to literature by identifying and detailing the key internal and external drivers essential for a successful adoption of AI for advancing sustainability. Guandalini (2022) identified a critical gap in integrating environmental sustainability considerations within digital transformation (DTx). Moreover, stated without a clear understanding of the relationship between these concepts, and various stakeholders such as businesses, government and policymakers may have struggled to make informed decisions regarding DTx investments.

The findings address the gap by providing empirical evidence and practical guidance. The study also confirms that AI and DTx are multifaced phenomena, corroborating with Gaundalini (2022), DTx and sustainability relationship is complex. Through thematic analysis, thirteen key themes were inductively derived from the study and

categorised according to internal or external associated challenges, benefits, opportunities, and risks facing manufacturers. Of these thirteen themes, eight are key drivers, two risks associated, and the remaining, benefits, challenges and opportunities. Appendix 7 contains themes linked to research questions.

The following theoretical implications, derived from the study, present a solid foundation for theory development on effective strategies for AI adoption and environmental sustainability.

Theme 1, **digital leadership** related to leadership support, alignment, and leadership conviction from top management, emerged as a key driver for AI adoption to advance sustainable practices. The study provides new insights into leadership theoretical aspects, indicating that the integration of AI and DTx for sustainability significantly impacts leadership and all spheres of an organisation. This corroborates with Horváth and Szabó (2019) adopting AI, manufacturers will likely navigate potentially disruptive shifts in leadership roles. To navigate the potential leadership disruption, the findings suggest that leadership training and support programs are essential to adapt effectively to AI and DTx impacts.

Theme 2, **organisational readiness** revealed effective change management, employee support and organisational cultural shifts, promoting innovation enterprise-wide as a challenge and a barrier. The participants cited that change management, including lower-level employee coaching, is often overlooked. The study provides new insights into change management theoretical aspects. It indicates ineffective change management in the context of AI integration and tendency to prioritise technology aspects. Data revealed the cultural aspects and change management is overlooked, particularly for lower-level employees. Holmstrom (2022), highlighted for organisations to reap full potential from AI, it is essential to align both technologies and organisation. This alignment necessitates a simultaneous adjustment of organisation resources. Effective change management that includes lower-level employee engagement strategies is needed.

Theme 3, **building a digital-ready workforce**, relates to digital expertise, especially data science and combination of digital and sustainability skills is hindered by shortage and a long development cycle. Lack of skills and expertise may slow the AI and DTx, therefore leading to targets not being met by manufacturers. These theme finding emerged from the study as a significant barrier to AI adoption for

sustainability. The study provides new insights into digital workforce development, indicating that shortage of skilled and experience, like data science, digital sustainability skill to translate sustainability will slow progress to sustainable practices. Holmstrom (2022) AI integration requires skilled resources. It is suggested that a partnerships between industry, government and universities to promote tailored and incentivised programs to support digital skills development. Universities can play a pivotal role and serve as institutions for addressing the skills shortage required for industry to build essential digital capabilities.

Theme 4, **investment for digital sustainability** relates to funding of sustainability initiatives emerged as a significant challenge and a barrier. Manufacturers are prioritising AI adoption investment for financial gains. The study provides new insights into huge upfront investment required for integration. Furthermore, cost pressure often shifts the AI investment towards short-term financial gains. This indicate that leadership theoretical aspects, indicating that the integration of significantly impacts leadership and all spheres of an organisation To address this, it is suggested that a model for integrating sustainability into financial planning and investment strategies must be developed.

Theme 5, **holistic performance measurement** related to how manufacturers evaluate AI and DTx full impact. These include evaluating AI integration effectiveness, scaling initial use case success, manufacturers compliance to integrated financial reporting, with disclosure on environmental targets and performance. This theme emerged as a key driver for the manufacturing sector. Manufacturers should consider a dual approach to address environmental challenges and position the organisation for long-term success. To achieve this, manufacturers require a robust theoretical framework and practical metrics, supported by best practices that can guide organisations' sustainability efforts.

Theme 6, **policy and regulation** as a significant barrier to AI adoption for the manufacturers. Participants raised notable disconnect between government and business, lack of tax incentives and support to manufacturers to promote AI adoption and DTx investment, which leads to a bias towards a short-term focus on financials and potential delays to advance sustainability practices. The study provides new insights into stakeholder management and policy, indicating that for successful AI

adoption, government must work with industry by forming partnerships that will result in favourable regulation backed by support in the form of tax breaks and subsidies.

Participants highlighted the view of sustainability as an unnecessary cost. To address this a healthy partnership between industry and government is essential.

Theme 7: **environmental sustainability** relates to compliance with minimum emissions standards and air quality standards. Manufacturers require a licence to operate which mandates compliance from various government regulatory bodies, such as the DFFE. In addition, the mandate requires comprehensive monitoring, reporting and acting non-compliance. Settembre-Blundo et al. (2021) revealed that risks of non-compliance can have severe consequences such as legal penalties, financial losses, and reputational damage. Proactive compliance strategies that go beyond minimum emission standards should be considered. Furthermore, dialogue between industry and regulatory bodies should be developed that ensure supportive regulations.

Theme 8, **AI driven environmental sustainability** as a significant barrier for AI adoption. Lack of integrated business digital strategy, low digital maturity, significant investment required, and various siloed proof of concepts may hinder advancing sustainability progress. Participants revealed it is crucial to scale initial success to accelerate adoption to the rest of the organisation and to support a systematic approach to implementation. Manufacturers should develop an integrated business and digital strategy that aligns with sustainability goals is required to improve digital maturity.

Theme 9; **sustainability risk**, relates to integrating digital technologies, transition to low emissions, carbon tax, emerging cybersecurity, and social implications. The study provides new insights risk associated with transition and emerging risk. This indicate that policy uncertainty, specifically carbon tax and other major risk cybersecurity are substantial risk facing manufacturing industry. Develop risk assessment frameworks that include cybersecurity and social implications of transition to low carbon world. Manufacturers should adopt proactive risk management strategies in their digital transformation efforts.

Theme 10: **AI and digital technologies driver** as a key enabler of AI adoption.

The study provides new insights into technology readiness for AI integration and Dtx for sustainability. It indicates that for AI integration, adequate financial investment is necessary framework must be expanded to cater for additional investment required for technology readiness. In addition, manufactures assess compatibility of their technology infrastructure and make necessary investment to modernise. Furthermore, cost pressure often shifts the AI investment towards short-term financial gains.

Findings revealed data strategy, including data quality challenges. The existing legacy infrastructure and operational technology have low digital maturity, skills and expertise as barriers for AI adoption. Advanced measurement technologies, unlocking insights through data analytics emerged as a driver for AI adoption. Manufacturers should consider investment to modernise legacy systems and develop data governance.

Theme 11: **benefits of AI and digital tech for sustainability**, AI is a key driver for sustainability. However, it can be a challenge the balancing sustainability targets with short-term profitability. Another barrier is optimising value exacerbated by multiple stakeholders' alignment on shared value. To address these challenges, manufacturers should consider strategies for aligning sustainability targets with financial performance metrics.

Theme 12: **challenges in implementing AI for Sustainable manufacturing**, a significant barrier to AI adoption. Stranded assets relate to outdated and analogue equipment with no signalling capability impact on data availability. Participants highlighted that the lack of data strategy hinders AI integration. Other obstacles are significant upfront costs for the IT infrastructure, ineffective system integration, and pressure to implement, leading to ineffective decisions, and ineffective change management. To address these manufacturers should consider targeted investments in upgrading technology and developing comprehensive change management.

Theme 13: **risk of IT technology adoption**, relates to the risk and negative impact of AI adoption. It has emerged from the findings that AI is a significant and only source of environmental impact. The study provides new insights into negative environmental impact of AI integration indicating that the current business value case

framework gap. The participants data revealed manufacturers find it difficult to quantify and include environmental impact of AI and DT integration into value case. This may suggest manufactures lack of awareness of the environmental impact of their AI and DTx. To address this, it is crucial to develop a value case that entail both direct and indirect benefits including comprehensive risk management framework that includes strategies for mitigating the negative impacts of AI adoption.

Study Contributions

This exploratory qualitative study makes valuable contributions to the field of Digital Transformation, AI, and Environmental Sustainability. Specifically, it identifies the key drivers, challenges, risks and opportunities of AI adoption for environmental GHG emissions. In addition, this study contributes to managerial practical implications, theoretical practical implications, policy and practice implications, and provides recommendations for future research. Moreover, the study introduces a framework based on empirical analysis outlining AI-powered DTx key success drivers for environmental sustainability. This framework can be used as a reference framework to help manufacturers with the conditions to be met for the successful integration of digital technologies for environmental sustainability. The themes contributions outlined above are summarised and consolidated into table 21 below structured per research question.

Table 21: AI and DTx for environmental sustainability theoretical contribution

RESEARCH QUESTIONS	THEMES	THEORETICAL CONTRIBUTIONS
1. What are the key drivers for the successful adoption	Theme 1: Digital Leadership Factors	Study extends: - Leadership and strategy theory - Personal motivation of leadership theory

of DT AI in the Manufacturing sector to achieve the environmental sustainability dimension of greenhouse gas emission reduction?	Theme 2: Organisational Readiness,	Study contradicts literature: - Effective change management - Organisational cultural shift
	Theme 3: Building a Digital-Ready Workforce	Study supports literature: - Highly skilled software engineers for AI technology. - Proactive development of digital skills and expertise
	Theme 4: Sustainable DTx: Investment	Study extends: - Top management's role in allocating funding to support the integration of digital technologies. Contradicts literature: - Sustainable manufacturing needs adequate financial resources and investments. - Siloed financial decision-making approach - Moderating negative effects on financial performance due to temporal lag between the implementation of sustainability initiatives
2. How is success measured for measuring the effect of adopting DT for the environmental sustainability dimension?	Theme 5: Holistic Performance Measurement	Study extends to literature: - Manufacturers to integrate sustainability into their core strategies. - Short-term economic performance over sustainability. - Holistic approach for measuring sustainability impact. - Quantifying environmental outcomes, such as GHG emissions reduction, energy conservation, and waste minimisation.
	Theme 6:	Study extends:

3. What policy initiatives and regulatory frameworks are necessary to promote sustainable development in the South African manufacturing sector?	Policy and Regulation	- Policy tax incentives and government financial support in the form of grants, subsidies could promote investment. - Policy uncertainty as a barrier Contradicts literature: - Government support to promote manufacturing sector investment
	Theme 7: Environmental Sustainability	Study supports literature: - Holistic environmental impact assessment. - Environmental sustainability - License to operate. Challenges to literature: - GHG and Energy consumption reduction
	Theme 8: Sustainable Manufacturing: AI-Driven Environmental Sustainability	Study extends literature: - AI has the potential for driving sustainability management. - Integration of AI for sustainability maturity level Study contradicts literature: - Strategic approach aligned with overall business objectives.
	Theme 9: Sustainability Risk Drivers	Study supports literature: - Technological obsolescence risk - AI and DTx social implications - AI and digital technologies cybersecurity
	Theme 10: Digital Sustainability: AI	Adds to literature: - AI key enabler of environmental sustainability
4. What are the potential environmental		

benefits and challenges, barriers, and constraints faced by manufacturing organisations when implementing DTx for sustainability purposes?	Digital Technologies Drivers,	Support literature: - Digital technologies - AI, cloud, big data analytics, and IoT - Low digital maturity operational technology - Ethical considerations - Continuous improvement of manufacturing sustainability
	Theme 11: Benefits of DTx for Environmental Sustainability,	Study supports literature: - Indirect effects of DTx and AI integration. - DTx and sustainability address different purposes - Complex stakeholder management Study contradict literature: - AI and sustainability for the export market
	Theme 12: Challenges in Implementing AI for Sustainable Manufacturing	Study extends literature: - Outdated operational technology - Barriers of AI technologies integration Support literature: - Big data analytics, AI, IoT, and blockchain are the primary DTx employed in the manufacturing sector. - Data analytics for environmental, social, and economic performance improvement.
5. What are the potential negative effects, direct and indirect, of implementing DT such as AI for	Theme 13: Digital Sustainability: Risk of AI Technology Adoption	Study contradicts literature: - Direct negative impact of AI and DT - Quantifying the impact of AI on sustainability - Direct and indirect effects of AI integration.

environmental sustainability?		
-------------------------------	--	--

7.6 LIMITATIONS TO THE RESEARCH STUDY

This qualitative research delved into the subjective experiences and perspectives of various stakeholders involved in Gauteng's manufacturing industry.

While the study identified key success drivers for successful DTx and AI adoption for reducing GHG emissions, however, it comes with a few limitations, outlined below.

The scope of this exploratory study was limited to the listed Gauteng manufacturing sector only. Therefore, the results may not be generalised to the entire population in Gauteng. Other key sectors, such as mining, energy, construction, agriculture, and transportation were purposefully excluded. While the study attempted to ensure diversity of manufacturers to reflect the industry's composition, due to a small sample size of the JSE-listed manufacturers, the findings might not be generalised to the entire Gauteng manufacturing industry.

For this exploratory study, participants were selected based on a defined criteria and with snowball purposive sampling method adopted. Though data triangulation strategy was adopted to improve the data reliability and validity, the researcher's choices and the participants' referrals and homogeneity can introduce bias into the sample.

The exploratory qualitative research identified key success drivers for digital transformation and AI adoption for sustainability that were not weighted or ranked according to importance.

While the cross-sectional approach adopted for this study offers a snapshot of the phenomena at a specific point, can be limiting for exploratory research.

The participants selected for this study comprised of sustainability experts, manufacturing industry practitioners, digital transformation experts, and

management consultants. While the intention was to include government policy makers, however, time constraints prohibited their involvement.

By acknowledging these limitations, the research leveraged the strengths of a qualitative approach to gain a nuanced understanding of how stakeholders perceive and experience the drivers for successful DTx in achieving environmental sustainability within Gauteng's manufacturing industry.

7.7 SUGGESTIONS FOR FUTURE RESEARCH

Building on the limitations of the exploratory study on AI adoption in the Gauteng manufacturing sector, potential future research directions:

Expand the research scope and conduct a similar study for the entire manufacturing sector to assess the generalisability of the findings beyond the Gauteng region. Explore AI adoption and DTx in other heavy resource sectors such as Energy, Mining and Agriculture to identify common key success drivers.

A larger sample size, particularly one that is more diverse and representative of the population, can help mitigate the impact of bias and improve the generalisability of the findings.

Conduct quantitative analysis to rank and prioritise the key drivers for AI adoption for advancing environmental sustainability to provide a clear focus for future efforts.

Conduct mixed method research methods to measure the impact of key success drivers identified on AI adoption and environmental sustainability objectives. Conduct a case study method to do in-depth studies of successful AI implementations in the manufacturing sector to validate strategies, challenges, and lessons learned.

Conduct a longitudinal study to assess the long-term impact of AI-driven environmental sustainability initiatives would provide a clear pathway for subsequent studies.

Analyse the role of government policies and regulations contributing to the manufacturing industry's environmental sustainability, facilitating or impeding AI adoption.

Compare the findings to other emerging economies' key success drivers for AI adoption in manufacturing for sustainability to identify global trends and best practices

In conclusion, the proposed studies present a comprehensive and systematic approach to understanding the key drivers of AI adoption within the framework of digital transformation. By filling these existing knowledge gaps, future studies can provide deeper insights into success drivers powering AI adoption in manufacturing and its potential contribution to environmental sustainability, ultimately contributing towards achieving broader Sustainable Development Goals.

