Innovation impact of adopting recent industrial revolution technologies on modernising the automotive manufacturing industry

by

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DECLARATION

I, **Manqoba Lwazi Nzama,** student number 21855825, do hereby declare that this thesis is the result of my investigation and research and that this has not been submitted in part or in full for any degree or any other degree to any other University.

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LIST OF ABBREVIATIONS

3IR	Third Industrial Revolution
4IR	Fourth Industrial Revolution
5IR	Fifth Industrial Revolution
AI	Artificial intelligence
AMI	Automotive manufacturing industry
AVE	Average variance extracted
CFA	Confirmatory factor analysis
CFI	Comparative fit index
CPS	Cyber-physical systems
CR	Composite reliability
DCT	Dynamic capabilities theory
DoI	Diffusion of innovation
DTT	Digital transformation theory
EFA	Exploratory factor analysis
EV	Electric vehicle
GDP	Gross domestic product
HCT	Human capital theory
ICT	Information and communications technology
IoT	Internet of Things
KMO	Kaiser-Meyer-Olkin Measure of Sampling Adequacy
MaaS	Mobility as a service
MICMAC	*Matrice d'Impacts Croisés Multiplication Appliquée á un Classement*
MLE	Maximum likelihood estimation
NAACAM	National Association of Automotive Component and Allied Manufacturers
NAAMSA	National Association of Automobile Manufacturers of South Africa
OEM	Original equipment manufacturer
PCA	Principal component analysis
POS	Perceived organisational support
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
R&D	Research and development
RBV	Resource-based view

RMSEA	Root mean square error of approximation
SAAM	South African Automotive Masterplan
SCIT	Support-driven capability and innovation theory
SEM	Structural equation modelling
SME	Small and medium-sized enterprise
SPSS	Statistical Package for the Social Sciences
SRMR	Standardised root mean square residual
STS	Socio-technical systems
TLI	Tucker-Lewis Index
TOE	Technology-organisation-environment
TVET	Technical and vocational education and training
USA	United States of America
WoS	Web of Science

ABSTRACT

The automotive manufacturing industry (AMI) is undergoing rapid transformation driven by Fourth and Fifth Industrial Revolution (4IR and 5IR) technologies such as artificial intelligence (AI), the Internet of Things (IoT), cyber-physical systems (CPS), and human–machine collaboration. While these technologies offer significant potential for productivity and competitiveness, their adoption in emerging economies such as South Africa remains uneven due to structural constraints. Existing studies have largely focused on technical and strategic adoption issues with a limited understanding of how technology adoption shapes innovation outcomes and modernisation within the South African AMI. This study addresses this gap by analysing how adoption drivers influence key modernisation outcomes – productivity, workforce upskilling, income growth, and digital commerce.

Grounded in the Technology-Organisation-Environment (TOE) framework, the Resource-Based View (RBV), and Human Capital Theory (HCT), and further integrated through the Support-Driven Capabilities and Innovation Theory (SCIT), the study adopts a quantitative, cross-sectional design. A survey was administered to 248 senior technology and operations leaders across firms listed under the National Association of Automotive Component and Allied Manufacturers (NAACAM) and the National Association of Automobile Manufacturers of South Africa (NAAMSA), yielding 221 valid responses. Measurement validity and reliability were established through pre-testing, Cronbach's alpha, composite reliability (CR), and discriminant validity. Structural equation modelling (SEM) with bootstrapping (5,000 resamples) was used to test 48 hypotheses covering direct and mediated relationships between technology adoption drivers – costs, labour availability, and infrastructure – and modernisation outcomes.

The findings show that labour availability and technology infrastructure are the strongest enablers of modernisation, exerting significant positive direct effects on productivity ($\beta = 0.792$; $\beta = 0.466$) and organisational support for upskilling ($\beta = 0.387$; $\beta = 0.230$). Cost pressures emerge as systemic barriers, negatively affecting most modernisation outcomes. The results further show that digital modernisation depends on both financial flexibility and access to enabling technologies, as reflected in the negative indirect effects of adoption costs on digital commerce (H16, H20, H24).

Infrastructure support enhances modernisation through the mediating effects of investment, education, and management, while high costs weaken these pathways and reduce the sector's ability to absorb advanced technologies. Digital commerce consistently emerges as the least responsive outcome, indicating persistent ecosystem-level barriers within South Africa's digital manufacturing landscape.

Theoretically, the study extends the RBV by demonstrating that modernisation outcomes are not solely technology-driven but are mediated by organisational capabilities, including investment, education, and managerial support. It further reinforces HCT by illustrating the central role of workforce upskilling in linking technology adoption to socioeconomic outcomes. Through SCIT, the study offers an integrated explanation of how support structures and organisational capabilities interact to drive innovation-led modernisation. Practically, the findings highlight the need for firms to balance cost management with sustained investments in skills and managerial capacity, while policymakers must prioritise infrastructure strengthening and education–industry partnerships to support inclusive digital modernisation in the South African AMI.

