Drivers for Successful Digital Transformation in Advancing Environmental Sustainability in Manufacturing

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Abstract

Digital technologies (DT) and AI are key drivers of Digital Transformation and have revolutionised how businesses operate, resulting in unprece- dented progress in promoting sustainability. A critical gap in integrating environ- mental 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 South African manufacturing sector is at a critical juncture as concerns about environmental degradation intensify and sustainable practices become im- perative. Studies in a different context found that DTx has the potential to trans- form traditional capital–intensive manufacturing assets to enhance environmen- tal sustainability.

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

This study uncovered eight key drivers for successfully integrating AI technol- ogies for sustainability, defined internal and external drivers, and benefits, chal- lenges 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 there are significant hurdles to overcome for a successful AI-driven DTx to advance manufacturing environmental sustainability practices. The present study will be valuable to researchers, practitioners, government and policymakers.

Keywords

Digital Transformation, Environmental Sustainability, Sustainable Manufacturing, Industry 4.0, Artificial Intelligence

ACM Reference Format:

Gwen Moshoeshoe and Theuns Pelser. 2025. Drivers for Successful Digital Transformation in Advancing Environmental Sustainability in Manufacturing. In *The Sixth edition of the International Conference on Digital Age & Technological Advances for Sustainable Development (DATA 2025), May 07–09, 2025, Tangier, Morocco.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3747897.3747906

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DATA 2025, Tangier, Morocco
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ACM ISBN 979-8-4007-1359-0/2025/05
https://doi.org/10.1145/3747897.3747906

1 Introduction

Digital technologies (DT) have transformed businesses and sustainability efforts [1]. AI is a key driver of Digital Transformation (DTx) [2]. The manufacturing industry, heavily reliant on resources and energy, faces unique environmental sustainability chal- lenges [3].

A critical gap exists in integrating environmental sustainability into DTx [4].

Without understanding their relationship, informed decisions regarding DTx invest- ments are difficult. Incorporating digital transformation technologies can promote sus- tainable practices in manufacturing [5, 6].

This research explores the potential of Artificial Intelligence (AI) in manufacturing to advance environmental sustainability and revolutionise capital-intensive manufac- turing assets [7-10]. This exploratory study investigates DTx's impact on environmental sustainability, specifically greenhouse gas emission (GHG) reduction, waste reduction, and energy efficiency within large manufacturing companies in Gauteng.

1.1 Background of Study

The manufacturing sector faces increasing pressure to adopt sustainable practices [11]. Environmental degradation, stemming from inefficient practices, has been a concern since the Industrial Revolution [11, 12]. Environmental sustainability involves reducing negative environmental impact and balancing protection with progress [13].

The global industrial sector, valued at USD 19 trillion, contributes significantly to the global GDP [14]. South Africa's (SA's) manufacturing sector contributes R 813 billion (14%) to SA's GDP [15] but also accounts for a substantial portion of greenhouse gas (GHG) emissions [South African Reserve Bank, 2020).

Gauteng is SA's manufacturing hub [15]. SA greenhouse emissions have increased significantly, driven by industrial activity [16]. The SA industry consumes a consider- able amount of water and generates high effluent [17]. Despite environmental chal- lenges, SA's economy is poised for growth, potentially increasing greenhouse gas emis- sions [18, 19]. Addressing the "awareness gap" is crucial for business prosperity [3, 6]. DTx global spending is projected to increase significantly [20]. Artificial Intelli- gence (AI) has a substantial economic impact estimated for 2030 [21], with a significant potential contribution for SA [22]. A large percentage of digital transformation initia- tives incorporate AI services [23], enhancing efficiency and providing valuable in-sights.

Gaffley and Pelser's [24] study revealed SA's Manufacturing Sector DTx standing at 47.7%. Despite economic challenges, their survey indicates a strong commitment to DTx within the manufacturing sector.

DTx lacks consistent definitions [4]. DTx leverages rapidly evolving DTx and capa- bilities to create new business models [25]. Digital technology in manufacturing, facil- itated by Industry 4.0 (I4.0), encompasses a comprehensive suite of technologies [26], transforming traditional manufacturing into advanced systems. The goal of DTx is to drive revenue growth [6].