7.8 CONCLUSION

Overall, the study contributes by adding to the AI adoption for environmental sustainability literature, key drivers and barriers were identified, compared and contrasted with the existing literature. In addition, the study made theoretical contributions by either supporting or extending existing literature. The study also highlighted several contradictions to existing literature. A total of thirteen themes emerged from thirteen semi-structured participant interviews. The results were analysed to compare contrast to the existing literature. The emerging themes were categorised and used to derive a framework model for the manufacturing industry context. The framework can be a useful reference and guide for manufacturing adopting AI and DTx for sustainability.

The study revealed the key drivers for the adoption of AI and DTx for advancing environmental sustainability within the manufacturing sector. In addition, the study provided practical insights and calls for addressing environmental sustainability through the integration of AI and DTx, for manufacturers, theory and policy makers.

Moreover, the study revealed, through the thirteen key themes, significant challenges the manufacturing industry must overcome, to achieve sustainability targets while meeting long-term business objectives.

In conclusion, this study also contributes towards literature with a comprehensive contribution to environmental sustainability, digital transformation, and AI technology.

7.9.1 SUMMARY OF THE MAJOR STUDY CONTRIBUTION

The study makes several valuable contributions, adds and extends to the existing body of knowledge, in addition, the study illuminates challenges and contradictions to the existing literature, in the field of Digital Transformation, AI, and Environmental Sustainability:

- The study found AI adoption has a potential to advancing environmental sustainability practices within the Gauteng manufacturing sector. The study provides empirical evidence supporting the previous assertion that AI has underutilised potential.
- Study identified key drivers and barriers, challenges, opportunities, benefits, and risks of AI adoption for environmental GHG emissions reduction targets.
- It contributes to managerial practical implications, theoretical practical implications, policy and practice, and provides recommendations for future research.
- The critical and urgent shifts needed in the role of government and policymakers to support industry large-scale AI adoption and DTx:
 - Through targeted strategic partnerships implement targeted policy to promote investment for advancing sustainability practices.
 - Readjust the existing skills levies for building digital talent and expertise
 - Incentivise tertiary institutions like universities to do more targeted research and develop industry-specific curricula and programs.

- The study introduces a framework based on empirical analysis outlining AI-powered DTx key success drivers for environmental sustainability.

7.9.2 URGENT CALL FOR ACTION

The South African Manufacturing Industry is at a critical juncture. The industry contributes significantly to the GDP and holds immense potential for economic growth and job creation. It faces significant challenges, including the transition to a low-carbon world.

For Policymakers

Government regulation and policy emerged from the present study as a barrier for AI adoption in the manufacturing sector. To turn it into a key driver, the government must reassess its role and support in promoting the transition to a low carbon world. Chiarini (2021) and Tseng et al. (2022) revealed government support model both in developed and developing nations.

The government should prioritise the critical role of manufacturing in the economy and allocate its resources to support its growth and sustainability. Develop and urgently implement tailored policies such as tax breaks, subsidies, and co-created regulations to accelerate sustainable practices.

For Business Leaders

The manufacturing industry should play an active role, work and collaborate with the government to shape policies that support the industry's embrace of DTx and invest in AI and DT to accelerate and achieve GHG emission ambitions. Sustainability should be included in the core strategy and digital of the business supported by adequate investment.

From the manufacturing sector perspective, government collaboration, industry requirements, and lack of incentives, policy uncertainty like carbon tax introduction were cited as key challenges facing the manufacturing sector. These barriers may

deter the manufacturing sector from investing in sustainable practices. Partnership between industry and academic can facilitate research and development, fostering innovation in sustainable practices.

Udeagha and Muchapondwa (2023) highlighted policy uncertainty as a significant barrier. To turn it into a key driver, the manufacturing industry must proactively engage the government to ensure policies are practical, achievable, and supportive of the transition to a low-carbon world. Chiarini (2021) and Tseng et al. (2022) revealed that a government support model both in developed and developing nations.

For Academia

Academia accelerates research and development to identify emerging trends and challenges facing the SA manufacturing sector. Develop specific curriculum and educational programs to address digital expertise shortages and future skills needed for a sustainable manufacturing industry.

In the context of this study, it emerged that manufacturers are individually addressing digital skills development through collaborative efforts with universities.

Academia plays a key role in preparing the economy's workforce for DTx and AI adoption. By integrating sustainability and digital skills into a specific curriculum, tertiary institutions can provide future employees with the knowledge and skills needed to drive and sustain DT and AI technologies.

8. REFERENCE LIST

- Abdalla, H. B. (2022). A brief survey on big data: technologies, terminologies and data-intensive applications. *Journal of Big Data*, 9(1), 107. <https://doi.org/10.1186/s40537-022-00659-3>
- Abdallah, Y. O., Shehab, E., & Al-Ashaab, A. (2022). Developing a digital transformation process in the manufacturing sector: Egyptian case study. *Information Systems and e-Business Management*, 20(3), 613-630. <https://doi.org/10.1007/s10257-022-00558-3>
- Abdullahi, M. A., Mohamed, Z., Shamsudin, M. N., Sharifuddin, J., & Ali, F. (2018). Effects of top leadership culture and strategic sustainability orientation on sustainable development among Malaysian herbal-based SME s. *Business Strategy & Development*, 1(2), 128-139. <https://doi.org/10.1002/bsd2.17>.
- Aftab, J., Abid, N., Sarwar, H., & Veneziani, M. (2022). Environmental ethics, green innovation, and sustainable performance: Exploring the role of environmental leadership and environmental strategy. *Journal of Cleaner Production*, 378, 134639. <https://doi.org/10.1016/j.jclepro.2022.134639>
- Anzolin, G., & Lebdioui, A. (2021). Three dimensions of green industrial policy in the context of climate change and sustainable development. *The European Journal of Development Research*, 33(2), 371-405. <https://doi.org/10.1057/s41287-021-00365-5>
- Ardito, L., Raby, S., Albino, V., & Bertoldi, B. (2021). The duality of digital and environmental orientations in the context of SMEs: Implications for innovation performance. *Journal of Business Research*, 123, 44-56. <https://doi.org/10.1016/j.jbusres.2020.09.022>
- Ash, C. G., & Burn, J. M. (2003). A strategic framework for the management of ERP enabled e-business change. *European journal of operational research*, 146(2), 374-387. [https://doi.org/10.1016/S0377-2217\(02\)00556-8](https://doi.org/10.1016/S0377-2217(02)00556-8)

- Awasthi, A., Saxena, K. K., & Arun, V. (2020). Sustainability and survivability in manufacturing sector. In *Modern Manufacturing Processes* (pp. 205-219). Woodhead Publishing. <https://doi.org/10.1016/B978-0-12-819496-6.00011-7>
- Bag, S., Gupta, S., Kumar, S., & Sivarajah, U. (2021a). Role of technological dimensions of green supply chain management practices on firm performance. *Journal of Enterprise Information Management*, 34(1), 1-27. <https://doi.org/10.1108/JEIM-10-2019-0324>.
- Bag, S., Pretorius, J. H. C., Gupta, S., & Dwivedi, Y. K. (2021b). Role of institutional pressures and resources in the adoption of big data analytics powered artificial intelligence, sustainable manufacturing practices and circular economy capabilities. *Technological Forecasting and Social Change*, 163, 120420. <https://doi.org/10.1016/j.techfore.2020.120420>
- Bag, S., Wood, L. C., Xu, L., Dhamija, P., & Kayikci, Y. (2020). Big data analytics as an operational excellence approach to enhance sustainable supply chain performance. *Resources, conservation and recycling*, 153, 104559. <https://doi.org/10.1016/j.resconrec.2019.104559>
- Baggia, A., Maletič, M., Žnidaršič, A., & Brezavšček, A. (2019). Drivers and outcomes of green IS adoption in small and medium-sized enterprises. *Sustainability*, 11(6), 1575. <https://doi.org/10.3390/su11061575>.
- Baumgartner, R. J., & Rauter, R. (2017). Strategic perspectives of corporate sustainability management to develop a sustainable organization. *Journal of Cleaner Production*, 140, 81-92. <https://doi.org/10.1016/j.jclepro.2016.04.146>
- Beier, G., Niehoff, S., & Xue, B. (2018). More sustainability in industry through industrial internet of things?. *Applied sciences*, 8(2), 219. <https://doi.org/10.3390/app8020219>
- Bekun, F. V. (2024). Race to carbon neutrality in South Africa: what role does environmental technological innovation play?. *Applied Energy*, 354, 122212. <https://doi.org/10.1016/j.apenergy.2023.122212>
- Bell, J. F., Goga, S., & Robb, N. (2021). Emerging issues for industrial policy in South Africa. *CCRED-IDTT working paper no*, 6.

- Berger, K., Schöggli, J. P., & Baumgartner, R. J. (2022). Digital battery passports to enable circular and sustainable value chains: Conceptualization and use cases. *Journal of Cleaner Production*, 353, 131492. <https://doi.org/10.1016/j.jclepro.2022.131492>
- Betti, F, Desnos, V, Giraud, Y, Torti, F: (2023) Global Lighthouse Network: Shaping the Next Chapter of the Fourth Industrial Revolution. (2023, November 16). World Economic Forum. Retrieved May 24, 2024, from <https://www.weforum.org/publications/global-lighthouse-network-shaping-the-next-chapter-of-the-fourth-industrial-revolution/>
- Birkel, H. S., Veile, J. W., Müller, J. M., Hartmann, E., & Voigt, K. I. (2019). Development of a risk framework for Industry 4.0 in the context of sustainability for established manufacturers. *Sustainability*, 11(2), 384. <https://doi.org/10.3390/su11020384>
- Booyse, D., & Scheepers, C. B. (2023). Barriers to adopting automated organisational decision-making through the use of artificial intelligence. *Management Research Review*, 47(1), 64-85.
- Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative research in psychology*, 3(2), 77-101.
- Brock, J. K. U., & Von Wangenheim, F. (2019). Demystifying AI: What digital transformation leaders can teach you about realistic artificial intelligence. *California management review*, 61(4), 110-134. <https://doi.org/10.1177/1536504219865226>
- Burawat, P. (2019). The relationships among transformational leadership, sustainable leadership, lean manufacturing and sustainability performance in Thai SMEs manufacturing industry. *International Journal of Quality & Reliability Management*, 36(6), 1014-1036. <https://doi.org/10.1108/IJQRM-09-2017-0178>
- Camacho, N. G. (2024). Unlocking the Potential of AI/ML in DevSecOps: Effective Strategies and Optimal Practices. *Journal of Artificial Intelligence General science (JAIGS)* ISSN: 3006-4023, 3(1), 106-115. <https://doi.org/10.60087/jaigs.v3i1.72>

- Chen, T., Dong, H., & Lin, C. (2020). Institutional shareholders and corporate social responsibility. *Journal of Financial Economics*, 135(2), 483-504. <https://doi.org/10.1016/j.jfineco.2019.06.007>
- Chiarini, A. (2021). Industry 4.0 technologies in the manufacturing sector: Are we sure they are all relevant for environmental performance?. *Business Strategy and the Environment*, 30(7), 3194-3207. <https://doi.org/10.1002/bse.2797>
- Chiarini, A., Belvedere, V., & Grando, A. (2020). Industry 4.0 strategies and technological developments. An exploratory research from Italian manufacturing companies. *Production Planning & Control*, 31(16), 1385–1398. <https://doi.org/10.1080/09537287.2019.1710304>
- Ching, N. T., Ghobakhloo, M., Iranmanesh, M., Maroufkhani, P., & Asadi, S. (2022). Industry 4.0 applications for sustainable manufacturing: A systematic literature review and a roadmap to sustainable development. *Journal of Cleaner Production*, 334, 130133. <https://doi.org/10.1016/j.jclepro.2021.130133>
- Colglazier, W. (2015). Sustainable development agenda: 2030. *Science*, 349(6252), 1048-1050.
- Corbin, J., & Strauss, A. (2008). Qualitative research. *Techniques and procedures for developing grounded theory*, 3.
- Creswell, J. W. (2014). Research design: Qualitative, quantitative, and mixed methods approaches (4th ed.). Sage Publications.
- Dabić, M., Maley, J. F., Švarc, J., & Poček, J. (2023). Future of digital work: Challenges for sustainable human resources management. *Journal of Innovation & Knowledge*, 8(2), 100353. <https://doi.org/10.1016/j.jik.2023.100353>
- Dauvergne, P. (2022). Is artificial intelligence greening global supply chains? Exposing the political economy of environmental costs. *Review of International Political Economy*, 29(3), 696-718. <https://doi.org/10.1080/09692290.2020.1814381>

- De Beer (2023): Provincial gross domestic product: experimental estimates, 2013–2022. StatsSA. Retrieved April 30, 2024, from <https://www.statssa.gov.za/publications/D04411/D044112022.pdf>
- De Boer. E, Torti. F (2023): Global Lighthouse Network: Adopting AI at Speed and Scale. (2023, December 13). World Economic Forum. <https://www.weforum.org/publications/manufacturing-lighthouses-and-the-path-to-impact-adopting-ai-at-speed-and-scale/>
- de Sousa Jabbour, A. B. L., Jabbour, C. J. C., Foropon, C., & Godinho Filho, M. (2018b). When titans meet—Can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors. *Technological Forecasting and Social Change*, 132, 18-25. <https://doi.org/10.1016/j.techfore.2018.01.017>
- de Sousa Jabbour, A. B.L., Jabbour, C. J. C., Godinho Filho, M., & Roubaud, D. (2018a). Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations. *Annals of Operations Research*, 270, 273-286. <https://doi.org/10.1007/s10479-018-2772-8>
- Debnath, B., Shakur, M. S., Bari, A. M., Saha, J., Porna, W. A., Mishu, M. J., ... & Rahman, M. A. (2023). Assessing the critical success factors for implementing industry 4.0 in the pharmaceutical industry: implications for supply chain sustainability in emerging economies. *Plos one*, 18(6), e0287149. <https://doi.org/10.1371/journal.pone.0287149>
- Demir, K. A., Döven, G., & Sezen, B. (2019). Industry 5.0 and human-robot co-working. *Procedia computer science*, 158, 688-695. <https://doi.org/10.1016/j.procs.2019.09.104>
- Denicolai, S., Zucchella, A., & Magnani, G. (2021). Internationalization, digitalization, and sustainability: Are SMEs ready? A survey on synergies and substituting effects among growth paths. *Technological Forecasting and Social Change*, 166, 120650. <https://doi.org/10.1016/j.techfore.2021.120650>
- Denzin, N. K., & Lincoln, Y. S. (Eds.). (2011). *The Sage handbook of qualitative research*. sage.