CHAPTER ONE

INTRODUCTION

The Fourth and Fifth Industrial Revolutions (4IR and 5IR) have greatly induced changes within the global economy through various technologies like artificial intelligence (AI), cyber-physical systems (CPS), the Internet of Things (IoT), and human-machine interfaces (Sahoo & Lo 2022). These technologies serve as the base drivers of the value chain of the Automotive Manufacturing Industry (AMI), leading to the addition of value during the production process of the products, the reduction of wastes during the production process of the products, and an increase in the competitive nature of the operations of the industries as a whole (Matamoros et al. 2025). The incorporation of the digital platform into the production system may create a great shift in the manner of value creation and the delivery of the value within the industry (Ahmed et al. 2022). Within the context of the South African economy, the above industrial revolutions have both great challenges and opportunities that require the proper alignment of technology solutions with the base infrastructure of the human capital (Kavre et al. 2025).

The AMI is highly capital-intensive and is characterised by high entry costs, including initial investment in establishing manufacturing units, new product development, and adherence to regulatory norms (Duffner *et al.* 2021). This is of particular concern for automotive manufacturers in emerging countries, where the availability of technology and funds is limited (Wuttke 2022). Automotive supply chains on a multinational scale are extremely intricate and liable to disruptions. Situations such as the COVID-19 pandemic, geopolitical conflicts, and disruptions in the supply of chips have revealed the vulnerability of such value supply chains (Pratap and Ishrat 2025). Such disruptions induce supply chain delay, inflated costs, and diminishing profitability (Richert and Dudek 2023).

The transition towards electric vehicles (EVs), self-driving, and digital connectivity has compelled conventional automotive manufacturers to invest more in innovation

(Akinsooto, Ogunnowo and Ezianochie 2025). However, return on investments for these technologies remains uncertain, and businesses may not have sufficient capacity to keep up with the pace of transition (Zhang 2024). Stringent environmental norms, particularly in Europe and North America, compel manufacturers to lower emissions and move towards sustainability (Ravi, Osipov and Turner 2023). Additionally, the cost of upgrading manufacturing techniques and materials can be a significant financial burden (Zhang, Bi and Yang 2024). In mature markets, automotive demand has flattened or decreased due to changes in demographics, urbanisation, and customer preferences (Honcharov 2025). While there is potential for development in new markets, there are also significant risks, such as political risks, currency risks, and inconsistent policy environments (Shuba and Karabanov 2021). Transitioning towards 4IR and 5IR technologies requires a highly educated labour force. However, manufacturers have not been able to attract and retain employees with the necessary skills in AI, robotics, and data science (Escobar *et al.* 2024). This scarcity of skills can undermine the benefits of new technologies, including productivity (Johnson *et al.* 2021). To remain competitive, manufacturers have formed strategic alliances with technology companies, including start-ups. While this can accelerate innovation, it may result in issues with integration, management of intellectual property, and cultural fit (Goel 2025).

The industrial landscape has entered a new era defined by rapid technological transformation. In the last two decades, this evolution has been expressed through the integration of modern digital technologies with traditional manufacturing bases, leading to the 4IR. This revolution builds on earlier industrial shifts, including mechanisation, electrification, and computerisation, and represents a convergence of CPS, AI, robotics, and the IoT (Péter and Levente 2023; Tsai *et al.* 2024). The origins of industrial change can be traced back to Industry 1.0, which introduced steam-powered mechanical production in the late 18th century; this was followed by Industry 2.0's widespread electrification and assembly lines in the 19th century and Industry 3.0's digitisation in the late 20th century (Adrita *et al.* 2021; Gloveli, Zaitseva and Minaeva 2024).

Industry 4.0, first formally conceptualised during the Hannover Messe in Germany in 2013, represents a marked acceleration of these trends. It is defined by the full integration of digital and physical production systems through smart technologies, real-time data exchange, and decentralised decision-making (Shalwani 2021; Vještica *et al.* 2023). Globally, the 4IR has encouraged increased competitiveness, innovation, and productive efficiency in manufacturing industries (Kovalev and Bekmurzaeva 2023; Maisiri and van Dyk 2021). Digitalisation has become a strategic imperative rather than merely a technological showcase. Enterprises are adopting robotics, automation, cloud computing, and CPS not only to streamline production processes but also, more substantially, to enable the development of new value propositions through complete global supply chains (Rogaczewski, Cieślak and Suszyński 2020).

Additionally, a parallel and more human-centred industrial paradigm has emerged: the 5IR. Rather than replacing the 4IR, the 5IR builds upon it by reintegrating the human element into production systems. The 5IR advances a vision of industrial development in which collaboration between people and machines, not substitution, is key. The 5IR emphasises ethical AI, personalised manufacturing, sustainability, and social inclusion (Kalateh *et al.* 2022; Pizoń and Gola 2023). By doing so, it addresses growing concerns about job displacement, inequality, and environmental degradation in the wake of digital transformation. Scholars have described this shift as moving from a purely efficiency-driven model to one that embeds values of care, creativity, and responsibility into production systems (Rani *et al.* 2024; Satpathy *et al.* 2024). This duality has led researchers and practitioners to conceptualise the 4IR and 5IR not as sequential revolutions but as a strategic continuum, referred to in the literature as 4IR/5IR technologies (Fanoro, Božanić and Sinha 2021; van der Poll 2024). In this continuum, firms harness the 4IR's efficiency of automation while incorporating the 5IR's focus on adaptability, empathy, and intelligence of human actors into manufacturing design and decision making.