1.2 Research Problem Statement

DTx can transform manufacturing assets and enhance environmental sustainability [8- 10], but most studies are in different contexts [27- 29, 31]. Studies in South Africa focus on specific areas [28]. Research indicates a significant association between I4.0 adop- tion and a decrease in South Africa's manufacturing value added (MVA) [30].

Conflicting results exist regarding the link between digital transformation and sus- tainability [4]. AI is crucial in promoting sustainable manufacturing (SM) practices [26, 29]. According to Veile et al. [32], SMEs may lag in DT adoption due to a knowledge gap that exists regarding manufacturing leaders leveraging DT, such as AI, to achieve environmental sustainability. The question of how DTx can improve sustainability re- mains largely unaddressed [4]. Addressing this gap is crucial for developing AI-driven strategies to support the transition towards environmental SM practices.

1.3 Research and Purpose Gap

Despite DTx's promise, a knowledge gap exists regarding the drivers of success for AI- driven environmental sustainability solutions in Gauteng, South Africa. This research explores AI's leverage for environmental sustainability and organisational factors driving success [29]. This research is crucial for meeting the needs of manufacturing indus- tries in the digital era.

The question of how digital transformation can improve sustainability requires at- tention [3, 4].

This qualitative research investigates the key drivers of successful DT initiatives that advance environmental sustainability in Gauteng's manufacturing industry. This study aims to equip manufacturers with actionable insights and provide guidance for policymakers and academic scholars. This research addresses the development of sustainable manufacturing through digital technologies in South Africa.

1.4 Research Questions

This study prioritises and explores the key drivers of successful DTx in advancing en- vironmental sustainability practices in the manufacturing sector in Gauteng, South Af- rica.

The following research questions (RQ#) for the study have been formulated below:

- RQ1 (Organisational Capabilities): What are the key drivers for the suc- cessful adoption of DT AI in the Manufacturing sector to achieve the envi- ronmental sustainability dimension of greenhouse gas emission reduction? [8, 33]
- RQ2 (Impact): How is success measured for measuring the effect of adopt- ing DT for environmental sustainability dimension? [34, 35]
- RQ3 (Opportunities and Challenges): What policy initiatives and regula- tory frameworks are necessary to promote sustainable development in the South African manufacturing sector? [19, 36]
- RQ4 (Challenges): What are the potential environmental benefits and chal- lenges, barriers, and constraints faced by manufacturing organisations when implementing DTx for sustainability purposes? [29]
- RQ5 (Risk): What are the potential negative effects, direct and indirect, of implementing DT such as AI for environmental sustainability? [26, 31]

2 Literature Review

2.1 Introduction

The manufacturing sector in Gauteng, South Africa, faces the persistent challenge of reconciling economic growth with environmental sustainability. Digital transformation (DTx), particularly through the adoption of Artificial Intelligence (AI), presents a promising avenue for achieving sustainability goals, especially in reducing greenhouse gas (GHG) emissions.

This literature review synthesises existing knowledge to identify key drivers, chal- lenges, and opportunities for successful DTx implementation focused on environmental sustainability in the Gauteng manufacturing sector. This review addresses critical research questions regarding organisational capabilities, impact measurement, policy frameworks, potential benefits and challenges, and the risks associated with DTx adop- tion.

2.2 Key Drivers for DTx Adoption

Successful adoption of DTx, especially AI, in manufacturing requires a foundation of organisational capabilities. Digital leadership is paramount, with CEOs and executive teams driving digital strategies [24]. This leadership must extend to a commitment to environmental sustainability, fostering innovation to reduce GHG emissions [32].

However, leadership faces a potential disruption as organisations integrate AI, as such Horváth and Szabó [37] acknowledge the significance of leadership, they argue that organisations may navigate potentially disruptive shifts in leadership roles to inte- grate AI and drive successful DTx. Organisational readiness is also crucial, encompass- ing technological, cultural, and strategic dimensions [12].

Overcoming organisational resistance to change [38] and adapting organisational re- sources and culture [2] are essential for leveraging DTx effectively. A key driver is building a digital-ready workforce through strategic HRM practices [39]. Researchers [12, 32, 37] indicate that the shortage of skilled digital talent is a significant obstacle in driving organisations' digital transformation journeys. This requires investment in em- ployee development to ensure individuals possess the necessary skills [39].