- DeStefano, T., Johnstone, N., Kneller, R., & Timmis, J. (2024). Do Capital Incentives Distort Technology Diffusion? Evidence on Cloud, Big Data and AI.
- Du, G., Sun, C., Ouyang, X., & Zhang, C. (2018). A decomposition analysis of energy-related CO₂ emissions in Chinese six high-energy intensive industries. *Journal of Cleaner Production*, 184, 1102-1112. <https://doi.org/10.1016/j.jclepro.2018.02.304>
- Dubey, R., Gunasekaran, A., Childe, S. J., Blome, C., & Papadopoulos, T. (2019). Big data and predictive analytics and manufacturing performance: integrating institutional theory, resource-based view and big data culture. *British Journal of Management*, 30(2), 341-361. <https://doi.org/10.1111/1467-8551.12355>
- Dubey, R., Gunasekaran, A., Childe, S. J., Bryde, D. J., Giannakis, M., Foropon, C., ... & Hazen, B. T. (2020). Big data analytics and artificial intelligence pathway to operational performance under the effects of entrepreneurial orientation and environmental dynamism: A study of manufacturing organisations. *International journal of production economics*, 226, 107599. <https://doi.org/10.1016/j.iipe.2019.107599>
- Edmondson, A. C., & McManus, S. E. (2007). Methodological fit in management field research. *Academy of management review*, 32(4), 1246-1264. <https://doi.org/10.5465/amr.2007.26586086>
- Egilmez, G., Kucukvar, M., & Tatari, O. (2013). Sustainability assessment of US manufacturing sectors: an economic input output-based frontier approach. *Journal of Cleaner Production*, 53, 91-102. <https://doi.org/10.1016/j.jclepro.2013.03.037>
- Eide, A. E., Saether, E. A., & Aspelund, A. (2020). An investigation of leaders' motivation, intellectual leadership, and sustainability strategy in relation to Norwegian manufacturers' performance. *Journal of Cleaner Production*, 254, 120053. <https://doi.org/10.1016/j.jclepro.2020.120053>
- Esfahbodi, A., Zhang, Y., Watson, G., & Zhang, T. (2017). Governance pressures and performance outcomes of sustainable supply chain management—An empirical analysis of UK manufacturing industry. *Journal of cleaner production*, 155, 66-78. <https://doi.org/10.1016/j.jclepro.2016.07.098>

- European Commission, 2020. A New Circular Economy Action Plan - *For a Cleaner and More Competitive Europe Brussels*.
- Ezici, B., Eğılmez, G., & Gedik, R. (2020). Assessing the eco-efficiency of US manufacturing industries with a focus on renewable vs. non-renewable energy use: An integrated time series MRIO and DEA approach. *Journal of Cleaner Production*, 253, 119630. <https://doi.org/10.1016/j.jclepro.2019.119630>
- Fenech, R., Baguant, P., & Ivanov, D. (2019). The changing role of human resource management in an era of digital transformation. *International Journal of Entrepreneurship*, 22(2), 166-175.
- Fofana, F., Bazeley, P., & Regnault, A. (2020). Applying a mixed methods design to test saturation for qualitative data in health outcomes research. *PloS one*, 15(6), e0234898. <https://doi.org/10.1371/journal.pone.0234898>
- Gaffley, G., & Pelser, T. G. (2021). Developing a digital transformation model to enhance the strategy development process for leadership in the South African manufacturing sector. *South African Journal of Business Management*, 52(1), 12. <https://doi.org/10.4102/sajbm.v52i1.2357>
- Gaglio, C., Kraemer-Mbula, E., & Lorenz, E. (2022). The effects of digital transformation on innovation and productivity: Firm-level evidence of South African manufacturing micro and small enterprises. *Technological Forecasting and Social Change*, 182, 121785. <https://doi.org/10.1016/j.techfore.2022.121785>
- Genghini, L. (2024): The Green Gap: *Unraveling the 6 Reasons Why Companies Struggle to Achieve Sustainability Goals*. Retrieved September 28, 2024, from <https://2030.builders/6-reasons-why-companies-struggle-to-achieve-sustainability-goals/>
- George, G., Merrill, R. K., & Schillebeeckx, S. J. (2021). Digital sustainability and entrepreneurship: How digital innovations are helping tackle climate change and sustainable development. *Entrepreneurship theory and practice*, 45(5), 999-1027. <https://doi.org/10.1177/1042258719899425>

- Gioia, D. A., Corley, K. G., & Hamilton, A. L. (2013). Seeking qualitative rigor in inductive research: Notes on the Gioia methodology. *Organizational research methods*, 16(1), 15-31.
- Grabowska, S., Saniuk, S., & Gajdzik, B. (2022). Industry 5.0: improving humanization and sustainability of Industry 4.0. *Scientometrics*, 127(6), 3117-3144. <https://doi.org/10.1007/s11192-022-04370-1>
- Grayson, D., Coulter, C., & Lee, M. (2018). *All in: The future of business leadership*. Routledge. <https://doi.org/10.4324/9781351001205>
- Guandalini, I. (2022). Sustainability through digital transformation: A systematic literature review for research guidance. *Journal of Business Research*, 148, 456-471. <https://doi.org/10.1016/j.jbusres.2022.05.003>
- Guest, G., Namey, E., & Chen, M. (2020). A simple method to assess and report thematic saturation in qualitative research. *PloS one*, 15(5), e0232076. <https://doi.org/10.1371/journal.pone.0232076>
- Hennink, M. M., Kaiser, B. N., & Marconi, V. C. (2017). Code saturation versus meaning saturation: how many interviews are enough?. *Qualitative health research*, 27(4), 591-608. <https://doi.org/10.1177/1049732316665344>
- Hennink, M., & Kaiser, B. N. (2022). Sample sizes for saturation in qualitative research: A systematic review of empirical tests. *Social science & medicine*, 292, 114523. <https://doi.org/10.1016/j.socscimed.2021.114523>
- Hernandez, A. A. (2020). Exploring the factors to green IT adoption of SMEs in the Philippines. In *Start-Ups and SMEs: Concepts, Methodologies, Tools, and Applications* (pp. 907-926). IGI Global. <https://doi.org/10.4018/JCIT.2018040104>
- Hilty, L.M., Aebischer, B., 2015. ICT Innovations for Sustainability. *Springer, Cham*.
- Holmström, J. (2022). From AI to digital transformation: The AI readiness framework. *Business Horizons*, 65(3), 329-339. <https://doi.org/10.1016/j.bushor.2021.03.006>

- Holopainen, M., Ukko, J., & Saunila, M. (2022). Managing the strategic readiness of industrial companies for digital operations. *Digital Business*, 2(2), 100039. <https://doi.org/10.1016/j.digbus.2022.100039>
- Horváth, D., & Szabó, R. Z. (2019). Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities?. *Technological forecasting and social change*, 146, 119-132. <https://doi.org/10.1016/j.techfore.2019.05.021>
- Huang, M. H., & Rust, R. T. (2018). Artificial intelligence in service. *Journal of service research*, 21(2), 155-172. <https://doi.org/10.1177/1094670517752459>
- Hwang, S. (2008). Utilizing qualitative data analysis software: A review of Atlas.ti. *Social Science Computer Review*, 26(4), 519-527. <https://doi.org/10.1177/0894439307312485>
- Isensee, C., Teuteberg, F., Griesse, K. M., & Topi, C. (2020). The relationship between organizational culture, sustainability, and digitalization in SMEs: A systematic review. *Journal of Cleaner Production*, 275, 122944. <https://doi.org/10.1016/j.jclepro.2020.122944>
- Jamwal, A., Agrawal, R., Sharma, M., Kumar, V., & Kumar, S. (2021). Developing A sustainability framework for Industry 4.0. *Procedia CIRP*, 98, 430-435. <https://doi.org/10.1016/j.procir.2021.01.129>
- Jia, Z., & Lin, B. (2020). Rethinking the choice of carbon tax and carbon trading in China. *Technological Forecasting and Social Change*, 159, 120187. <https://doi.org/10.1016/j.techfore.2020.120187>
- Jimenez, D.-Z., Lim, V., Cheok, L., & Ng, H. (2018). Unlocking the Economic Impact of Digital Transformation in Asia. *Unlocking the Economic Impact of Digital Transformation in Asia Pacific*, 2018(1), 31. Retrieved September 20, 2024 from <https://news.microsoft.com/wp-content/uploads/prod/sites/43/2018/11/Unlocking-the-economic-impact-of-digital-transformation.pdf>
- Johnson, M., Jain, R., Brennan-Tonetta, P., Swartz, E., Silver, D., Paolini, J., ... & Hill, C. (2021). Impact of big data and artificial intelligence on industry: developing

- a workforce roadmap for a data driven economy. *Global Journal of Flexible Systems Management*, 22(3), 197-217. <https://doi.org/10.1007/s40171-021-00272-y>
- Jonsson, K., Mathiassen, L., & Holmström, J. (2018). Representation and mediation in digitalized work: evidence from maintenance of mining machinery. *Journal of Information Technology*, 33(3), 216-232. <https://doi.org/10.1057/s41265-017-0050-x>
- Junior, J. A. G., Busso, C. M., Gobbo, S. C. O., & Carreão, H. (2018). Making the links among environmental protection, process safety, and industry 4.0. *Process safety and environmental protection*, 117, 372-382. <https://doi.org/10.1016/j.psep.2018.05.017>
- Kauffman, R. J., & Walden, E. A. (2001). Economics and electronic commerce: Survey and directions for research. *International journal of electronic commerce*, 5(4), 5-116. <https://doi.org/10.1080/10864415.2001.11044222>
- Kiefer, C. P., Del Río González, P., & Carrillo-Hermosilla, J. (2019). Drivers and barriers of eco-innovation types for sustainable transitions: A quantitative perspective. *Business Strategy and the Environment*, 28(1), 155-172. <https://doi.org/10.1002/bse.2246>
- Kiel, D., Müller, J. M., Arnold, C., & Voigt, K. I. (2017). Sustainable industrial value creation: Benefits and challenges of industry 4.0. *International journal of innovation management*, 21(08), 1740015. <https://doi.org/10.1142/S1363919617400151>
- Kraus, S., Jones, P., Kailer, N., Weinmann, A., Chaparro-Banegas, N., & Roig-Tierno, N. (2021). Digital transformation: An overview of the current state of the art of research. *Sage Open*, 11(3), 21582440211047576. <https://doi.org/10.1177/21582440211047576>
- Lamb, W. F., Wiedmann, T., Pongratz, J., Andrew, R., Crippa, M., Olivier, J. G., ... & Minx, J. (2021). A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environmental research letters*, 16(7), 073005. [10.1088/1748-9326/abee4e](https://doi.org/10.1088/1748-9326/abee4e)

- LeHong, H. & Waller, G. (2022): *Digital Business Ambition: Transform or Optimise?* Gartner. ID G00739742. Retrieved May 2, 2024, from <https://www.gartner.com/mysearch/all?q=G00739742>.
- Li, B. H., Hou, B. C., Yu, W. T., Lu, X. B., & Yang, C. W. (2017). Applications of artificial intelligence in intelligent manufacturing: a review. *Frontiers of Information Technology & Electronic Engineering*, 18(1), 86-96. <https://doi.org/10.1631/FITEE.1601885>
- Li, H., Yang, H., Yang, B., Zhu, C., & Yin, S. (2018). Modelling and simulation of energy consumption of ceramic production chains with mixed flows using hybrid Petri nets. *International Journal of Production Research*, 56(8), 3007-3024. <https://doi.org/10.1080/00207543.2017.1391415>
- Li, Y., Dai, J., & Cui, L. (2020). The impact of digital technologies on economic and environmental performance in the context of industry 4.0: A moderated mediation model. *International Journal of Production Economics*, 229, 107777. <https://doi.org/10.1016/j.ijpe.2020.107777>
- Lohrmann, C. (2017). Leadership in a digital world: New ways of leadership for sustainable development. *Sustainability in a Digital World: New Opportunities Through New Technologies*, 51-58. https://doi.org/10.1007/978-3-319-54603-2_4
- Lutfi, A., Alsyouf, A., Almaiah, M. A., Alrawad, M., Abdo, A. A. K., Al-Khasawneh, A. L., ... & Saad, M. (2022). Factors influencing the adoption of big data analytics in the digital transformation era: Case study of Jordanian SMEs. *Sustainability*, 14(3), 1802. <https://doi.org/10.3390/su14031802>
- Ma, S., Ding, W., Liu, Y., Ren, S., & Yang, H. (2022). Digital twin and big data-driven sustainable smart manufacturing based on information management systems for energy-intensive industries. *Applied energy*, 326, 119986. <https://doi.org/10.1016/j.apenergy.2022.119986>
- Ma, S., Huang, Y., Liu, Y., Kong, X., Yin, L., & Chen, G. (2023). Edge-cloud cooperation-driven smart and sustainable production for energy-intensive manufacturing industries. *Applied Energy*, 337, 120843. <https://doi.org/10.1016/j.apenergy.2023.120843>

- Ma, S., Zhang, Y., Liu, Y., Yang, H., Lv, J., & Ren, S. (2020). Data-driven sustainable intelligent manufacturing based on demand response for energy-intensive industries. *Journal of Cleaner Production*, 274, 123155. <https://doi.org/10.1016/j.jclepro.2020.123155>
- Machado, E., Scavarda, L. F., Caiado, R. G. G., & Thomé, A. M. T. (2021). Barriers and enablers for the integration of Industry 4.0 and sustainability in supply chains of MSMEs. *Sustainability*, 13(21), 11664. <https://doi.org/10.3390/su132111664>
- Macke, J., & Genari, D. (2019). Systematic literature review on sustainable human resource management. *Journal of cleaner production*, 208, 806-815. <https://doi.org/10.1016/j.jclepro.2018.10.091>
- Malek, J., & Desai, T. N. (2019). Prioritization of sustainable manufacturing barriers using Best Worst Method. *Journal of Cleaner Production*, 226, 589-600. <https://doi.org/10.1016/j.jclepro.2019.04.056>
- Mangla, S. K., Luthra, S., Rich, N., Kumar, D., Rana, N. P., & Dwivedi, Y. K. (2018). Enablers to implement sustainable initiatives in agri-food supply chains. *International Journal of Production Economics*, 203, 379-393. <https://doi.org/10.1016/j.ijpe.2018.07.012>.
- Mariappanadar, S., Maurer, I., Kramar, R., & Muller-Camen, M. (2022). Is it a sententious claim? An examination of the quality of occupational health, safety and well-being disclosures in global reporting initiative reports across industries and countries. *International Business Review*, 31(2), 101922. <https://doi.org/10.1016/j.ibusrev.2021.101922>
- Mashishi, A (2023): South Africa's Artificial Intelligence (AI) Planning: *Adoption of AI by Government: Department of Communications and Digital Technologies (DCDT)*. Retrieved May 25, 2024, from https://www.dcdt.gov.za/images/phocadownload/AI_Government_Summit/National_AI_Government_Summit_Discussion_Document.pdf.
- Mhlungu, N. S., Chen, J. Y., & Alkema, P. (2019). The underlying factors of a successful organisational digital transformation. *South African Journal of*

Information Management, 21(1), 1-10. <https://hdl.handle.net/10520/EJC-1693a0fd5a>