Notwithstanding the universally acclaimed importance of 4IR and 5IR technologies, empirical studies examining their realisation in emerging market economies, including those in sub-Saharan Africa, are in short supply. Developed countries with a strong infrastructure, a stable policy environment, and a technologically skilled workforce still dominate the current body of scholarly analysis (Kruger and Steyn 2025; Zhang *et al.* 2023). Developing countries in Africa, including South Africa, find themselves faced with a more complex environment in which digital technology adoption is influenced not only by the level of technological preparedness but also by socioeconomic inequities, a shortfall of skills, and systemic deficiencies (Tajuddin 2025).

The South African industrial sector, which includes the automotive cluster, is a central pillar of the country's developmental plan. It is vital for raising the value of the country's gross domestic product (GDP), supplementing revenue through exports, and generating employment (Kaplan, Morris and Barnes 2021). Implementation of technologies associated with the 4IR, such as IoT supply webs, AI quality management, and robotics, is being undertaken in this sector, though not universally (Javaid *et al.* 2022b; Sen *et al.* 2024). However, the shift to a 4IR and 5IR model is not yet complete. While some original equipment manufacturers (OEMs) and parts manufacturers are adopting digital technologies, the overall prevalence of 4IR and 5IR technologies remains limited by infrastructural issues, budgetary constraints, and a lack of workforce readiness (Ayinde, Adedeji and Ajayi 2024). Additionally, a significant literature gap exists regarding how 4IR and 5IR technologies affect economic outcomes in the South African automotive manufacturing context (Serumaga-Zake and van der Poll 2021; Sutherland 2020). Prior studies have examined individual technologies or broader industrial strategies but have rarely focused on how technology adoption interacts with productivity, income growth, workforce upskilling, or digital commerce (Saah and Mbohwa 2025; Khuzwayo 2023). There is also insufficient understanding of how firm-level and systemic factors, such as technology adoption costs, infrastructure support, and skilled labour availability, facilitate or constrain digital transformation (Akanmu, Anumba and Ogunseiju 2021; Dahmani 2024).

The primary concern that this study aims to address is the shortage of empirical knowledge about the innovation impact of 4IR and 5IR technologies on modernisation of AMI in South Africa. More specifically, there is a lack of evidence about how these technologies impact productivity, worker remuneration, workforce development, and digital commerce integration in the AMI. Without such insight, businesses, policymakers, or other stakeholders might unwittingly adopt digital plans that amplify current inequalities or fail to produce substantial effects. This concern is compounded by parallel pressures faced by the industry: on the one hand, the need to upgrade and compete on the global stage, and on the other, the need for sustainable and inclusive modernisation (Inyang, Kanakana and Laseinde 2023). In addition, the COVID-19 crisis aggravated already-existing challenges, revealing supply chain weaknesses, accelerating digital technology adoption, and further increasing unemployment rates and skills imbalances (Paul *et al.* 2023). This study investigates the empirical innovation effects of 4IR and 5IR technology adoption on the modernisation of the AMI.

Several theoretical frameworks have been employed to examine technology adoption, with the technology-organisation-environment (TOE) framework and the resource-based view (RBV) being two of the most influential. The TOE model considers how technological readiness, organisational capacity, and external environmental factors influence a firm's decision to adopt new technologies (Satyro *et al.* 2024). In the context of the 4IR and 5IR, scholars have expanded the TOE framework to include constructs such as ethical governance, human-machine collaboration, and digital maturity (Martín-Gómez, Agote-Garrido and Lama-Ruiz 2024). The RBV, in contrast, focuses on how firms generate competitive advantage from internal resources and capabilities. This view is particularly relevant to the 5IR, which highlights human capital, skills development, and adaptive leadership as critical resources (Oladokun *et al.* 2025; van der Poll 2024). The RBV has been extended to explore how organisational learning, innovation capability, and employee empowerment shape digital transformation outcomes.

Empirical studies have increasingly called for hybrid frameworks that capture the complexity of modern industrial ecosystems. Kruger and Steyn (2025) assert that most recent studies now modify traditional adoption models to account for 4IR- and 5IR-specific variables such as digital ethics, green technology practices, and inclusive innovation. In doing so, they reflect the growing consensus that technology adoption is not simply about deploying tools but about reconfiguring organisational strategies and values.