2.3 Measuring the Impact of DTx on Environmental Sustainability

Measuring the success of DTx in achieving environmental sustainability requires a ho- listic performance measurement framework

[34]. This framework must extend beyond financial metrics to include environmental outcomes, such as GHG emission reduc- tions, energy conservation, and waste minimisation [40].

As Dauvergne [35] points out, a crucial paradox is that while this technological ad- vancement 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. Organisations must quantify environmental outcomes alongside financial performance to demonstrate their commitment to sustainable practices.

Policy and Regulatory Frameworks

Supportive policy initiatives and regulatory frameworks are vital for promoting sus- tainable development in the South African manufacturing sector [9]. Developing econ- omies like South Africa must industrialise while minimising environmental impact [19]. Green industrial policies promoting green manufacturing and low-carbon innova- tion offer a potential solution [18]. Government support through subsidies, tax breaks, and financial assistance is critical for incentivising sustainable practices [40]. However, Udeagha and Muchapondwa [19] acknowledge policy uncertainty as a significant bar- rier.

The efficacy of digitalisation strategies in achieving environmental sustainability hinges on robust regulatory frameworks and targeted policy initiatives, similar to the European Union's (EU) upcoming implementation of digital product passports, man- dated by recent legislation [29].

2.4 Benefits, Challenges, and Barriers of DTx Implementation

Implementing DTx for sustainability purposes presents both significant opportunities and challenges. DTx, specifically AI, big data, and the IoT, presents a compelling so- lution suite for addressing environmental sustainability challenges [31]. Potential ben- efits include increased efficiency, reduced emissions, and new business model devel- opment [38].

However, challenges include the need for significant collaboration and planning across the value chain [38], the potential for high energy consumption in energy-inten- sive manufacturing environments [16, 18], and the complexities of integrating AI tech- nologies with legacy systems [19]. Legacy systems create outdated process equipment that lacks monitoring and data transmission capabilities. The economic landscape of Africa is rapidly transforming, with SA leading the charge as the continent's third-larg- est economy [19].

2.5 Potential Negative Effects and Risks

Despite the potential benefits, implementing DTx, such as AI, for environmental sus- tainability carries potential risks. Chiarini [26] identified, the direct environmental ef- fects of DTx include (1) the production of digital infrastructure, (2) the energy con- sumption of digital infrastructure, (3) mining of the hardware to be used as digital in- frastructure, (4) collection, recycling, and disposal of digital assets physical infrastruc- ture, (5) greenhouse emissions for the generation of power used by DTx. These include increased GHG emissions, electronic waste generation, and rebound effects [16].

Additionally, there are risks associated with rapid technological advancements ren- dering investments obsolete [29], the potential for increased cybersecurity threats [2], and the need for careful consideration of ethical implications [2, 28].

Dauvergne [35] identified the following indirect effects: (1) forecasting waste gen- eration, (2) unveiling resource waste, and (3) designing more efficient waste manage- ment models. As Omri et al. [13] stated, 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, elec- tronic waste generation, and rebound effects.

3 Research Methodology

3.1 Introduction

This study employs a qualitative research approach to explore the key drivers of suc- cessful Digital Transformation (DTx) in advancing environmental sustainability prac- tices within the manufacturing sector in Gauteng, South Africa. The research focuses on understanding organisational capabilities, measuring impact, identifying opportuni- ties and challenges, and assessing the potential risks associated with DTx implementa- tion. The methodology is designed to provide rich, in-depth insight into the experiences and perspectives of individuals within manufacturing organisations.

3.2 Data Collection and Sampling

Semi-structured interviews were conducted with participants from manufacturing or- ganisations in Gauteng. While the target population was the Gauteng manufacturing industry, the sample frame for this study was initially unknown. Therefore, a purposeful sampling method was used to select participants based on their expertise and experience in I4.0 adoption, Digital Transformation (DTx), and/or environmental and sustainabil- ity practices. This ensured a diverse range of perspectives relevant to the research ques- tions.

The sample size consisted of 13 industry professionals and experts. The number of participants was determined based on data saturation and theoretical saturation princi- ples, ensuring that the data collected was rich and comprehensive. Data saturation refers to the point where no new information or themes emerge from subsequent interviews, indicating that the research has captured the full range of perspectives on the topic.