- Mikalef, P., Boura, M., Lekakos, G., & Krogstie, J. (2019). Big data analytics and firm performance: Findings from a mixed-method approach. *Journal of business research*, 98, 261-276. <https://doi.org/10.1016/j.jbusres.2019.01.044>
- Mngxati, V. & Seedat, Y. (2023): Total Enterprise Reinvention Thriving amid Disruption in South Africa. Accenture (p.27). Retrieved May 28, 2024, from <https://www.accenture.com/content/dam/accenture/final/capabilities/strategy-and-consulting/strategy/document/Accenture-Total-Enterprise-Reinvention-Thriving-amid-disruption-in-South-Africa.pdf>
- Moghrabi, I. A., Bhat, S. A., Szczuko, P., AlKhaled, R. A., & Dar, M. A. (2023). Digital transformation and its influence on sustainable manufacturing and business practices. *Sustainability*, 15(4), 3010. <https://doi.org/10.3390/su15043010>
- Möller, D. P. (2023). Cybersecurity in digital transformation. In *Guide to Cybersecurity in Digital Transformation: Trends, Methods, Technologies, Applications and Best Practices* (pp. 1-70). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-26845-8_1
- Muhr, T. (2004). *Atlas. ti V5. 0: user s guide and reference; the knowledge workbench; visual qualitative data analysis & knowledge management in education, business, administration & research*. Scientific Software Development.
- Muthuswamy, M., & Ali, A. M. (2023). Sustainable supply chain management in the age of machine intelligence: addressing challenges, capitalizing on opportunities, and shaping the future landscape. *Sustainable Machine Intelligence Journal*, 3, 3-1. <https://doi.org/10.61185/SMIJ.2023.33103>
- Nair, K. (2019). Overcoming today's digital talent gap in organizations worldwide. *Development and Learning in Organizations: An International Journal*, 33(6), 16-18. <https://doi.org/10.1108/DLO-02-2019-0044>
- Narkhede, G., Chinchani, 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*, (ahead-of-print).
<https://doi.org/10.1108/JSMA-06-2023-0144>
- Ngepah, N., Saba, C. S., & Kajewole, D. O. (2024). The impact of industry 4.0 on South Africa's manufacturing sector. *Journal of Open Innovation: Technology, Market, and Complexity*, 10(1), 100226.
<https://doi.org/10.1016/j.joitmc.2024.100226>
- Nguyen, T., Duong, Q. H., Van Nguyen, T., Zhu, Y., & Zhou, L. (2022). Knowledge mapping of digital twin and physical internet in Supply Chain Management: A systematic literature review. *International Journal of Production Economics*, 244, 108381. <https://doi.org/10.1016/j.ijpe.2021.108381>
- Nimawat, D., & Das Gidwani, B. (2022). Challenges facing by manufacturing industries towards implementation of industry 4.0: an empirical research. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 16(4), 1371-1383. <https://doi.org/10.1007/s12008-022-00961-7>
- 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.
<https://doi.org/10.1177/1609406917733847>
- Okorie, O., Russell, J., Cherrington, R., Fisher, O., & Charnley, F. (2023). Digital transformation and the circular economy: Creating a competitive advantage from the transition towards Net Zero Manufacturing. *Resources, Conservation and Recycling*, 189, 106756. <https://doi.org/10.1016/j.resconrec.2022.106756>
- Omri, A., Euch, J., Hasaballah, A. H., & Al-Tit, A. (2019). Determinants of environmental sustainability: evidence from Saudi Arabia. *Science of the Total Environment*, 657, 1592-1601.
<https://doi.org/10.1016/j.scitotenv.2018.12.111>
- Osburg, T. (2017). *Sustainability in a digital world needs trust* (pp. 3-19). Springer International Publishing. https://doi.org/10.1007/978-3-319-54603-2_1

- Patton, M. Q. (2002). *Qualitative research and evaluation methods*. Thousand Oaks, Cal.: *Sage Publications*, 4.
- Poursoltan, L., Mohammad Seyedhosseini, S., & Jabbarzadeh, A. (2021). A two-level closed-loop supply chain under the constraint Of vendor managed inventory with learning: A novel hybrid algorithm. *Journal of Industrial and Production Engineering*, 38(4), 254-270.
<https://doi.org/10.1080/21681015.2021.1878301>
- Rantala, T., Ukko, J., Saunila, M., & Havukainen, J. (2018). The effect of sustainability in the adoption of technological, service, and business model innovations. *Journal of cleaner production*, 172, 46-55.
<https://doi.org/10.1016/j.jclepro.2017.10.009>
- Rao. A.S., & Verweij. G (2017): Sizing the Price. *What's the real value of AI for your business and how you can capitalise*. Retrieved May 24, 2024, from <https://www.pwc.com/gx/en/issues/analytics/assets/pwc-ai-analysis-sizing-the-prize-report.pdf>.
- Ros-Dosdá, T., Fullana-i-Palmer, P., Mezquita, A., Masoni, P., & Monfort, E. (2018). How can the European ceramic tile industry meet the EU's low-carbon targets? A life cycle perspective. *Journal of Cleaner Production*, 199, 554-564. <https://doi.org/10.1016/j.jclepro.2018.07.176>.
- Rusch, M., Schöggel, J. P., & Baumgartner, R. J. (2023). Application of digital technologies for sustainable product management in a circular economy: A review. *Business strategy and the environment*, 32(3), 1159-1174.
<https://doi.org/10.1002/bse.3099>
- Ryan, G. W., & Bernard, H. R. (2003). Techniques to identify themes. *Field methods*, 15(1), 85-109. <https://doi.org/10.1177/1525822X02239569>
- Saeed, S., Altamimi, S. A., Alkayyal, N. A., Alshehri, E., & Alabbad, D. A. (2023). Digital transformation and cybersecurity challenges for businesses resilience: Issues and recommendations. *Sensors*, 23(15), 6666.
<https://doi.org/10.3390/s23156666>

- Saldanha, T. (2019). *Why digital transformations fail: The surprising disciplines of how to take off and stay ahead*. Berrett-Koehler Publishers.
- Saunders, M., Lewis, P. (2018). *Doing research in Business and Management (2nd ed.)*. Pearson.
- Saunila, M., Ukko, J., & Rantala, T. (2018). Sustainability as a driver of green innovation investment and exploitation. *Journal of cleaner production*, 179, 631-641. <https://doi.org/10.1016/j.jclepro.2017.11.211>
- Savastano, M., Amendola, C., Bellini, F., & D'Ascenzo, F. (2019). Contextual impacts on industrial processes brought by the digital transformation of manufacturing: A systematic review. *Sustainability*, 11(3), 891. <https://doi.org/10.3390/su11030891>
- Schöggel, J. P., Rusch, M., Stumpf, L., & Baumgartner, R. J. (2023). Implementation of digital technologies for a circular economy and sustainability management in the manufacturing sector. *Sustainable Production and Consumption*, 35, 401-420. <https://doi.org/10.1016/j.spc.2022.11.012>
- Schwandt, T. A. (2001). *Dictionary of qualitative inquiry*. Sage Publications.
- Settembre-Blundo, D., González-Sánchez, R., Medina-Salgado, S., & García-Muiña, F. E. (2021). Flexibility and resilience in corporate decision making: a new sustainability-based risk management system in uncertain times. *Global Journal of Flexible Systems Management*, 22(Suppl 2), 107-132. <https://doi.org/10.1007/s40171-021-00277-7>
- Sherif, A. (2024). *Digital Transformation global spending 2017 – 2027*: Retrieved May 24, 2024, from <https://www.statista.com/statistics/870924/worldwide-digital-transformation-market-size/>.
- Shivaani, M. V. (2018). Does regulatory flexibility affect risk disclosures in annual report?. *Global Journal of Flexible Systems Management*, 19(4), 321-336. <https://doi.org/10.1007/s40171-018-0196-6>
- Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of business research*, 104, 333-339. <https://doi.org/10.1016/j.jbusres.2019.07.039>

- South African Reserve Bank. (2020). *South African Reserve Bank Occasional Bulletin of Economic Notes OBEN/20/02*. <https://www.resbank.co.za/>
- Steyn, M., Genthe, B., Banoo, I., Thwala, M., Roos, T., Walters, C., & Ramakhwatho, F. (2020); *A decision support tool for industrial water reuse in South Africa*. Retrieved May 24, 2024, from https://researchspace.csir.co.za/dspace/bitstream/handle/10204/11964/Steyn_2020.pdf?sequence=1&isAllowed=y.
- Sun, W., Xu, X., Lv, Z., Mao, H., & Wu, J. (2019a). Environmental impact assessment of wastewater discharge with multi-pollutants from iron and steel industry. *Journal of environmental management*, 245, 210-215. <https://doi.org/10.1016/j.jenvman.2019.05.081>. <https://doi.org/10.1016/j.jenvman.2019.05.081>
- Sun, W., Zhou, Y., Lv, J., & Wu, J. (2019b). Assessment of multi-air emissions: Case of particulate matter (dust), SO₂, NO_x and CO₂ from iron and steel industry of China. *Journal of Cleaner Production*, 232, 350-358. <https://doi.org/10.1016/j.jclepro.2019.05.400>.
- Thomas, D. R. (2006). A general inductive approach for analyzing qualitative evaluation data. *American journal of evaluation*, 27(2), 237-246. <https://doi.org/10.1177/1098214005283748>
- Tiseo, I. (2023): *Global carbon dioxide emissions 2010-2022*: Retrieved May 24, 2024, from <https://www.statista.com/statistics/270499/co2-emissions-in-selected-countries/>.
- Truong, T. C. (2022). The impact of digital transformation on environmental sustainability. *Advances in Multimedia*, 2022(1), 6324325. <https://doi.org/10.1155/2022/6324325>
- Tseng, M. L., Bui, T. D., Lim, M. K., Fujii, M., & Mishra, U. (2022). Assessing data-driven sustainable supply chain management indicators for the textile industry under industrial disruption and ambidexterity. *International Journal of Production Economics*, 245, 108401. <https://doi.org/10.1016/j.ijpe.2021.108401>

- Tseng, M. L., Chang, C. H., Lin, C. W. R., Wu, K. J., Chen, Q., Xia, L., & Xue, B. (2020). Future trends and guidance for the triple bottom line and sustainability: A data driven bibliometric analysis. *Environmental Science and Pollution Research*, 27, 33543-33567. <https://doi.org/10.1007/s11356-020-09284-0>
- Udeagha, M. C., & Muchapondwa, E. (2023). Environmental sustainability in South Africa: Understanding the criticality of economic policy uncertainty, fiscal decentralization, and green innovation. *Sustainable Development*, 31(3), 1638-1651. <https://doi.org/10.1002/sd.2473>
- Ukko, J., Nasiri, M., Saunila, M., & Rantala, T. (2019). Sustainability strategy as a moderator in the relationship between digital business strategy and financial performance. *Journal of Cleaner Production*, 236, 117626. <https://doi.org/10.1016/j.jclepro.2019.117626>
- United Nations Development Organization. (2023). *International Yearbook of Industrial Statistics*. <https://stat.unido.org/>
- Ustundag, A., Cevikcan, E., & Karacay, G. (2018). Talent development for Industry 4.0. *Industry 4.0: Managing the digital transformation*, 123-136. https://doi.org/10.1007/978-3-319-57870-5_7
- Van der Velden, M. (2018). Digitalisation and the UN Sustainable Development Goals: What role for design. *ID&A Interaction design & architecture (s)*, (37), 160-174. <http://urn.nb.no/URN:NBN:no-74756>
- Veile, J. W., Kiel, D., Müller, J. M., & Voigt, K. I. (2020). Lessons learned from Industry 4.0 implementation in the German manufacturing industry. *Journal of Manufacturing Technology Management*, 31(5), 977-997. <https://doi.org/10.1108/JMTM-08-2018-0270>
- Vukšić, V. B., Ivančić, L., & Vugec, D. S. (2018). A preliminary literature review of digital transformation case studies. *International Journal of Computer and Information Engineering*, 12(9), 737-742.
- Wang, J., Rodrigues, J. F., Hu, M., Behrens, P., & Tukker, A. (2019). The evolution of Chinese industrial CO2 emissions 2000–2050: a review and meta-analysis of

- historical drivers, projections and policy goals. *Renewable and Sustainable Energy Reviews*, 116, 109433. <https://doi.org/10.1016/j.rser.2019.109433>
- Wang, Z., Zhang, T., Ren, X., & Shi, Y. (2024). AI adoption rate and corporate green innovation efficiency: Evidence from Chinese energy companies. *Energy Economics*, 132, 107499. <https://doi.org/10.1016/j.eneco.2024.107499>
- Weston, C., Gandell, T., Beauchamp, J., McAlpine, L., Wiseman, C., & Beauchamp, C. (2001). Analyzing interview data: The development and evolution of a coding system. *Qualitative sociology*, 24, 381-400.
- Woolley, D (2024): AI and environmental sustainability – a symbiotic relationship. Dell Technologies. Retrieved September 28, 2024, from <https://www.itweb.co.za/article/ai-and-environmental-sustainability-a-symbiotic-relationship/8OKdWMDXAaIMbznQ>.
- Xu, G., Li, G., Sun, P., & Peng, D. (2023). Inefficient investment and digital transformation: What is the role of financing constraints?. *Finance Research Letters*, 51, 103429. <https://doi.org/10.1016/j.frl.2022.103429>
- Yadav, G., Kumar, A., Luthra, S., Garza-Reyes, J. A., Kumar, V., & Batista, L. (2020). A framework to achieve sustainability in manufacturing organisations of developing economies using industry 4.0 technologies' enablers. *Computers in industry*, 122, 103280. <https://doi.org/10.1016/j.compind.2020.103280>
- Yin, R. K. (2009). *Case study research: Design and methods* (Vol. 5). sage.
- Zakaria, N., & Zakaria, N. (2016). *Qualitative content analysis: A paradigm shift from manual coding to computer-assisted coding using ATLAS. ti* (pp. 2-17). SAGE Publications. <https://doi.org/10.4135/978144627305015599170>
- Zhang, H., Veltri, A., Calvo-Amodio, J., & Haapala, K. R. (2021). Making the business case for sustainable manufacturing in small and medium-sized manufacturing enterprises: a systems decision making approach. *Journal of Cleaner Production*, 287, 125038. <https://doi.org/10.1016/j.jclepro.2020.125038>

APPENDIX 1: INTERVIEW GUIDE

Interview Questions Guide

Time estimate: 8 min

Drivers for Successful Digital Transformation in Advancing Environmental Sustainability in Gauteng's Manufacturing Industry

		Item Code	Semi-Structure Interview Question
Participant Introduction General Questions		C1	Tell us about what your Organisation does
		C2	Your Organisation Industry?
		C3	Tell us about what you do and what your background.
		C4	What is your role category (Senior, Middle, or Junior Management)
		C5	Number of years in the Organisation
		C6	Number of years in the current role
		C7	Number of years working with Digital Technologies Adoption Projects in your current organization

Topic 1

Time estimate: 10 min

Drivers for Successful Digital Transformation in Advancing Environmental Sustainability in Gauteng's Manufacturing Industry

	Prompt to Lead Questions	Item Code	Semi-Structure Interview Question	Source
RQ1 (Organisational Capabilities): What are the key drivers for successful adoption of DT AI in the Manufacturing sector to achieve the environmental sustainability dimension greenhouse gas emission reduction?	Prompt: To successfully integrate AI into sustainable development initiatives, organizations must align their strategies, goals, and objectives This requires strong commitment and support from top management, as well as effective communication and collaboration among various organizational stake-holders.	OR1	Where would you say the industry is on the spectrum of adopting digital technologies like artificial intelligence? The level of digital transformation and AI integration (e.g., exploratory, pilot projects, scaling up)	Chiarini 2021
		OR2	In your experience what is the manufacturing customer's approach to adopting digital technologies such as AI? Is there a formal strategy in place, and if so, what are the key elements and objectives? How does this strategy align with their overall vision and goals?	Bag et al., 2021 Rusch et al., 2023
		OR3	How has their top management demonstrated their commitment to leveraging AI and digital technologies for environmental sustainability and emissions reduction?	Mikalef et al., 2019
		OR4	What opportunities have their top management provided to build organisational capabilities? employee training and development in AI, digital technologies, and sustainability?	Horvath & Szabo, 2019

Topic 2

Time estimate: 6 min

Drivers for Successful Digital Transformation in Advancing Environmental Sustainability in Gauteng's Manufacturing Industry

	Prompt to Lead Questions	Item Code	Semi-Structure Interview Question	Source
RQ2 (Impact): How is success measured for measuring the effect of adopting DT for the environmental sustainability dimension?	Prompt: Organizations should also develop clear performance metrics and targets related to sustainability and AI, monitor progress regularly, and adjust their strategies as needed to ensure continuous improvement	I1	How do digital technologies create value for your customers in terms of environmental sustainability and greenhouse gas reduction? Describe how do you quantify the value derived from digital technologies	Mikalef et al., 2019
		I2	What metrics or key performance indicators (KPIs) has top management established to measure progress towards sustainability and emissions reduction goals?	Mikalef et al., 2019
		I3	How do you see the role of Digital Technologies evolving in driving environmental sustainability and greenhouse gas reduction efforts within the company?	Mikalef et al., 2019