This study contributes to the growing body of scholarly knowledge by framing technology adoption as a unifying framework relevant to the 4IR and 5IR. Instead of portraying the 4IR and 5IR as separate periods or disconnected phenomena, this study situates them as interdependent aspects of industrial development. Such a framing facilitates novel theoretical questions that acknowledge the interplay between the technology-led efficiencies that are the hallmark of the 4IR and the human-centric innovations that are the hallmark of the 5IR, which together are necessary for realising competitive edges and social value creation (Hein-Pensel *et al.* 2023; Shibambu 2025).

Specifically, the study considers the economic effects of implementing 4IR and 5IR technologies in the South African automotive sector. It evaluates the effects of these technologies on productivity, income growth, workforce upskilling, and digital commerce engagement. It also integrates the TOE framework and the human capital theory (HCT) to examine the role of enablers, such as infrastructure, labour availability, and adoption cost. By doing so, it not only fills a critical gap in the literature but also offers practical insights for industry leaders and policymakers navigating the transition toward inclusive digital industrialisation.

1.1 Contextual information

This study is positioned at the important juncture of technological progress and manufacturing economics in the South African automotive sector, which is considered one of the highest contributors to the economy of the country. The South African AMI, which contributes significantly to the country's GDP and level of employment, is experiencing a significant transformation as a result of embracing technologies related to the 4IR and 5IR. However, available evidence suggests that the industry faces significant challenges in adopting these technologies, mainly because of high technology costs, poor digital infrastructure, and a lack of the necessary skills (Anzolin 2024; Bühler, Nübel and Jelinek 2022; Mosleuzzaman, Siddiki and Arif 2024).

The industry, on account of technologies, has experienced changes in productivity and efficiency indicators, variations in employment patterns, workforce competencies, alterations in supply chain dynamics, adjustments to production cost frameworks and pricing processes, e-market competitiveness, the promotion of digital commerce, and other consequences of these technological integrations. Indeed, these advanced technologies are not merely transforming production processes but are fundamentally reshaping the economic landscape of the AMI (Lopes, Rahmani and Jesus 2024). This approach acknowledges the interconnected characteristics of economic factors within industrial environments and aims to clarify the intricate network of cause-and-effect relationships that arise from technological innovation.

All member organisations of the National Association of Automotive Component and Allied Manufacturers (NAACAM) and the National Association of Automobile Manufacturers of South Africa (NAAMSA) form the sampling frame for this study, reflecting the broader automotive industry landscape and ensuring that the study includes a distinct range of automotive manufacturers, from larger corporations to smaller businesses. By including the entire population of automotive manufacturers, the study aims to achieve a representative and generalisable understanding of the innovation impact of 4IR and 5IR technology adoption on the modernisation of the South African AMI.

The methodology utilised for this study involves a systematic survey of top automotive executives and a rating of combined constructs to form a solid empirical foundation. This methodology responds to calls in the current literature for multi-dimensional, context-sensitive studies that move beyond purely theoretical models to examine empirical, real-world impact (van der Poll 2024; Zhang *et al.* 2023). By positioning itself within the wider 4IR and 5IR technology adoption discourse, this thesis, which is anchored in the reality of the South African AMI, seeks to create scholarship that is not merely of theoretical benefit but also of practical use. It provides a strategic blueprint for the interpretation of digital and people-centred innovation that can be aligned to economic performance, workforce development, and shared prosperity for the manufacturing industry.

The following sections of this chapter outline the specific goals of the study and define hypotheses based on the conceptual framework described above. Chapter Two presents a bibliometric literature review, while Chapter Three explains the theoretical foundation of the study. Chapter Four describes the study's methodology, including the research design, instrument development, sampling plans, and procedures for data analysis. Chapters Five and Six report and discuss the results, while Chapter Seven incorporates the implications of the study, recommendations, and opportunities for future studies.

1.2 Problem statement

Manufacturing is undergoing a paradigm shift due to the uptake of technologies associated with the 4IR and 5IR. These technologies, such as AI, the IoT, CPS, and cooperative human-machine interactions, present substantial opportunities for productivity, sustainability, and innovation improvements (Fanoro, Božanić and Sinha 2021; Pizoń and Gola 2023). However, the adoption of these technologies in industrial ecosystems, especially in developing economies, is marked by inconsistent levels of technological readiness, uneven digital infrastructure, and highly variable organisational capabilities, and is further hindered by multiple structural and operational challenges.

Similarly, South African AMI is experiencing significant transformation as a result of embracing technologies associated with the 4IR and 5IR. However, available evidence suggests that the industry faces significant challenges in adopting these technologies, mainly because of high technology costs, poor digital infrastructure, and a lack of the necessary skills (Anzolin 2024; Bühler, Nübel and Jelinek 2022; Mosleuzzaman, Siddiki and Arif 2024). These challenges are compounded by inadequate policy support and a lack of organisational preparedness, which hinder the industry from fully leveraging the prospective benefits of digitalisation (Macpherson, Werner and Mey 2023; Moeletsi 2021; Putu *et al.* 2025).