Data saturation appeared 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 cate- gories and relevant themes, as evidenced by the diminishing number of new data from later interviews.

3.3 Data Analysis

Thematic analysis was employed to analyse the interview data. This involved system- atically coding the transcripts, identifying recurring patterns and themes, and interpret- ing the underlying meanings. To ensure the rigour and validity of the research, several strategies were implemented, including triangulation through the use of multiple data sources (e.g., interviews, documents) to corroborate findings and enhance credibility, member checking by sharing the preliminary findings with participants to ensure accuracy and resonance with their experiences, reflexivity through acknowledging and ad- dressing the researcher's own biases and assumptions to minimise their influence on the research process, and maintaining a comprehensive audit trail and analysis process to ensure transparency and accountability.

3.4 Ethical Considerations

Ethical considerations were paramount throughout the research process. Informed con- sent was obtained from all participants, and their anonymity and confidentiality were protected. The research adhered to ethical guidelines and principles to ensure the well-being and rights of participants.

Having outlined the research methodology, the paper will now proceed to present the findings and analysis, directly addressing the core research questions regarding the drivers, challenges, and impact of DTx for environmental sustainability in the Gauteng manufacturing industry.

4 Key Findings & Discussion

4.1 Introduction

The study identified several key themes through the thematic analysis of interview data. These themes encompass internal and external drivers influencing the successful inte- gration of AI for environmental sustainability, as well as associated benefits, opportu- nities, challenges, and risks. The findings are structured around the research questions (RQ1-RQ5) that guided this study:

- **RQ1 (Organisational Capabilities): What are the key drivers for the suc- cessful adoption of DT AI in the Manufacturing sector to achieve the en- vironmental sustainability dimension of greenhouse gas emission reduc- tion?** The study uncovered eight key drivers for the successful integration of AI technologies for sustainability, defined along both internal and external di- mensions. These drivers are: (1) digital leadership, (2) organisational readi- ness, (3) building a digital-ready workforce, (4) sustainable DTx investment, (5) holistic performance measurement, (6) policy and regulation, (7) environ- mental sustainability, and (8) AI-driven sustainable manufacturing. Furthermore, several themes associated with benefits, opportunities, challenges, and risks associated with these drivers were observed.
- **RQ2 (Impact): How is success measured for measuring the effect of adopting DT for environmental sustainability dimension?** The study found that AI adoption has the potential to advance environmental sustainability practices within the Gauteng manufacturing sector. However, the results indi- cate that AI adoption by manufacturers is still in a nascent stage, with the pri- mary benefits observed being indirect, such as efficiency gains, energy con- sumption optimisation, and predictive maintenance, leading to greenhouse gas reduction and less wastage. Manufacturers have adopted comprehensive emis- sions monitoring and KPIs to track performance against environmental targets, encompassing financial, operational, and environmental aspects through inte- grated reporting.
- **RQ3 (Opportunities and Challenges): What policy initiatives and regula- tory frameworks are necessary to promote sustainable development in the South African manufacturing sector?** The absence of incentives to fund the manufacturing sector's DTx initiatives aimed at fostering sustainability has emerged as a notable obstacle. Compounding this issue is a perceived discon- nect between governmental bodies and the manufacturing sector, which fur- ther hinders progress towards sustainable practices. The findings indicated the lack of incentives and the disconnect from government as a key challenge.
- **RQ4 (Challenges): What are the potential environmental benefits and challenges, barriers, and constraints faced by manufacturing organisa- tions when implementing DTx for sustainability purposes?** A prevalent skills gap, particularly concerning data science and sustainability-focused IT experts, poses a substantial challenge. This shortage is exacerbated by the pro- tracted development cycle required to cultivate the necessary expertise. Man- ufacturers often prioritise short-term financial objectives over long-term envi- ronmental goals, particularly given the high upfront costs associated with in- tegrating AI technology and DTx initiatives. Manufacturers face challenges such as outdated process equipment, significant upfront costs for IT infrastruc- ture, and the need for effective systems integration.
- **RQ5 (Risk): What are the potential negative effects, direct and indirect, of implementing DT such as AI for environmental sustainability?** The re- sults show that AI technology is the major contributor, potentially the only source directly impacting the environment. Despite the potential benefits, im- plementing DTx, such as AI, for environmental sustainability carries potential risks, including direct environmental effects of DTx from production and min- ing, the energy consumption of digital infrastructure, and collection, recycling, and disposal of digital assets. The manufacturing industry tends to neglect the environmental sustainability impact in the sustainability digital initiatives value case.