Topic 3

Time estimate: 15 min

Drivers for Successful Digital Transformation in Advancing Environmental Sustainability in Gauteng's Manufacturing Industry

	Prompt to Lead Questions	Item Code	Semi-Structure Interview Question	Source
RQ3 (Opportunities and Challenges): What policy initiatives and regulatory frameworks are necessary to promote sustainable development in the South African manufacturing sector? Regulations are likely to play a multifaceted role, incentivize adoption, set clear goals, promote collaboration, and address potential downside	Prompt: Laws and regulations are often credited with driving positive environmental changes in manufacturing.	PR1	Can you elaborate on how, in your experience, environmental regulations have influenced your customer's approach to safeguarding the environment and implementing cleaner manufacturing practices?	Bag et al., 2021
		PR2	How do you see the role of regulations evolving in promoting the use of digital technologies for a cleaner future?	Mikalef et al., 2019
		PR3	In your experience, how do you see digital technologies impacting your customer's approach to reducing greenhouse gas emissions?	Bag et al., 2021
	Prompt: Balancing environmental responsibility with economic considerations is a constant challenge for many companies.	PR4	Can you describe any specific digital tools or technologies your customers are adopting to improve its environmental footprint?	Bag et al., 2021
	Prompt: With the rapid growth of digital technologies, concerns are rising about their impact on greenhouse gas emissions. However, some argue that digital solutions can also help reduce emissions in other sectors.	PR5	In your opinion, what are the most promising areas for digital innovation to further reduce greenhouse gas emissions across various industries?	Bag et al., 2021

Topic 4

Time estimate: 6 min

Drivers for Successful Digital Transformation in Advancing Environmental Sustainability in Gauteng's Manufacturing Industry

	Prompt to Lead Questions	Item Code	Semi-Structure Interview Question	Source
RQ4 (Challenges) What are the potential environmental benefits and challenges, barriers, and constraints faced by manufacturing organisations when implementing DTx for sustainability purposes?	Prompt: DTx, with digital technologies, offers significant potential for sustainable manufacturing. However, overcoming challenges and trade-offs is crucial to unlock its full potential.	C1	How have they strived to achieve compliance with environmental regulations while maintaining economic viability? Can you walk me through some specific examples of how your customers have approached this challenge?	Mikalef et al. 2019
		C2	Are there any challenges associated with implementing these digital solutions for greenhouse gas emissions reduction?	Bag et al., 2021
		C3	Can you describe any specific regulations that have had a significant impact on your customer's environmental practices	Bag et al., 2021

Topic 5

Time estimate: 6 min

Drivers for Successful Digital Transformation in Advancing Environmental Sustainability in Gauteng's Manufacturing Industry

	Prompt to Lead Questions	Item Code	Semi-Structure Interview Question	Source
RQ5 (Risk): The potential negative effects direct and indirect of implementing DT such as AI and Digital Technologies on environmental sustainability?	Prompt: Though Digital Transformation (DTx) has brought about benefits, there is effects associated with the adoption of Digital Technology associated risks that may arise from digitalization. Such as an increase in energy consumption, disposal of digital hardware	R1	Can you share any specific concerns or risks related to the adoption of digital technologies, such as AI for environmental sustainability that are top of mind for you?	Dauvergne 2022 Truong 2022
		R2	And how are you actively addressing or planning to mitigate those risks or concerns?	Dauvergne 2022 Truong 2022
		R2.1	How do you think that concern might impact your organization or the environment? Can you elaborate on what specifically worries you about the risk or concern?	Optional probing question
		R2.2	What steps have you taken or plan to take to address that concern?	Optional probing question
		R2.3	Are there any resources or support systems you need to help address that concern?	Optional probing question

Research Questions

Topic: Drivers for Successful Digital Transformation in Advancing Environmental Sustainability in Gauteng's Manufacturing Industry.

1. Where would you say your organization is on the spectrum of adopting digital technologies like artificial intelligence?
The level of digital transformation and AI integration (e.g., exploratory, pilot projects, scaling up)
2. Can you describe your company's approach to adopting digital technologies such as AI? Is there a formal strategy in place, and if so, what are the key elements and objectives? How does this strategy align with the company's overall vision and goals?
3. How has top management demonstrated their commitment to leveraging AI and digital technologies for environmental sustainability and emissions reduction?
4. What opportunities has top management provided for employee training and development in AI, digital technologies, and sustainability?
5. How do digital technologies create value for your organization in terms of environmental sustainability and greenhouse gas reduction?
Describe how do you quantify the value derived from digital technologies
6. What metrics or key performance indicators (KPIs) has top management established to measure progress towards sustainability and emissions reduction goals?
7. How do you see the role of Digital Technologies evolving in driving environmental sustainability and greenhouse gas reduction efforts within the company?
8. Can you elaborate on how, in your experience, environmental regulations have influenced your company's approach to safeguarding the environment and implementing cleaner manufacturing practices?
9. How do you see the role of regulations evolving in promoting the use of digital technologies for a cleaner future?
10. In your experience, how do you see digital technologies impacting your company's approach to reducing greenhouse gas emissions?

11. Can you describe any specific digital tools or technologies your company is using to improve its environmental footprint?
12. In your opinion, what are the most promising areas for digital innovation to further reduce greenhouse gas emissions across various industries
13. How have you strived to achieve compliance with environmental regulations while maintaining economic viability?
Can you walk me through some specific examples of how your company has approached this challenge?
14. Are there any challenges associated with implementing these digital solutions for greenhouse gas emissions reduction at your organisation?
15. Can you describe any specific regulations that have had a significant impact on your company's environmental practices
16. Can you share any specific concerns or risks related to the adoption of digital technologies, such as AI for environmental sustainability that are top of mind for you?
17. And how are you actively addressing or planning to mitigate those risks or concerns?
How do you think that concern might impact your organization or the environment?
Can you elaborate on what specifically worries you about the risk or concern?
What steps have you taken or plan to take to address that concern?
Are there any resources or support systems you need to help address that concern?

APPENDIX 2: EMAIL INVITE

Dear Participant,

Thank you very much for your willingness to participate in my Gordon Institute of Science (GIBS) academic research topic Drivers for Successful Digital Transformation in Advancing Environmental Sustainability

Your insights are invaluable to this research project and appreciate you taking the time to share your experiences.

Preparation:

There is no specific preparation required for the interview. However, the questions will be focused on the following themes:

- Key Drivers for Digital technology such as AI in GHG Emission Reduction
- Quantifying Environmental Sustainability in Manufacturing
- Policy Pathways for Sustainable Manufacturing in South Africa
- The potential benefits, challenges, and roadblocks
- Unveiling the Environmental Downsides of Digital Transformation

Confidentiality:

We want to assure you that your participation in this research is completely confidential. All recordings and transcripts will be anonymized, and your name and company will not be associated with any of the data we collect.

Thank you again for your participation. Looking forward to speaking with you soon!

Best regards,

GIBS MBA Student

APPENDIX 3: CONSENT FORM

Informed consent for interview

I am a student at the Gordon Institute of Business Science (GIBS) enrolled in the master's in business administration (MBA) program. The purpose of this master's level research study is to gain a deeper understanding of the **key drivers of successful digital technologies, such as AI, to advance environmental sustainability in Gauteng's manufacturing industry**. The study aims to employ a qualitative approach to explore and undiscovered insights, build knowledge grounded in the lived experience of people within the industry.

The semi-structured interview will be employed and is expected to last approximately 60 minutes. The information provided from the expert interview will be kept strictly confidential. Interviewees' names and other identifying information will not be used in any reports or publications resulting from this research. Each interviewee will be assigned a pseudonym.

In addition, all information provided during the interview will be used for scholarly research study purposes only.

Your participation is voluntary, and you can withdraw at any time without penalty.

By signing this letter, you are indicating that you have given permission for:

- The interview is to be recorded.
- Verbatim quotations from the interview may be used in the report, provided they are not identified with your name or that of your organisation.
- The data to be used as part of a report that will be publicly available once the examination process has been completed; and
- All data to be reported and stored without identifiers.

If you have any concerns, please contact my supervisor or me. Our details are provided below.

Researcher name: GN Moshoeshoe

Research Supervisor name: T Pelsner

Email : 23984083@mygibs.co.za

Email theuns.pelsner@twinsafrika.com

Phone: +27 76 481 3884

Phone: +27 83 324 0402

Signature of participant: _____ Date: ____

Signature of researcher: _____ Date: _____

APPENDIX 4: ETHICAL CLEARANCE

**Gordon Institute
of Business Science**
University of Pretoria

**Ethical Clearance
Approved**

Dear Gwendoline Nyakallo Moshoeshoe,

Please be advised that your application for Ethical Clearance has been approved.
You are therefore allowed to continue collecting your data.
We wish you everything of the best for the rest of the project.

[Ethical Clearance Form](#)

Kind Regards

This email has been sent from an unmonitored email account. If you have any comments or concerns, please contact the GIBS Research Admin team.

APPENDIX 5: AI-GENERATED CODES

Research Question 1

Theme 1: Digital Leadership Drivers

Codes	Count	Category	Sub Themes	Key Themes
Lack of Global Digital Strategy	1	Global Digital Strategy	Leadership and Vision: Sustainability Digital Transformation	Leadership and Vision: Sustainability Digital Transformation
Leadership	8	Leadership	Leadership and Vision: Sustainability Digital Transformation	Leadership and Vision: Sustainability Digital Transformation
Sponsorship	5	Leadership	Leadership and Vision: Sustainability Digital Transformation	Leadership and Vision: Sustainability Digital Transformation
Leadership experience	2	Leadership	Leadership and Vision: Sustainability Digital Transformation	Leadership and Vision: Sustainability Digital Transformation
Leadership and Vision	1	Leadership	Leadership and Vision: Sustainability	Leadership and Vision: Sustainability Digital Transformation

			Digital Transformation	
Leadership Understanding of AI	1	Leadership	Leadership and Vision: Sustainability Digital Transformation	Leadership and Vision: Sustainability Digital Transformation
Leadership and Vision: Leadership understanding of AI's role Starting with business case and vision	1	Leadership and Vision	Leadership and Vision: Sustainability Digital Transformation	Leadership and Vision: Sustainability Digital Transformation
Sponsorship; HR Development; Training Promotion; Employee Growth; Skills Development	1	Leadership, Organisational Development	Leadership and Vision: Sustainability Digital Transformation	Leadership and Vision: Sustainability Digital Transformation
Business alignment	8	Organisational Alignment	Leadership and Vision: Sustainability Digital Transformation	Leadership and Vision: Sustainability Digital Transformation
Organisational alignment	7	Organisational Alignment	Leadership and Vision: Sustainability Digital Transformation	Leadership and Vision: Sustainability Digital Transformation

Balance: Need for balancing various factors.	1	Organisational Alignment	Leadership and Vision: Sustainability Digital Transformation	Leadership and Vision: Sustainability Digital Transformation
Business	1	Organisational Alignment	Leadership and Vision: Sustainability Digital Transformation	Leadership and Vision: Sustainability Digital Transformation
Problem Understanding: Need to understand business issues or customer problems.	1	Organisational Alignment	Leadership and Vision: Sustainability Digital Transformation	Leadership and Vision: Sustainability Digital Transformation
Use case analysis: Company alignment	1	Organisational Alignment	Leadership and Vision: Sustainability Digital Transformation	Leadership and Vision: Sustainability Digital Transformation
Business Alignment; Emerging Technologies; Phase of Implementations; Value Creation	1	Organisational Alignment; Digital Technologies, Business Value	Leadership and Vision: Sustainability Digital Transformation	Leadership and Vision: Sustainability Digital Transformation
predictive Thinking	1	Strategic Thinking	Leadership and Vision: Sustainability Digital Transformation	Leadership and Vision: Sustainability Digital Transformation

Strategy Implementation	1	Strategy Implementation	Leadership and Vision: Sustainability Digital Transformation	Leadership and Vision: Sustainability Digital Transformation
Management Buy-In: Difficulty in getting management and executives on board.	1	Top Management Support	Leadership and Vision: Sustainability Digital Transformation	Leadership and Vision: Sustainability Digital Transformation
Support from Group Executive	1	Top Management Support	Leadership and Vision: Sustainability Digital Transformation	Leadership and Vision: Sustainability Digital Transformation

Theme 2: Organisational Readiness for DTx Drivers

Codes	Count	Category	Sub Themes	Key Themes
Technology adoption	5	Change Management	Change and Adoption	Organisational Readiness
Change and Adoption Management: Importance of managing change and adoption.	1	Change Management	Change and Adoption	Organisational Readiness

Burning Platform for business turnaround	1	Change Management	Change and Adoption	Organisational Readiness
Buy-In Process: The process of gaining engineers' trust in digital data.	1	Change Management	Change and Adoption	Organisational Readiness
Engineer Resistance: Engineers' initial resistance to relying on digital data.	1	Change Management	Change and Adoption	Organisational Readiness
Resistance to Change: Questioning the need for new technologies.	1	Change Management	Change and Adoption	Organisational Readiness
Stakeholder Buy-In: Importance of getting buy-in from multiple stakeholders.	1	Change Management	Change and Adoption	Organisational Readiness
Transformation to Belief: Moving from resistance to acceptance and belief in data.	1	Change Management	Change and Adoption	Organisational Readiness
Responsibility	7	Organisational Culture	Cultural and Mindset Shifts for Environmental Stewardship	Organisational Readiness
Responsibilities	4	Organisational Culture	Cultural and Mindset Shifts for	Organisational Readiness

			Environmental Stewardship	
Work ethic	4	Organisational Culture	Cultural and Mindset Shifts for Environmental Stewardship	Organisational Readiness
Professionalism	3	Organisational Culture	Cultural and Mindset Shifts for Environmental Stewardship	Organisational Readiness
Organisational culture	2	Organisational Culture	Cultural and Mindset Shifts for Environmental Stewardship	Organisational Readiness
Baseline Behavior	1	Organisational Culture	Cultural and Mindset Shifts for Environmental Stewardship	Organisational Readiness
Corporate culture	1	Organisational Culture	Cultural and Mindset Shifts for Environmental Stewardship	Organisational Readiness
Organisational behavior	1	Organisational Culture	Cultural and Mindset Shifts for Environmental Stewardship	Organisational Readiness
Workplace dynamics	1	Organisational Culture	Cultural and Mindset Shifts for Environmental Stewardship	Organisational Readiness

Theme 3: Building a Digital-Ready Workforce Drivers

Codes	Count	Category	Sub Themes	Key Themes
Age Factor: Older age of senior managers and executives.	1	Human Capital	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Generational Differences: Younger generations are more open to adopting new technologies.	1	Human Capital	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Use case analysis: Organisational tenure	1	Human Capital	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Self-paced Learning	1	Learning Methods	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Self-Skilling: Employees independently acquiring new skills.	1	Learning Methods	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Encouragement of Self-Study	1	Learning Methods	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Professional Experience	7	Organisational Capability	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce

Technology expertise	5	Organisational Capability	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Work experience	4	Organisational Capability	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Professional background	3	Organisational Capability	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Professional role	3	Organisational Capability	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Experience	2	Organisational Capability	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Expertise	2	Organisational Capability	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Organisational role	2	Organisational Capability	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Internal Programs	1	Organisational capability	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Lack of Personal Adoption: Limited personal use and familiarity with AI among senior managers.	1	Organisational Capability	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Technical Expertise	1	Organisational Capability	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Career responsibilities: Career role	1	Organisational Capability	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce

Citizen Data Scientists	1	Organisational capability	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Individual Responsibility: Employees taking personal initiative for growth.	1	Organisational Capability	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Job description	1	Organisational Capability	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Technical Teams Efforts	1	Organisational Capability	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Career	8	Organisational Development	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Training and development	8	Organisational Development	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Career responsibilities: Proactiveness	6	Organisational Development	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Job responsibilities	6	Organisational Development	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
South African Context: Specific focus on skill development in South Africa.	1	Skills Development	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Business Skills Modules	1	Skills Development	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce

Holistic Personal Improvement	1	Skills Development	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
User Education: Importance of educating users about digital technologies.	1	Skills Development	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Data Science and Engineering Modules	1	Skills Development	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Open Source Learning Platform	1	Skills Development	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Skill Development: Need for developing skills to understand and work with digital solutions.	1	Skills Development	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Training and Skill Retention	1	Skills Development	Building a Digital-Ready Workforce	Building a Digital-Ready Workforce
Organisation	7	Organisational Structure	Empowering Employees: Sponsorship and Development	Building a Digital-Ready Workforce
Organisational development	5	Organisational Development	Organisation Development	Building a Digital-Ready Workforce
Professional development	4	Organisational Development	Organisation Development	Building a Digital-Ready Workforce

Human resources	3	Organisational Development	Organisation Development	Building a Digital-Ready Workforce
Capability Assessments	1	Organisational Development	Organisation Development	Building a Digital-Ready Workforce
Digital Academy	1	Organisational Development	Organisation Development	Building a Digital-Ready Workforce
Learning Curve	1	Organisational Development	Organisation Development	Building a Digital-Ready Workforce
Lack of Formal Structure: Absence of an Organisational framework for AI and technology training.	1	Organisational Structure	Organisation Development	Building a Digital-Ready Workforce

Theme 4: Sustainable DTx: Investment Drivers

Codes	Count	Category	Sub Themes	Key Themes
Cost management	2	Financial Management Resources	Sustainable Digital Transformation: Investment	Sustainable Digital Transformation: Investment
Investment in Technology	1	Financial Management Resources	Sustainable Digital Transformation: Investment	Sustainable Digital Transformation: Investment
Budget management	1	Financial Management Resources	Sustainable Digital Transformation: Investment	Sustainable Digital Transformation: Investment

Consultation Costs: High costs and difficulty of consulting with stakeholders.	1	Financial Management Resources	Sustainable Digital Transformation: Investment	Sustainable Digital Transformation: Investment
Financial Investment	1	Financial Management Resources	Sustainable Digital Transformation: Investment	Sustainable Digital Transformation: Investment
Financial management	1	Financial Management Resources	Sustainable Digital Transformation: Investment	Sustainable Digital Transformation: Investment
Upfront Investment vs. Returns: Concerns about the cost-benefit ratio of new technologies.	1	Financial Management Resources	Sustainable Digital Transformation: Investment	Sustainable Digital Transformation: Investment

Research Question 2

Theme 5: Holistic Performance Measurement

Codes	Count	Category	Sub Themes	Key Themes
Solution Impact	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement

Value alignment: Value alignment	8	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Value creation	6	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Value-driven	5	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Opportunity	3	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Use case analysis: Alignment with top management	3	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Business success: Company performance	2	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Business value	2	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Use case analysis: Alignment to company objectives	2	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Use case analysis: Organisational Alignment	2	Business Value	Holistic Performance Measurement	Holistic Performance Measurement

Use case analysis: Use case alignment	2	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Value alignment: Alignment to value	2	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Value alignment: HR	2	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Multiplier Effect	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Value Delivery: Importance of understanding where digital delivers value.	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Value of Digital Technologies	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Value Levers	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Value-Based Coding	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Open Platform Hackathons	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement

Achievement orientation	1	Business value	Holistic Performance Measurement	Holistic Performance Measurement
Business success: Focus on results	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Consultation and Quantification	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Cost Savings	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Customer Experience and Satisfaction	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Data Value	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Employee Benefits	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Financial Impact	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Financial Impact: Financial improvements Cost savings	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement

Financial Measurements	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
High expectations	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
High Value Products	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Increased Margins	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Opportunity for Improvement	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Opportunity Identification	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Opportunity Identification: Identifying opportunities for improvement Business unit level focus	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Use case analysis: Alignment with company objectives	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement

Use case analysis: Alignment with management	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Use case analysis: Corporate alignment	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Use case analysis: Golden use case	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Use case analysis: Organisation	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Use case analysis: Organisational level	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Use case analysis: Organisational Optimisation	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Use case analysis: Use case	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Use cases	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Value alignment: Value-driven approach	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement

Value-driven decision making	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Wider Benefits	1	Business Value	Holistic Performance Measurement	Holistic Performance Measurement
Business success: Company Growth	2	Business Value and Measurement	Holistic Performance Measurement	Holistic Performance Measurement
Projects: High profile projects	1	Strategic Business Value	Holistic Performance Measurement	Holistic Performance Measurement

Research Question 3

Theme 6: Policy and Regulatory

Codes	Count	Category	Sub Themes	Key Themes
Exceeding Minimum Requirements: Striving to comply beyond basic requirements.	1	Environmental Regulatory and Compliance	Environmental Sustainability: Role of Regulatory Bodies	Policy and Regulation
License to Operate	1	Environmental Regulatory and Compliance	Environmental Sustainability: Role	Policy and Regulation

			of Regulatory Bodies	
Compliance Efforts	1	Environmental Regulatory and Compliance	Environmental Sustainability: Role of Regulatory Bodies	Policy and Regulation
Environmental Regulations: Adherence to environmental regulations	1	Environmental Regulatory and Compliance	Environmental Sustainability: Role of Regulatory Bodies	Policy and Regulation
Exceeding Legal Requirements	1	Environmental Regulatory and Compliance	Environmental Sustainability: Role of Regulatory Bodies	Policy and Regulation
Government Commitments	1	Environmental Regulatory and Compliance	Environmental Sustainability: Role of Regulatory Bodies	Policy and Regulation
Lagging Policymakers: Policymakers are slow to adapt to new technologies.	1	Environmental Regulatory and Compliance	Environmental Sustainability: Role of Regulatory Bodies	Policy and Regulation
Law and Regulation; Validity in Reporting; Auditability Requirements, Technology driven by Audit; Impact of Law on Technology	1	Environmental Regulatory and Compliance	Environmental Sustainability: Role of Regulatory Bodies	Policy and Regulation

and Reactionary Regulation				
Legislation compliance	1	Environmental Regulatory and Compliance	Environmental Sustainability: Role of Regulatory Bodies	Policy and Regulation
Minimum Emission Standards	1	Environmental Regulatory and Compliance	Environmental Sustainability: Role of Regulatory Bodies	Policy and Regulation
Minimum Emissions Standards	1	Environmental Regulatory and Compliance	Environmental Sustainability: Role of Regulatory Bodies	Policy and Regulation
Proactive Compliance: Efforts to stay ahead of regulations.	1	Environmental Regulatory and Compliance	Environmental Sustainability: Role of Regulatory Bodies	Policy and Regulation
Punitive System	1	Environmental Regulatory and Compliance	Environmental Sustainability: Role of Regulatory Bodies	Policy and Regulation
Regulation of Operating Licenses	1	Environmental Regulatory and Compliance	Environmental Sustainability: Role of Regulatory Bodies	Policy and Regulation
Government Departments	1	Government Policies and Incentives	Government Policies and Incentives	Policy and Regulation

Government Incentives	1	Government Policies and Incentives	Government Policies and Incentives	Policy and Regulation
Core of Compliance: Digital technologies are central to regulatory compliance.	1	Digital Sustainability	Regulatory Compliance: Driver of Digital Transformation	Policy and Regulation
ESG Importance: Environmental, Social, and Governance as a critical focus.	1	Digital Sustainability	Regulatory Compliance: Driver of Digital Transformation	Policy and Regulation
Carbon Emissions Reduction: Energy Efficiency: Waste Management; Water usage; Sustainable Sourcing; Community Impact	1	Environmental Impact	Regulatory Compliance: Driver of Digital Transformation	Policy and Regulation
Government Compliance	1	Government Policies and Regulations	Regulatory Compliance: Driver of Digital Transformation	Policy and Regulation
Incentivising Economies	1	Incentives	Regulatory Compliance: Driver of Digital Transformation	Policy and Regulation
Penalties and Licenses: Errors can lead to penalties	1	License to Operate	Regulatory Compliance: Driver	Policy and Regulation

and license suspensions.			of Digital Transformation	
DMR Relationship: Challenging relationship with the Department of Mineral Resources (DMR).	1	Regulatory and Compliance	Regulatory Compliance: Driver of Digital Transformation	Policy and Regulation
Regulatory Compliance	1	Regulatory and Compliance	Regulatory Compliance: Driver of Digital Transformation	Policy and Regulation
Regulatory Compliance: Ensuring operations are within regulatory levels.	1	Regulatory and Compliance	Regulatory Compliance: Driver of Digital Transformation	Policy and Regulation
Compliance with Regulations	1	Regulatory and Compliance	Regulatory Compliance: Driver of Digital Transformation	Policy and Regulation
Tax Penalties	1	Regulatory and Compliance	Regulatory Compliance: Driver of Digital Transformation	Policy and Regulation
License to Operate	1	Regulatory and Compliance	Regulatory Compliance: Driver of Digital Transformation	Policy and Regulation

Compliance Consequences: Serious repercussions for non-compliance.	1	Regulatory and Compliance	Regulatory Compliance: Driver of Digital Transformation	Policy and Regulation
Compliance with legislation	1	Regulatory and Compliance	Regulatory Compliance: Driver of Digital Transformation	Policy and Regulation
Department of Fisheries, Forestry, and Environment	1	Regulatory and Compliance	Regulatory Compliance: Driver of Digital Transformation	Policy and Regulation
Industry-Regulator Collaboration: Need for cooperation between industry and regulators.	1	Regulatory and Compliance	Regulatory Compliance: Driver of Digital Transformation	Policy and Regulation
Law and Regulation	1	Regulatory and Compliance	Regulatory Compliance: Driver of Digital Transformation	Policy and Regulation
Regulated Environment: Operating in a highly regulated sector.	1	Regulatory and Compliance	Regulatory Compliance: Driver of Digital Transformation	Policy and Regulation
Regulatory Catch- Up: Expectation that regulators will eventually update their methods.	1	Regulatory and Compliance	Regulatory Compliance: Driver of Digital Transformation	Policy and Regulation

Sulphur Content Regulation	1	Regulatory and Compliance	Regulatory Compliance: Driver of Digital Transformation	Policy and Regulation
Critical Role of Regulators: Importance of regulators understanding digital technologies.	1	Regulatory Framework	Regulatory Compliance: Driver of Digital Transformation	Policy and Regulation
Digital Technologies for Compliance: Using digital tools to achieve compliance.	1	Sustainability Digital Transformation	Regulatory Compliance: Driver of Digital Transformation	Policy and Regulation

Theme 7: Environmental Sustainability

Codes	Count	Category	Sub Themes	Key Themes
Air and Water Samples	1	Environmental Impact	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Environmental Influence	1	Environmental Factors	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Dust Emissions: Monitoring dust	1	Environmental Impact	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability

emissions at the plant.				
Reduce Pollution: Efforts to minimise environmental impact.	1	Environmental Impact	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Reducing Emissions: Efforts to lower NOx and SOx levels.	1	Environmental Impact	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
People and Environment Safety	1	Environmental Impact	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Carbon Footprint Reduction	1	Environmental Impact	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Emissions Reduction	1	Environmental Impact	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Environmental Care	1	Environmental Impact	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Carbon Footprint Reduction: Initiatives to lower the carbon footprint.	1	Environmental Impact	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability

Dirty Business: Cement manufacturing is inherently polluting.	1	Environmental Impact	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Dust Control: Managing dust emissions.	1	Environmental Impact	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Emissions Focus: Primary focus on emissions.	1	Environmental Impact	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Emissions Management	1	Environmental Impact	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Emissions Reduction Targets	1	Environmental Impact	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Equipment Damage: Risks of equipment damage due to faulty data.	1	Environmental Impact	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
NOx and SOx KPIs: Focus on key performance indicators for nitrogen oxide and sulphur dioxide.	1	Environmental Impact	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
NOx and SOx Levels: Ensuring nitrogen oxide and sulphur dioxide	1	Environmental Impact	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability

levels are acceptable.				
NOx and SOx: Specific focus on nitrogen oxide and sulphur dioxide.	1	Environmental Impact	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Proactive Leak Detection: Using technology to detect water leaks early.	1	Environmental Impact	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Water Resource Management: Managing water usage and detecting leaks.	1	Environmental Impact	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Environmental Monitoring: Monitoring environmental conditions like dust and air pollution.	1	Environmental Monitoring	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Varying Environmental Limits	1	Environmental Sustainability	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Employee and Community Safety: Ensuring the safety of employees and surrounding communities.	1	Environmental Sustainability	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability

People and Planet	1	Environmental Sustainability	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Sustainability Commitment	1	Environmental Sustainability	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Sustainability Improvement	1	Environmental Sustainability	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Environmental Sustainability Approach	1	Environmental Sustainability	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Macro Standards	1	Environmental Sustainability	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Specific Focus on Nox and SO2	1	Environmental Sustainability	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability
Carbon Tax	1	Regulatory and Compliance	Digital Innovation: Environmental Sustainability	Digital Innovation: Environmental Sustainability

Theme 8: Sustainable Manufacturing: AI-Driven Environmental Sustainability

Codes	Count	Category	Sub Themes	Key Themes
-------	-------	----------	------------	------------

Model Building	1	Digital AI Technology	Sustainable Manufacturing	Sustainable Manufacturing
Model Performance and Benefits	1	Digital AI Technology	Sustainable Manufacturing	Sustainable Manufacturing
AI in Operations: Use of AI models in operations for several years.	1	Digital AI Manufacturing	Sustainable Manufacturing	Sustainable Manufacturing
Digital Monitoring: Use of digital technologies for monitoring emissions.	1	Digital Monitoring	Sustainable Manufacturing	Sustainable Manufacturing
Visualisation and UX Modules	1	Digital Monitoring	Sustainable Manufacturing	Sustainable Manufacturing
Innovation	1	Innovation	Sustainable Manufacturing	Sustainable Manufacturing
2022 goal for AI-driven operations improvement	1	Smart Manufacturing	Sustainable Manufacturing	Sustainable Manufacturing
Energy Efficiency Technology	1	Smart Manufacturing	Sustainable Manufacturing	Sustainable Manufacturing
Sustainability of Digital Transformation	1	Sustainability Digital Transformation	Sustainable Manufacturing	Sustainable Manufacturing
Safety and Sustainability	1	Sustainability Digital Transformation	Sustainable Manufacturing	Sustainable Manufacturing