Furthermore, outcomes of the adoption of technology innovations in the AMI are evident in productivity gains, workforce income growth, digital commerce expansion, and organisational support for upskilling; however, these remain underexplored in the context of the South African AMI (Anzolin 2024). This study identifies two interrelated research problems: firstly, there is limited empirical understanding of the drivers influencing the innovation impact of adopting 4IR and 5IR technologies in the South African AMI (Macpherson 2024; Macpherson and Werner 2025), and secondly, there is limited evidence of the modernisation outcomes of such adoption, especially with regard to how innovation affects productivity, labour competencies, income distribution, and digital commerce (Gonese and Ngepah 2024; Mkansi and Landman 2021). These gaps are not only academic but also practical as they hinder strategic decision-making for firms, policymakers, and educators.

1.3 Conceptual clarification of Innovation and Modernisation

In this study, innovation is understood as the set of organisational, technological, and workforce-related changes that enable firms to adopt and utilise 4IR and 5IR technologies effectively. Innovation reflects the internal capability enhancements that arise through investment in technology, workforce education, and managerial support. Modernisation, in turn, refers to the measurable outcomes that emerge from these innovation processes, captured in this study through four key variables: productivity improvement, organisational support for upskilling, workforce income growth, and the promotion of digital commerce. These outcomes collectively represent the extent to which the South African automotive manufacturing industry is transitioning toward digitally enabled, efficient, and competitive production systems. Linking innovation and modernisation directly to these variables ensures conceptual alignment between the theoretical framing, the operationalisation of constructs, and the empirical evaluation undertaken in this research.

1.4 Aim of the study

This study aims to investigate the innovation impact of adopting 4IR and 5IR technologies on the modernisation of the AMI in South Africa by examining the relationships between factors influencing innovation and outcomes of modernisation of the AMI using the structural equation modelling (SEM) technique.

1.5 Research objectives

To achieve the aim, this study seeks to accomplish the following important objectives:

a) to use a bibliometric literature review to identify relevant factors influencing 4IR- and 5IR-related innovation and modernisation in the AMI;
b) to develop a theoretical model of research hypotheses that will enable the researcher to achieve the aim of the study; and
c) to apply SEM to validate the theoretical research model and to identify valid theories to understand and explain the innovation impact of adopting 4IR and 5IR technologies on the modernisation of the AMI in South Africa.

1.6 Research hypotheses

The development of the hypotheses in this study is grounded in the objectives and supported by established theoretical perspectives and empirical literature. The specific objectives identify the key drivers of 4IR and 5IR technology adoption, the organisational and workforce-related capabilities that shape innovation, and the modernisation outcomes relevant to the South African AMI. These objectives were further informed by the TOE framework, the RBV, and HCT, which collectively highlight how technological readiness, organisational capabilities, and workforce competencies influence innovation-led outcomes. Empirical studies on digital transformation and industrial upgrading also emphasise relationships among adoption costs, labour availability, infrastructure, investment, education, management practices, and performance outcomes in manufacturing settings. Drawing from these theoretical and empirical insights, the hypotheses were formulated to reflect the expected direct and mediated relationships among the variables identified in the study objectives and operationalised within the conceptual model. The full hypothesis of the study are provided in Chapter Three. Table 1.1 below presents the grouped hypotheses organised into thematic categories aligned with the study's conceptual model:

Table 1.1: Visual grouping of hypotheses

Hypothesis Group	Hypotheses	Description
Direct Effects (H1–H12)	H1 – H12	These hypotheses examine direct relationships between technology adoption drivers (costs, labour availability, infrastructure) and modernisation outcomes (productivity, upskilling support, income growth, digital commerce).
Investment as Mediator (H13–H16)	H13 – H16	These hypotheses test whether investment in 4IR/5IR technologies mediates the relationship between adoption drivers and modernisation outcomes.
Education as Mediator (H17–H20)	H17 – H20	These hypotheses evaluate the mediating role of workforce education and upskilling in linking adoption drivers to outcomes.
Management as Mediator (H21–H24)	H21 – H24	These hypotheses examine the mediating role of management support and practices.
Technology Adoption Factors (H25–H48)	H25 – H48	These hypotheses capture extended mediation pathways and additional relationships within the conceptual model.

1.7 Rationale for the study

The rapid advancement of Industry 4.0 and 5.0 technologies is significantly changing the worldwide manufacturing landscape, with the automotive sector playing a key role in this technological shift. The main rationale for this study is therefore to generate empirical evidence on the innovation impact of adopting 4IR/5IR technologies on the modernisation of the South African AMI, with specific focus on productivity, workforce upskilling, income generation, and digital commerce. Understanding these impacts is essential for informing strategic decision-making at both industry and policy levels, especially given the country's ongoing challenges related to skills shortages, infrastructural constraints, cost barriers, and uneven digital readiness. The rationale includes several important aspects, which are discussed in turn below.