4.2 Key Themes: Benefits, Opportunities, Challenges, and Risks

The thirteenth themes which emerged from the analysis are summarised below:

1. **Digital Leadership:** Securing consistent alignment and conviction from top leadership is crucial for driving AI integration. Leaders must navigate poten- tially disruptive shifts and foster enterprise-wide innovation [37]. Top management commitment drives innovation to reduce GHG emissions [18, 19].
2. **Organisational Readiness:** Effective change management and communica- tion are essential for digital sustainability initiatives [2]. Employee coaching is crucial to overcome resistance to change [38].
3. **Building a Digital-Ready Workforce:** Addressing the significant lack of dig- ital talent, especially data science

and sustainability IT experts, requires short and long-term strategies to build organisational digital capabilities [32]. The shortage of skilled individuals slows AI adoption and innovation [28, 38].

4. **Sustainable DTx Investment:** Overcoming the challenge of high upfront costs associated with AI technology integration, and DTx requires prioritising long-term environmental goals over short-term financial objectives [24, 26]. Low digital maturity increases the financial burden for manufacturers [40].
5. **Holistic Performance Measurement:** Implementing a holistic performance management system is crucial for assessing the full impact of DTx and bal- ancing economic growth with sustainability goals [27]. Most manufacturers have set 2030 ambitions of 30% GHG emissions targets aligned with the Paris Agreement [40].
6. **Policy and Regulation:** Addressing the lack of incentives to fund the manu- facturing sector's DTx for sustainability is a significant challenge, requiring policy initiatives that promote long-term investments in sustainable practices. There is a notable disconnect between the government and the manufacturing industry [41].
7. **Environmental Sustainability:** Comprehensive emissions monitoring is es- sential to guide the effective implementation of environmental sustainability initiatives, ensuring compliance with regulations and minimum standards [13]. Manufacturers' GHG emissions are primarily carbon-related emissions, nitrogen oxide (NOx), and Sulphur Dioxide (SOx) [16].
8. **AI-Driven Sustainable Manufacturing:** Recognizing the early stage of AI technology integration for advancing environmental sustainability, a formal, integrated business and digital strategy and strong senior management support are needed [24].
9. **Sustainability Risk:** Integration of AI introduces risks such as the cost burden for transitioning to a low-emissions environment, cybersecurity threats, and the social impact of AI adoption. Cost burden, the introduction of carbon tax cybersecurity threats [18].
10. **AI Technology Drivers:** AI is a key enabler of sustainability strategies. The emergence of advanced measurement technologies, especially AI-powered, is a key driver [27, 41].
11. **Benefits of DTx for Environmental Sustainability:** Practical applications in manufacturing improve operational efficiency, optimise energy consumption, enhance predictive maintenance and improve throughput Truong [31] listed the following indirect effects of DTx and AI integration, supported by Dau- vergne [35]: (1) forecasting waste generation, (2) unveiling resource waste, (3) designing more efficient waste management models, (4) reduction of greenhouse gas emissions
12. **Challenges for Implementing AI for Sustainable Manufacturing:** Manu- facturers still have outdated process equipment that lacks monitoring and data transmission capabilities. Also, significant upfront costs are required for com- plex IT infrastructure [32].
13. **Risk of AI Technology Adoption:** Difficultly quantifying the indirect envi- ronmental impacts of AI adoption and neglect of the environmental sustaina- bility impact in the sustainability digital initiatives value case [35].

Findings confirmed that for a successful AI-driven DTx to advance manufacturing en- vironmental sustainability practices, significant hurdles must be overcome, and associ- ated risks must be mitigated.