Theme 9: Sustainability Risk Drivers

Codes	Count	Category	Sub Themes	Key Themes
IT Functionality: Ensuring IT systems work properly without environmental impact.	1	Technology Performance and Sustainability	Digital Sustainability: Risk of AI and technology Adoption	Digital Sustainability: Risk of AI and technology Adoption
Cybersecurity Risks: Concerns about cybersecurity and potential attacks.	1	Technology Risk	Digital Sustainability: Risk of AI and technology Adoption	Digital Sustainability: Risk of AI and technology Adoption
Data Misinterpretation: Risks of misinterpreting data.	1	Technology Risk	Digital Sustainability: Risk of AI and technology Adoption	Digital Sustainability: Risk of AI and technology Adoption
AI Hallucination: Potential for AI tools to produce incorrect data.	1	Technology Risk	Digital Sustainability: Risk of AI and technology Adoption	Digital Sustainability: Risk of AI and technology Adoption
Digital Technology Impact	1	Technology Risk	Digital Sustainability: Risk of AI and	Digital Sustainability: Risk of AI and technology Adoption

			technology Adoption	
Risk of Model Regression	1	Technology Risk	Digital Sustainability: Risk of AI and technology Adoption	Digital Sustainability: Risk of AI and technology Adoption
Vigilance: Constant vigilance in digital operations.	1	Technology Risk	Digital Sustainability: Risk of AI and technology Adoption	Digital Sustainability: Risk of AI and technology Adoption
Business Continuity: Ensuring policies and processes for continuity in case of cyber-attacks.	1	Technology Risk	Digital Sustainability: Risk of AI and technology Adoption	Digital Sustainability: Risk of AI and technology Adoption
Cybersecurity Vigilance: Continuous effort to secure digital environments.	1	Technology Risk	Digital Sustainability: Risk of AI and technology Adoption	Digital Sustainability: Risk of AI and technology Adoption
Danger of Inaccurate Data: Potential dangers of incorrect data.	1	Technology Risk	Digital Sustainability: Risk of AI and technology Adoption	Digital Sustainability: Risk of AI and technology Adoption
Risk of Cyber Attacks: Potential severe impact of cyber-attacks on	1	Technology Risk	Digital Sustainability: Risk of AI and	Digital Sustainability: Risk of AI and technology Adoption

business operations.			technology Adoption	
Reputational Risk: Higher risks in customer-facing AI applications.	1	Reputational Risk	Digital Sustainability: Risk of AI and technology Adoption	Digital Sustainability: Risk of AI and technology Adoption

Research Question 4

Theme 10: Digital Sustainability: AI Digital Technologies Drivers

Codes	Count	Category	Sub Themes	Key Themes
Artificial Intelligence (AI)	8	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Technology	8	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Emerging technology	7	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Digital technologies	6	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies

Emerging technologies	4	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Automated Machine Learning Tool	1	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
IoT Tools: Use of Internet of Things tools and sensors.	1	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Sensor Functionality	1	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Core Technologies: Key technologies being used.	1	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
IoT TechnologiesA1:C445: Integration of IoT for monitoring and Optimisation.	1	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
ABB Knowledge Manager: Specific tool used for data management.	1	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies

AI as a tool for achieving business strategy	1	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
AI Model	1	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
AI Utilisation	1	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Digital as Utilities: Digital technologies are as fundamental as utilities like power.	1	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Digital Pillars: Importance of foundational digital elements.	1	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Digital Technologies: Use of digital tools to improve sustainability.	1	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Essential Role of Digital Technologies: Digital technologies are indispensable.	1	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies

Foundational Element: Digital is a foundational aspect, not a standalone pillar.	1	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Information Technology	1	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Low Code/No Code Development	1	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Measurement Technology	1	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Microsoft Azure: Platform for data storage and analysis.	1	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Solution Fit: Ensuring digital solutions fit business problems.	1	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Technology landscape	1	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies

Technology role	1	Digital Technology	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Technology Exploration; Equipment Replacement; Pollution Effect	1	Environmental Impact	Digital Sustainability: AI and Digital Technologies	Digital Innovation: Environmental Sustainability
Technology innovation	3	Innovation	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Digital Solutions Usage and Satisfaction	1	Technology Adoption	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Next Step: Machine Learning	1	Technology Adoption	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Adoption and Implementation	1	Technology Adoption	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
AI Deployment	1	Technology Adoption	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies

AI Deployment at business unit level	1	Technology Adoption	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
AI Deployment: Using AI for operational improvements AI as a tool and technology	1	Technology Adoption	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Digital Maturity Continuum: Varying levels of digital maturity across the company.	1	Technology Adoption	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Digital Technology as Enabler	1	Technology Adoption	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Digital Transformation (2): Digital Technology Adoption	1	Technology Adoption	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Integration of AI	1	Technology Adoption	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Technology adaptation	1	Technology Adoption	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies

Digital Transformation	8	Digital Transformation	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Digital Transformation (2): Digital strategy	2	Digital Transformation	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Slow Transformation: Slow rate of digital transformation.	1	Digital Transformation	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Digital Transformation (2): AI implementation	1	Digital Transformation	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Digital Transformation (2): Digital initiatives	1	Digital Transformation	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Digital Transformation (2): IT expertise	1	Digital Transformation	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Digital Transformation (2): IT strategy and implementation	1	Digital Transformation	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies

Digital Transformation (2): Phase two	1	Digital Transformation	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Digital Transformation (2): Technology Strategy	1	Digital Transformation	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Enabling Technology: Digital as a tool to support business strategy.	1	Digital Transformation	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Indispensability of Digital Technologies: Digital technologies are essential.	1	Digital Transformation	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Old vs. New Methods: Discrepancy between traditional compliance methods and new digital approaches.	1	Digital Transformation	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies
Sustainability	7	Sustainability Digital Transformation	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: AI and Digital Technologies

Theme 11: Benefits of DTx for Environmental Sustainability

Codes	Count	Category	Sub Themes	Key Themes
Applied in Maintenance	1	Application of Manual Processes in Maintenance	Application of Manual Processes in Maintenance	Benefits of DTx for Environmental Sustainability
Efficiency	5	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Organisational improvement	3	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Operational Excellence	2	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Continuous Improvement	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Technology and People	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Cost Efficiency: Manual processes are not cost-effective.	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Yield Optimisation	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability

Cost Efficiency	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Energy Consumption: Impact on energy consumption.	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Efficiency Improvement	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Effort Reduction	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Production Optimisation: Using digital technologies to optimise production processes.	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Asset o	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Coal Consumption: Monitoring and reducing coal usage.	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Continuous Improvements	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability

Energy Consumption Optimisation	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Energy Efficiency	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Energy Optimisation	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Equipment Optimisation	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Identify operational improvement opportunities	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Improving performance	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Operational Asset Setup	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Operational Excellence: Efficiency improvement Specific focus on ammonia and methanol business unit	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability

Operations Throughput	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Resource Efficiency: Efficient use of natural resources Reduction in natural gas consumption	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Resource Efficiency	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Task-oriented	1	Operational Efficiency	Environmental and Operational Efficiency	Benefits of DTx for Environmental Sustainability
Performance improvement	8	Operational Efficiency	Maximise Operational Efficiency	Benefits of DTx for Environmental Sustainability
Proactivity	8	Operational Efficiency	Maximise Operational Efficiency	Benefits of DTx for Environmental Sustainability

Theme 12: Challenges in Implementing AI for Sustainable Manufacturing

Codes	Count	Category	Sub Themes	Key Themes
Repetition and Persistence: Need	1	Application of Manual	Sustainable Manufacturing Challenges	Sustainable Manufacturing Challenges

for repeating efforts and persistence.		Processes in Maintenance		
Work pressure	2	Challenges	Sustainable Manufacturing Challenges	Sustainable Manufacturing Challenges
Acknowledging Challenges: Recognising that transformation is not quick or easy.	1	Challenges	Sustainable Manufacturing Challenges	Sustainable Manufacturing Challenges
Challenges	1	Challenges	Sustainable Manufacturing Challenges	Sustainable Manufacturing Challenges
Challenges in implementations	1	Challenges	Sustainable Manufacturing Challenges	Sustainable Manufacturing Challenges
Difficulty in Adoption: Challenges in adopting new technologies.	1	Challenges	Sustainable Manufacturing Challenges	Sustainable Manufacturing Challenges
Missed Targets: Difficulty in meeting business targets.	1	Challenges	Sustainable Manufacturing Challenges	Sustainable Manufacturing Challenges
Tough Operating Environment: Challenging business conditions affecting investment in training.	1	Challenges	Sustainable Manufacturing Challenges	Sustainable Manufacturing Challenges

Manual Processes Cumbersome: Manual methods are impractical.	1	Manual Processes Cumbersome	Sustainable Manufacturing Challenges	Sustainable Manufacturing Challenges
Error Prone: Manual methods are prone to errors.	1	Manual Processes Cumbersome	Sustainable Manufacturing Challenges	Sustainable Manufacturing Challenges
Work responsibilities	1	Work	Sustainable Manufacturing Challenges	Sustainable Manufacturing Challenges
Work-related stress	1	Work	Sustainable Manufacturing Challenges	Sustainable Manufacturing Challenges

Research Question 5

Theme 13: Digital Sustainability: Risk of AI Technology Adoption

Codes	Count	Category	Sub Themes	Key Themes
AI Energy Consumption	2	Indirect Environmental Impact	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: Risk of AI technology adoption
Carbon Emissions	2	Indirect Environmental Impact	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: Risk of AI technology adoption

Cloud Utilisation	2	Direct Environmental Impact	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: Risk of AI technology adoption
Cloud vs. On-Site Deployment	1	Direct Environmental Impact	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: Risk of AI technology adoption
Consulting Resources	1	Operational Efficiency	Environmental and Operational Efficiency	Digital Sustainability: Risk of AI technology adoption
Cost Considerations	1	Indirect Environmental Impact	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: Risk of AI technology adoption
Cost Management Concern	1	Resource Management	Maximise Operational Efficiency	Digital Sustainability: Risk of AI technology adoption
Data Center Efficiency	2	Indirect Environmental Impact	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: Risk of AI technology adoption
Design Considerations	1	Resource Management	Maximise Operational Efficiency	Digital Sustainability: Risk of AI technology adoption
Green Hardware	3	Direct Environmental Impact	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: Risk of AI technology adoption

Digitalisation Impact	1	Indirect Environmental Impact	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: Risk of AI technology adoption
Electricity consumption awareness	1	Resource Management	Maximise Operational Efficiency	Digital Sustainability: Risk of AI technology adoption
Environmental Tangibility	1	Sustainability Challenge	Balancing Economic and Environmental Priorities in Industrial Production	Digital Sustainability: Risk of AI technology adoption
ESG evaluation gaps	1	Sustainability Challenge	Balancing Economic and Environmental Priorities in Industrial Production	Digital Sustainability: Risk of AI technology adoption
Hybrid Environment	1	Indirect Environmental Impact	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: Risk of AI technology adoption
Inefficiency and Environmental Impact	1	Indirect Environmental Impact	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: Risk of AI technology adoption
Manufacturing Constraints	1	Sustainability Challenge	Balancing Economic and Environmental Priorities in	Digital Sustainability: Risk of AI technology adoption

			Industrial Production	
Negligible User Impact	1	Indirect Environmental Impact	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: Risk of AI technology adoption
Net Positive Impact	1	Direct Environmental Impact	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: Risk of AI technology adoption
Net positive impact of digital adoption	1	Indirect Environmental Impact	Digital Sustainability: AI and Digital Technologies	Digital Sustainability: Risk of AI technology adoption
Operational Flexibility	1	Resource Management	Maximise Operational Efficiency	Digital Sustainability: Risk of AI technology adoption
Optimisation of hybrid environments	1	Operational Efficiency	Environmental and Operational Efficiency	Digital Sustainability: Risk of AI technology adoption
Optimised Resource Usage	4	Resource Management	Maximise Operational Efficiency	Digital Sustainability: Risk of AI technology adoption
Pay-for-Use Model	3	Resource Management	Maximise Operational Efficiency	Digital Sustainability: Risk of AI technology adoption
Recycling Challenges	1	Sustainability Challenge	Balancing Economic and Environmental Priorities in	Digital Sustainability: Risk of AI technology adoption

			Industrial Production	
Risk factors in sustainability	1	Sustainability Challenge	Balancing Economic and Environmental Priorities in Industrial Production	Digital Sustainability: Risk of AI technology adoption
Scalability in Cloud	1	Operational Efficiency	Environmental and Operational Efficiency	Digital Sustainability: Risk of AI technology adoption

APPENDIX 6: FINDINGS

Theme	Key Findings	Implications	Challenges
Research Question 1 (Organisational Capabilities): What are the key drivers for the successful adoption of DT AI in the Manufacturing sector to achieve the environmental sustainability dimension of greenhouse gas emission reduction?			
Theme 1. Digital Leadership Drivers	Leadership is key driver: - defines the vision and overall integrated business strategy, - supports the overall DTx including AI integration	Supports Literature: - CEOs and C-Suite Executive Teams must lead digital strategies. - leadership and strategy are key elements successful integration of DTx.	Getting leadership alignment and conviction
	Organisations will likely navigate potentially disruptive shifts in leadership roles	Extends Literature: leaders with specific qualities and capabilities, particularly strategic thinking across complex networks, the existing capabilities of the current leadership within organisations	Securing leadership alignment and conviction, even in companies with capable leaders

	Senior leader's proactive championing of digital initiatives promotes innovation at lower levels	Supports Literature: The personal motivation of leaders: - impacts organisation's sustainability strategy, - leads to greater value creation and positive outcomes from sustainability initiatives - managerial influence, shaping employee attitudes for successful DTx to achieve environmental sustainability targets	Global manufacturers, local leadership lack of passion for driving innovation, unless mandated from global headquarters
	Cultural shift is essential to promote: - innovation - technology adoption - sustainability	Supports Literature: managerial influence and a positive attitude can contribute to the successful implementation of digital initiatives to achieve environmental sustainability targets.	Adoption and overcoming organisational inertia
Theme 2. Organisational readiness for DTx drivers	Effective change management: - change management and communication is often overlooked for digital sustainability initiatives. - technology is the main priority and people aspects are not considered.	Contradict Literature: - radical transformation of workforce skillsets, - role of effective leadership to drive change - specific strategies for AI adoption and digital transformation change management.	Change management: - driven at the project initiative level - not supported by a comprehensive change strategy optimal for

			disruptive technologies such as AI and DTx requirements
	Cultural shift is essential to promote: - innovation - technology adoption to enhance sustainability at lower levels. Coaching is essential to adjust: - a large contingent of blue-collar workers. - integrate coaching as a strategic intervention to support employees navigate change and to embrace desired behaviours	Contradicts Literature: - the role of coaching - organisational factors, including the culture of openness to change are critical for realising the benefits of digital technology implementation.	Employee coaching is often overlooked. AI fundamentally going to change employees' work
Theme 3. Building a digital-ready workforce	Lack of digital talent: - shortage of skills and expertise to develop and integrate AI solutions to address environmental sustainability.	Supports Literature: - only highly skilled software engineers can use AI technology.	Employee development: slow and long development cycle required to cultivate the necessary skills.

drivers Findings	- data scientist skills and expertise talent shortage	- companies struggle to realise the full potential of AI technology advances due to skill shortages. - prioritise talent development by identifying valuable skills for now and in the future. - be proactive in developing digital skills rather than reactive. - adapt to the rapid changes brought by Industry 4.0. - development cycle is slow and takes time	
	Effective HRM should: - streamline the skill development process, - align with business changing needs and DTx strategy.	Extends Literature: HRM offers long-term economic success in the digital era, beyond CSR.	Training and development funding allocation challenges, hamper the efforts to develop the needed capacity to implement digital technologies.
	Short and long-term strategies to build organisations digital capabilities.	Supports Literature: - a blended training approach is undertaken to address the current needs. - companies through strategic workforce planning, should assess current and future needs.	Digital talent and skills availability to advance AI adoption

Theme 4. Sustainable DTx: Investment Drivers	The AI technology integration upfront costs often exceed the immediate benefits	Supports Literature: - hidden costs of AI integration - balancing short-term financial objectives with long-term environmental goals. - efficient investment is a key driver Extends Literature: - top management plays a crucial role in allocating funding to support the integration of digital technologies. Contradict Literature: To transform traditional to sustainable manufacturing, adequate financial resources and investments in essential.	Investment required to upgrade outdated or modernise the manufacturer's operational technology for DTx readiness which might be higher than the initial investment
	Manufacturing sector generally lags in technology adoption due to initial investment concerns versus immediate expected returns.	Contradicts Literature: - Emerging economies challenge of adopting sustainable practices - Siloed decision- making short-term financial objectives versus long-term sustainability.	The financial burden may lead to a focus on the challenges of investment rather than potential long- term benefits

		Negative moderating effects on financial performance due to temporal lag between the implementation of sustainability initiatives	
Theme	Key Findings	Implications	Challenges
Research Question 2 (Impact): How is success measured for measuring the effect of adopting DT for the environmental sustainability dimension?			
Theme 5. Holistic Performance Measurement	Holistic performance measurement is crucial for assessing the full impact of DTx.	Support Literature: Environmental sustainability encompasses: - the strategies, - processes, - measures, - initiatives of an organisation to reduce its negative and increase its positive impact on the natural environment. Extends Literature: - Manufacturers must consider strategic approach, balance trade-offs and define comprehensive	Balancing trade-offs

		environmental strategies meaning both positive and negative effects are considered. - Reinforces the need for manufacturers to integrate sustainability into their core strategies. Awareness of the interdependence of the sustainability pillars is crucial for strategic approach and for fostering a more integrated approach.	
	Manufacturers are committed to compliance to global integrated financial reporting requirements.	Extends Literature: to effectively measure the impact of sustainability initiatives, a holistic approach is necessary. This involves quantifying environmental outcomes, such as greenhouse gas emissions reduction, energy conservation, and waste minimisation.	
	Manufacturers measurements and performance includes measuring the effectiveness of AI integration	Manufacturers need to consider beyond comprehensive approaches to measuring AI and measure the adoption thereof. Support literature: for full potential: - manufacturers must follow a strategic approach.	