Firstly, the study addresses a notable lack in the existing literature of an exploration of the precise innovation impact of Industry 4.0 and 5.0 technology adoption on the modernisation of AMI in developing nations such as South Africa. While the impact of these technologies in developed countries has been studied extensively, there is a shortage of data-based studies exploring their impact in developing countries. This study aims to bridge this gap by offering important perspectives that might improve understanding of how these technologies are changing economic paradigms in different economic settings, both locally and globally.

Secondly, the study's focus on the NAACAM and the NAAMSA ensures that it reflects the broader AMI and includes a diverse range of manufacturers, from large multinational corporations to smaller local suppliers. This viewpoint makes it possible to examine how Industry 4.0 and 5.0 technologies interact with current economic structures, labour markets, and supply chains. The results of this study could serve as a model for understanding similar patterns in automotive plants in South Africa and other developing countries.

Thirdly, the study has significant real-world relevance for a broad range of stakeholders within South Africa's automotive manufacturing ecosystem. By providing an empirical examination of how 4IR and 5IR technologies influence productivity, workforce development, income generation, and digital commerce, the study offers actionable insights in the following ways:

a) Industry stakeholders, including OEMs, component manufacturers, and digital transformation teams, can apply the findings to refine technology adoption strategies, strengthen workforce upskilling initiatives, and make informed long-term economic and operational projections based on the modernisation outcomes identified in the study.
b) Government officials and policymakers can utilise the evidence to design targeted industrial, labour-market, and digital-infrastructure policies that support the AMI's transition toward advanced manufacturing. The findings highlight where structural constraints, such as skills shortages, infrastructure gaps, and cost pressures, must be addressed for inclusive technological upgrading.
c) Educational institutions, such as universities, can align curricula and training programmes with the evolving digital skills requirements revealed by the study, thereby preparing a workforce capable of supporting 4IR/5IR-enabled production systems and human-machine collaborative environments.
d) Economic planners and development agencies can use the insights on the economic consequences of technology adoption to inform broader national and regional development strategies. The study provides evidence on how modernisation outcomes relate to competitiveness, employment patterns, and

digital commerce integration-factors essential for long-term industrial and economic planning in South Africa.

Finally, the current relevance of the study adds to its significance. As the global AMI increasingly faces significant challenges and opportunities related to changing consumer preferences and environmental factors, understanding the innovation impact of advanced manufacturing technologies is becoming more crucial. This study positions itself at the intersection of global trends and local economic conditions, offering relevant and timely insights. Its quantitative approach provides a solid, evidence-driven framework for understanding the relevant complex economic phenomena. The study aims to move beyond theoretical discussions about Industry 4.0 and 5.0 by generating valuable real-world data to support informed decision-making and future research paths.

The rationale for this study is multifaceted, incorporating academic, applied, and tactical perspectives. The study aims to address a significant knowledge gap, to provide useful insights for various parties, and to add to the larger conversation about the future of manufacturing in developing countries. By focusing on the economic effects of the adoption of advanced technologies within a particular and significant industrial context, the study positions itself as a significant contribution to both academic scholarship and practical economic strategising in the context of rapid technological evolution.

1.8 Scope of the study

The study focuses exclusively on the AMI and on technologies linked to Industry 4.0, such as automation, cloud computing, and CPS, as well as those associated with Industry 5.0, including human-machine collaboration, personalisation, and sustainability-oriented technologies. It investigates the innovation impact of the adoption of 4IR and 5IR technologies on the modernisation of the AMI, which may potentially include changes in productivity and efficiency, patterns of employment and requisite skills, and advancement of digital commerce.

The study focuses on key stakeholders who are directly involved in the adoption of cutting-edge 4IR and 5IR technologies in the AMI, such as management staff, production managers, technical specialists, and other important role players. A quantitative research approach is used, with questionnaires as the data-gathering strategy. The study aims to gather quantifiable and statistically analysable information about the innovation impact of 4IR and 5IR technology adoption on the modernisation of the AMI.

1.9 Thesis overview

The study comprises seven chapters, which are outlined in the subsections below.

1.9.1 Chapter One: Introduction

This chapter provides an overview of the study, including the background, problem statement, research aim and objectives, hypotheses, significance, and scope. Brief reference is made to the literature and methodology underpinning the study.

1.9.2 Chapter Two: Bibliometric literature review

This chapter examines the existing literature on the industrial revolution, factors influencing innovation, outcomes of modernisation, and challenges facing innovation and modernisation in the context of the South African AMI. It also analyses gaps in the literature.

1.9.3 Chapter Three: Theoretical foundation

This chapter discusses the theories underpinning this study's examination of the innovation impact of the adoption of 4IR and 5IR technologies on the modernisation of the AMI.

1.9.4 Chapter Four: Research methodology

This chapter outlines the research paradigm, approach, and design, the population and sample, methods for data collection and analysis, validity and reliability considerations, and ethical considerations.

1.9.5 Chapter Five: Results

This chapter provides a description of the sample, an analysis of the economic impact of 4IR and 5IR technologies on automotive manufacturers, and the results of the testing of the hypotheses.