4.3 Discussion and Analysis

The study reinforces the existing literature on the importance of digital leadership [2, 24, 27], highlighting that the impact of leadership support and leadership conviction from top management is a key driver for AI adoption to advance sustainable practices. However, in contrast to previous research, the results indicate there is a significant lack of digital talent, especially data science and sustainability IT experts. Echoing previous research, the findings indicated the lack of incentives and the disconnect from the government as a key challenge in SA [28]. This contradicts the belief that industrial policy is key to promoting sustainable development [41]. While confirming that manufacturers are using AI technology, the results demonstrated that it positively impacts reducing GHG emissions [29].

4.4 Proposed Framework

The proposed framework emerged from the empirical findings based on 13 semi-struc- tured interviews with manufacturing executives and sustainability experts in Gauteng, with data saturation achieved after the 11th interview. Bottlenecks were categorised into internal (e.g., skills gaps, leadership inertia) and external (e.g., policy disconnect, lack of incentives) drivers using grounded thematic analysis.

Notably, firms observed indirect performance gains such as enhanced energy effi- ciency and predictive maintenance capabilities, which contribute to reduced greenhouse gas emissions—illustrating the practical potential of the proposed mitigation strategies. The findings contribute to the development of a comprehensive framework for un- derstanding the key drivers behind successful digital transformation. The framework, represented in Figure 1, highlights the interdependence of internal and external forces. As illustrated in Figure 1, the proposed framework holistically integrates internal and external factors impacting successful DTx initiatives. Key drivers include internal elements like digital leadership and organisational readiness and external factors such as policy and regulation. This model emphasises the interconnectedness of these themes in driving sustainable digital transformation.

4.5 Conclusion

This study embarked on a journey to explore the intricate relationship between AI adop- tion, digital transformation, and environmental sustainability within the manufacturing sector of Gauteng, South Africa. We sought to uncover the key drivers and barriers that influence the successful integration of AI for sustainable practices, ultimately contrib- uting to reducing greenhouse gas emissions.

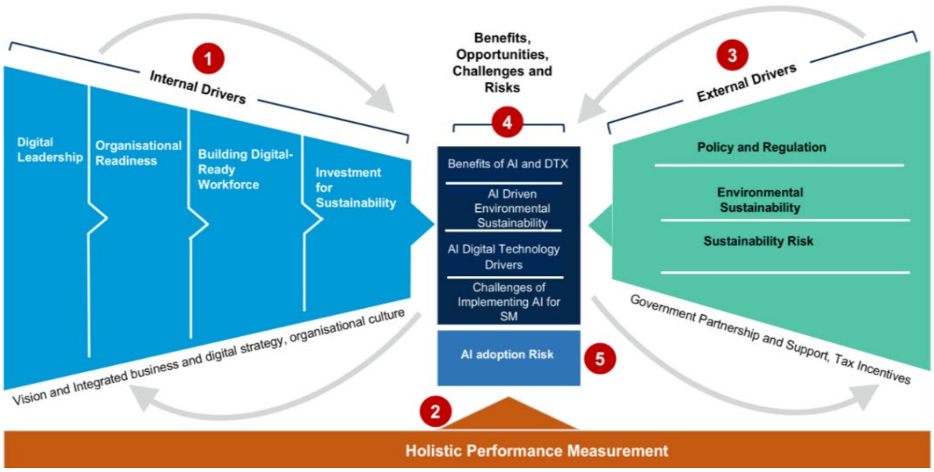

Figure 1: Drivers for Successful Digital Transformation

Our investigation revealed a complex landscape with promising opportunities and significant challenges. The research notes indirect benefits like predictive maintenance, energy optimisation, and GHG tracking via KPIs.

We identified key themes, categorised along internal and external dimensions, that either propel or hinder the progress of AI-driven sustainability initiatives. The emerging themes led to the creation of a comprehensive framework model tailored to the context of the manufacturing industry.

In reflecting on the initial purpose of this research, it is evident that the South African manufacturing sector is indeed at a critical juncture. While AI adoption holds immense potential for advancing environmental sustainability practices, its implementation is still in a nascent stage.

This research was exploratory in nature and based on a small, purposive sample, limiting the generalisability of its findings. The absence of quantitative validation and the early stage of AI adoption among participants constrained the ability to assess per- formance outcomes empirically. Additionally, the reliance on self-reported data and limited sectoral representation may introduce bias and restrict broader applicability.

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