		Contradict literature: careful planning and execution of initiatives align with overall business objectives.	
	Manufacturers uses AI and other DT for environmental monitoring and improvement	Support literature: Environmental sustainability encompasses strategies and measurement	
	Manufacturers has set ambitious emissions reduction targets	Support literature: Policy on 2030 sustainability targets	

Theme	Key Findings	Implications	Challenges
Research Question 3 (Opportunities and Challenges): What policy initiatives and regulatory frameworks are necessary to promote sustainable development in the South African manufacturing sector?			
Theme 6. Policy and Regulation	Green industrial policy:- promoting green manufacturing - low-carbon innovation, - offers a potential solution for SA to achieve sustainable development. Due to lack of incentives: - prioritise short-term financial objectives from their AI and other digital technologies investments, which undermines AI integration for achieving long-term sustainability goals	Supports Literature: - an effective industrial policy is essential for promoting sustainability initiatives. - Regulations can act as a catalyst for the adoption of sustainability-oriented DTx. Contradict Literature: - in today's digital world, government agencies influence businesses. - government support in the form of tax breaks, subsidies, financial and technical assistance.	The lack of incentives underscores a critical barrier to promoting green manufacturing and low-carbon innovation.
	There is a notable disconnect between the government and the manufacturing industry.	Extends Literature: - policy uncertainty as a barrier.	Current frameworks often hinder widespread renewables utilisation.

		- supportive policy and regulations can empower businesses to leverage digitalisation for environmental sustainability - targeted policy changes can advance environmental sustainability - policy reforms are essential to incentivise renewable energy adoption and align with SDGs	
	The competitive landscape is the primary driver of digital transformation in the manufacturing industry	Support Literature: Manufactures primarily focus on competition, in addition must also consider the role of other drivers, such as innovation capacity, sustainability, customer expectations, and business model innovation Contradicts Literature: Government support to promote manufacturing sector investment in digital technology adoption	
Theme 7. Environmental Sustainability	Manufacturing operating license: - Requires a license to operate	Supports Literature: - the critical need to holistically assess the environmental impact.	Environmental challenges to be addressed

	- must implement monitoring systems. - must implement alerts and address non-compliance to targets	- the license to operate.	
	Merely adopting green technologies does not automatically reduce energy consumption or lower pollution.	Despite advanced green production models, energy consumption will remain high with severe pollution levels.	Economic growth leading to an increase in GHG emissions
	AI technology has the potential to advance environmental sustainability practices. Manufacturers are increasingly adopting digital technologies to achieve environmental targets.	Supports Literature: AI possesses significant potential for driving CE and sustainability management.	Slow adoption rate
	A comprehensive strategy that includes both industrial and natural sources for effective environmental impact management.	Supports Literature: - trends and drivers of global GHG emissions and sources	
Theme 8. Sustainable Manufacturing:	Manufacturing industry is at a low digital maturity, specifically a sector is in early stage of integrating AI	Extends Literature:	Return on investment from implemented use cases or solution

AI-Driven Environmental Sustainability	technologies for advancing environmental sustainability	AI possesses potential for driving CE and sustainability management. - the integration of Industry 4.0 and sustainability is still in its early stages. - the risk associated with technological obsolescence in the context of innovation may erode value. Contradict Literature: to transform traditional to sustainable manufacturing, adequate financial resources and investments required	
	Urgent need for a formal, integrated business and digital strategy along with strong senior management support.	Supports Literature: CEOs and C-Suite Executive Teams must lead digital strategies; leadership and strategy are key elements that contribute to the successful integration of DTx	Lack of alignment and commitment from senior management is a significant impediment to effective business and digital strategy
	Manufacturers are running various number of environmental	Extends Literature:	The number of POCs are siloed and this fragmented

	sustainability initiatives in the form of proof of concepts.	- Awareness of the interdependence of the concepts is crucial for a strategic approach and for fostering a more integrated approach. - Rigorous planning to ensure sustainability initiatives align with overall business objectives	approach may lead to ineffective integration into the broader program.
	Scaling initial success: adopt a systematic approach to drive AI technology integration from unit level to factory level, and ultimately to the enterprise level: - organisations can effectively leverage digital technologies to enhance operational efficiency - drive sustainable practices	Contradicts Literature: Environmental sustainability encompasses the strategies, processes, measures, and initiatives: - follow a strategic approach aligned with overall business objectives. - works of careful planning and execution of initiatives align with overall business objectives.	Many uncoordinated AI proof of concepts are not scalable
Theme 9. Sustainability Risk Drivers	Significant risks associated with the integration of digital technologies: rapid pace of technology development may render implemented technologies obsolete.	Support Literature: - the rapid pace of technological progress can render investments obsolete before they yield a return. - Carbon tax considerations	Rendering investments obsolete before generating a return on investment

	A significant threat of emerging cybersecurity risks for the manufacturing industry.	Supports Literature: - the cybersecurity an essential component of DTx and AI technology integration - Cybersecurity measures - AI as a potent cyber defense tool	Manufacturers often see environmental sustainability as a cost
	Addressing the social implications of DTx is overlooked: - prioritising AI integration and technology aspects and overlooking human related aspects.	Employees' resistance to change and fears about AI and digital technologies can be a major obstacle to successful implementation.	Employee impact and support
Theme	Key Findings	Implications	Challenges
Research Questions 4 (Benefits and Challenges): What are the potential environmental benefits and challenges, barriers, and constraints faced by manufacturing organisations when implementing DTx for sustainability purposes?			
Theme 10. Digital Sustainability: AI Digital Technologies drivers	AI is a key enabler of sustainability strategies in the manufacturing sector.	Adds literature AI key enabler of environmental sustainability Support Literature:	- lack of data strategy and data quality - current infrastructure and outdated operational technology

		- DTx, specifically AI, big data, and the IoT, offer a compelling solution for addressing environmental sustainability challenges.	- skills and digital talent availability - ethical and social considerations
	Manufacturers use the advanced measurement technologies to leverage vast amounts of data through data analytics.	Support Literature: Innovative approach: - harnesses advanced technologies to optimise data management, - improves efficiency and sustainability in manufacturing. Continuous improvement of manufacturing sustainability is crucial and improves their competitiveness. Extends Literature: - the convergence of digital technologies and intelligent manufacturing has given rise to sustainable intelligent manufacturing	Data readiness and lack of clear data strategy
Theme 11. Benefits of DTx for	The adoption of AI and other digital technologies is identified as a key	Supports Literature: Indirect effects of DTx and AI integration	The need to balance environmental sustainability

Environmental Sustainability	driver for achieving environmental sustainability within manufacturing.	Contradict Literature: AI and sustainability global market growth reveals: - competing priorities, - forcing difficult trade-offs.	targets with profitability objectives.
	Optimising for value is complex; leveraging AI and advanced analytics can help find a solution that maximises business value.	Support Literature: - a positive influence between digital transformation and sustainability performance - digital transformation and sustainability practices were conceived to address different purposes.	- complexity is compounded, multiple stakeholders' - overall benefits of sustainability initiatives alignment.
	Achieving environmental impact may often be an indirect benefit of adopting digital technologies.	Support Literature: - stakeholder involvement and incorporating the perspectives of various stakeholders, - to maximise the benefits of sustainability strategies, businesses must carefully consider the specific context in which they operate and tailor their approaches accordingly	Complex stakeholder alignment and buy-in
	Not all opportunities will yield desired outcomes, manufacturers must prioritise and invest in high-	Extends Literature:	- Identifying high potential value use cases.

	potential AI technology-enabled use cases	managers often prioritise short-term economic performance over sustainability.	- Short-term economic focus over sustainability
Theme 12. Challenges in Implementing AI for Sustainable Manufacturing	Manufacturers outdated process equipment that lacks monitoring and data transmission capabilities: - making it harder to integrate with AI and other digital technologies. - makes it difficult to track and report on greenhouse gas emissions effectively. Digital maturity of companies is a critical factor in their sustainability efforts.	Extends Literature: - the integration of Industry 4.0 and sustainability is still in its early stages. - operational technology readiness and digital maturity - invest to replace or modernise the current outdated manufacturing equipment - enable data-driven operations and sustainability.	Stranded assets
	The need for substantial upfront costs poses a considerable barrier for many organisations.	Extends literature: - sustainable manufacturing adequate financial resources and investments - new technologies increase competitiveness by reducing costs	Financial burden and huge capital outlay

		- the rapid rate of technology changes and emerging disruptive technologies may result in making earlier technology absolute	
	AI technology integration to generate sustainable value, an effective systems integration is needed.	Extends Literature: - AI system integration challenges for leveraging data - organisational readiness for successful DTx implementation	Value case complexity
	Change management must not be underestimated. AI technologies adoption to advance sustainable practices often involves significant changes to manufactures. Changes can be met with resistance from employees.	Contradicts Literature: organisational culture transformation	
	A clear data strategy is a key driver for the successful integration of AI and digital technologies. Without a clear strategy and a solid data foundation, manufacturers may	Support Literature: - enterprise-level data strategy to support data-driven operations and enable manufacturing DTx and AI integration	Data readiness and lack of data strategy to support DTx and AI integration

	struggle to leverage the full potential of AI technologies fully.	- big data analytics, AI, IoT, and blockchain are the primary DTX employed in the manufacturing sector. - to fully comprehend data-driven sustainability, it is essential to understand how data and analytics can be used to measure and improve environmental, social, and economic performance.	
Theme	Key Findings	Implications	Challenges
Research Question 5 (Risk): The potential negative effects, direct and indirect, of implementing DT such as AI for environmental sustainability?			
Theme 13. Digital Sustainability: Risk of AI technology adoption	Manufacturing industry tends to neglect the environmental sustainability impact in the sustainability digital initiatives value case	Contradict Literature: the direct environmental effects as: - the production of digital infrastructure, - the energy consumption of digital infrastructure, - mining of the hardware to be used as digital infrastructure, - collection, recycling, and disposal of digital assets physical infrastructure,	AI technology is the major contributor directly impacting the environment.

		- greenhouse emissions for the generation of power used by DTx.	
	Manufacturers have difficulty quantifying the indirect environmental impacts of AI adoption. This may lead to value assessment gaps.	Contradict literature: - the direct and indirect effects of AI integration. - urgent need for sustainable practices; while green production models, energy consumption remains high, and pollution levels can be severe.	- Quantifying environmental outcomes and impact of AI - Complex value case and well-defined value logic

APPENDIX 7: THEMES LINKED TO THE RESEARCH QUESTIONS

RESEARCH QUESTIONS	THEMES
1. What are the key drivers for successful adoption of DT AI in the Manufacturing sector to achieve the environmental sustainability dimension greenhouse gas emission reduction?	• Digital Leadership Factors • Organisational Readiness • Building a Digital-Ready Workforce • Sustainable DTx: Investment
2. How is success measured for measuring the effect of adopting DT for the environmental sustainability dimension?	• Holistic Performance Measurement
3. What policy initiatives and regulatory frameworks are necessary to promote sustainable development in the South African manufacturing sector?	• Policy and Regulation • Environmental Sustainability • Sustainable Manufacturing: AI-Driven Environmental Sustainability • Sustainability Risk Drivers
4. What are the potential environmental benefits and challenges, barriers, and constraints faced by manufacturing organisations when implementing DTx for sustainability purposes?	• Digital Sustainability: AI Digital Technologies Drivers • Benefits of DTx for Environmental Sustainability • Challenges in Implementing AI for Sustainable Manufacturing
5. What are the potential negative effects, direct and indirect, of implementing DT such as AI for environmental sustainability?	• Digital Sustainability: Risk of AI Technology Adoption

APPENDIX 8: CONSISTENCY MATRIX

TITLE: Drivers for Successful Digital Transformation in Advancing Environmental Sustainability in Gauteng's Manufacturing Industry.			
PROPOSITIONS/ QUESTIONS/ HYPOTHESES	LITERATURE REVIEW	DATA COLLECTION TOOL	ANALYSIS
1. What are the key drivers for successful adoption of DT AI in the Manufacturing sector to achieve the environmental sustainability dimension greenhouse gas emission reduction?	Brock & Wangenheim, 2019; Chiarini, 2021; Guandalini, 2022; Horváth & Szabó, 2019; Li et al., 2018; Mangla et al., 2018b; Mariappanadar et al., 2022; Rusch et al., 2023; Mikalef et al., 2019; Nguyen et al., 2022	Interview guide, Topic 1: Organisational Capabilities (OC) Questions OR1 - OR4	Thematic Content Analysis

2. How is success measured for measuring the effect of adopting DT for the environmental sustainability dimension?	Ash & Burn, 2003; Horváth & Szabó, 2019; Kauffman & Walden, 2001; Li et al., 2018; Tseng et al., 2022	Interview guide, Topic 2: Impact (I) Questions I1 - I3	Thematic Content Analysis
3. What policy initiatives and regulatory frameworks are necessary to promote sustainable development in the South African manufacturing sector?	Bag et al., 2021; Chiarini, 2021; de Sousa Jabbour et al., 2018a; Dubey et al., 2020; Harvath & Szabo, 2019; Li et al., 2018; Mangla et al., 2018b; Tseng et al., 2022;	Interview guide, Topic 4: Opportunities and Challenges (PR) Questions PR1 - PR5	Thematic Content Analysis
4. What are the potential environmental benefits and challenges, barriers, and constraints faced by manufacturing organisations when implementing DTx for sustainability purposes?	Bag et al., 2021; Dauvergne, 2022; de Sousa Jabbour et al., 2018; Denicolai et al., 2021; Mangla et al., 2018b; Mariappanadar et al., 2022; Mikalef et al., 2019;	Interview guide, Topic 4: Challenges (C) Questions C1 - C4	Thematic Content Analysis

	Tseng et al., 2022; Yadav et al., 2020		
5. What are the potential negative effects, direct and indirect, of implementing DT such as AI for environmental sustainability?	Chiarini, 2021 Dauvergne, 2022	Interview guide, Topic 5: Risk (R) Questions R1 - R2 (R2.1-R2.3)	Thematic Content Analysis

APPENDIX 9: PROPOSED FRAMEWORK