1.9.6 Chapter Six: Discussion of results

This chapter provides an interpretation of the study's findings, a comparison of the results with the existing literature, an analysis of the study's implications for manufacturers, and an exploration of the study's implications for industry stakeholders.

1.9.7 Chapter Seven: Conclusion and future work

This final chapter summarises the key findings, discusses the implications of the study, and offers recommendations for future research.

1.10 Chapter summary

This chapter began by outlining the background of the study and expounding upon the research problem that underlies the study. Thereafter, the aim, objectives, and hypotheses of the study were formulated. This was followed by a discussion of the study's rationale and scope. Finally, an overview of the chapters of the thesis was provided.

The next chapter presents a bibliometric review of literature relevant to the innovation impact of the adoption of 4IR and 5IR technologies on the modernisation of the AMI.

CHAPTER TWO

BIBLIOMETRIC LITERATURE REVIEW

2.1 Introduction

This chapter provides a background overview of the five industrial revolutions before presenting a bibliometric analysis to map the research area. Drawing on this analysis, the chapter examines factors influencing the adoption of 4IR and 5IR technologies, factors influencing innovation in the AMI, outcomes of modernisation in the AMI, and challenges relating to innovation and modernisation in the South African AMI. Gaps in the literature are identified.

The pace of development of modern industrial technologies driven by the 4IR and the subsequent 5IR has led to a marked shift in the global manufacturing sector, thereby initiating a major shift in the AMI. AMI, one of the most technologically advanced and economically significant business realms, has emerged as an area of crucial examination of the implications of the phenomenon of digital transformation. The principal agenda of the 4IR rests with the amalgamation of CPS, automation, AI, and the Internet of Things, whereas the subsequent agenda of the 5IR rests with human-involved functionalities, underlining the need for human-related aspects and ethical issues of innovation (Lazaroiu et al. 2022; Radanliev et al. 2021). On the other hand, the automobile sector has made substantial investments in advanced production setup infrastructure, digital management of the value chain, and automatically driven cars with the singular agenda of maximising productivity, customizability, safety, and flexibility under turbulent environmental conditions (Ma and Chang 2024; Panichakarn et al. 2024). Nevertheless, the innovation significance of the adoption of these technologies remains an intricate phenomenon.

2.2 Overview of the five industrial revolutions

The Industrial Revolution marked a momentous transition in economic endeavours from agriculture to industry and manufacturing during the 18th and 19th centuries. It began in England in the 17th century with the advent of mechanical facilities and steam-powered machinery, which vastly improved production efficiency and volume (Loy, Chin and Sankaran 2021). This era, known as the First Industrial Revolution, also witnessed the proliferation of large organisations and the establishment of industrial customs (Jerath and Jerath 2021).

The Subsequent Industrial Revolution commenced in the 1870s, centred on the development of electrical machinery and further advancements in production management techniques (Jerath and Jerath 2021). These developments triggered global impacts, including economic expansion, enhancements in transportation and communication systems, and changes in population growth and labour conditions (Shaw-Taylor *et al.* 2024). However, they also caused a growing divide between the wealthy and the impoverished, as well as increased pollution in urban areas (Adekanbi 2024).

The Third Industrial Revolution (3IR) was characterised by the integration of services and goods using technological facilitators such as big data analytics, adaptive services, and digital manufacturing (Geuna *et al.* 2021). It included the advancement of digital manufacturing devices and the democratisation of production, resulting in modifications in social organisation (Colombo *et al.* 2021). The 3IR also comprised developments in information technology, telecommunications, means of transport, and nuclear energy (Geuna *et al.* 2021). Technological innovations in the 3IR have had a considerable effect on the economy, democracy, interpersonal relationships, and the labour market (Huang *et al.* 2021). The 3IR, which is seen as a step toward the mass customisation and collaborative production of goods and services in real time, is considered the precursor of the 4IR, as shown in Figure 2.1 below.

The 4IR, also known as Industry 4.0, is a technological disruption that has drastically changed people’s jobs and way of life in general. While every industrial revolution gradually develops more advanced production techniques by building on the creative accomplishments of its predecessors (Muthuswamy and Santhi 2023), and many global benefits and challenges have been brought about by earlier industrial revolutions, the 4IR is continuously changing the global economic landscape, especially with the emergence of the IoT and the idea of a collaborative economy (Vrana 2021).

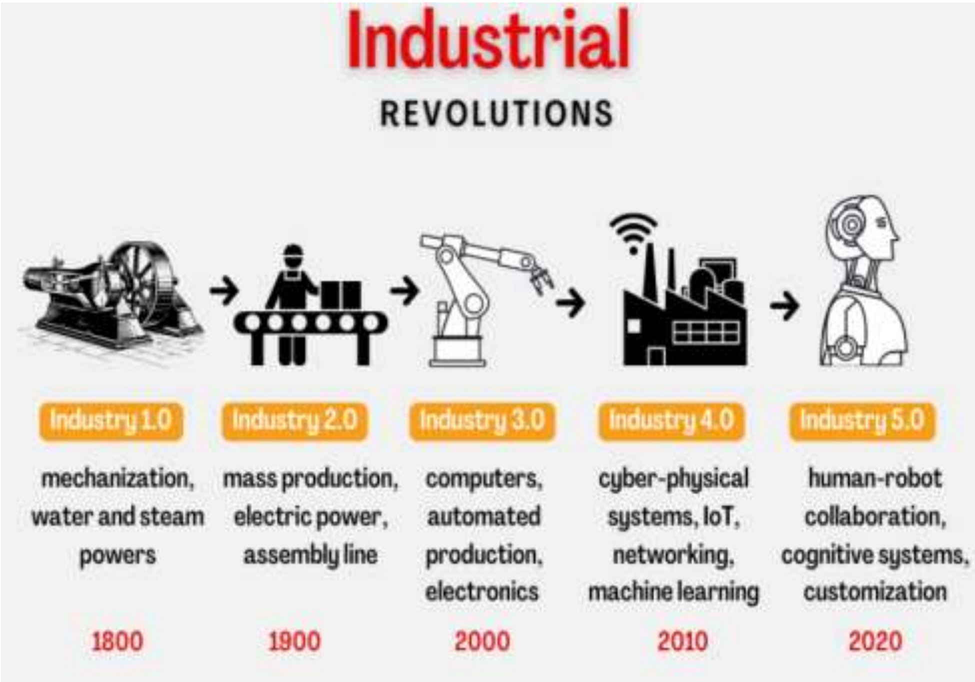

Figure 2.1: The Outline of the Five Industrial Revolutions
Source: Matuszak (2022)

The 4IR is characterised by the integration of digital technologies into manufacturing processes to improve productivity, efficiency, and sustainability (Onu, Pradhan and Mbohwa 2023). This entails the use of technologies such as the IoT, AI, advanced data analytics, and automation to connect physical assets, enable real-time control and monitoring, and optimise decision-making based on real-time data (Patil *et al.* 2023). The goal of the 4IR is to transform traditional manufacturing facilities into intelligent factories that can more effectively utilise resources, adjust to changing customer demands, and enable smooth communication and cooperation between workers, tools, and machines (De Oliveira-Dias *et al.* 2023). Since its inception in 2011, this approach has gained traction as a calculated strategy to propel technical development and address issues across various industries, such as creating sustainable materials and renewable energy (Ghodsian *et al.* 2023). Technological advancements and their socioeconomic impact are expected to increase exponentially throughout the 4IR, requiring an all-encompassing approach that combines social and technological innovation (Wilson 2021). Given its significant effects on economies and society as a whole, a thorough and coordinated response to the changes brought about by the 4IR, including all stakeholders, is needed (Wilson 2021).

The 5IR, which recently drew the attention of researchers with its immense potential, marks a major turning point in the evolution of industries and societally integrated systems. The characteristics of the 5IR paradigm are the intersection of humans and a set of cutting-edge technologies like AI, robots, the IoT, and nanotechnology; this promises a radical transformation of the world (Engelbrecht, Yitmen and Almusaed 2024). At its core, the 5IR corresponds with the concept of Society 5.0—a technologically mediated, human-centred, and sustainably oriented conception of society that promises the solution of serious world problems (Ziatdinov, Atteraya and Nabiyev 2024). It is anticipated that the great similarity of physical, virtual, and biological systems during the 5IR will greatly affect the financial sector as well as the manufacturing sector, particularly with the inclusion of AI and other new technologies (Varriale *et al.* 2023). Furthermore, the 5IR may make the most of these game-changing technologies to resolve issues regarding poverty and sustainability and further accelerate the world's economy (Huang *et al.* 2022). Nevertheless, there have been expressions of concern regarding the plausible detrimental impacts on civil society that may arise due to the 5IR and the desire to make sure that the benefits of the technology are properly disseminated (Costa, Martinez-Galán and Leandro 2022). Other industries, like the healthcare sector, will need to undergo these advancements with the development of new paradigms regarding educational training programs in the virtual world (Rajamäki 2024). The 5IR bears relevance regarding the structure of supply chain networks, particularly with the inclusion of the medical devices sector and the association of sustainability and human-machine collaboration being of utmost significance (Nayeri, Heydari and Sazvar 2023). On the other hand, the AMI could make the most of the technology of the 5IR with the development of more intelligent and more adaptable manufacturing systems that evaluate the maturity levels of machine vision systems and integrate them with the target of accomplishing zero-defect manufacturing with higher efficiency (Konstantinidis *et al.* 2023).

While the use of 4IR and 5IR technologies is expanding in both developed and developing economies, the innovation impact of adopting these technologies remains uneven and difficult to measure. This concern is especially noticeable in emerging economies such as South Africa, where systemic deficiencies marked by poor infrastructure, shortages of skilled labour, and high capital outlays compromise the full realisation of these technological benefits (Das and Drine 2020; Kowal and Paliwoda-Pękosz 2017). While investigation in this field has thrived, the literature remains uneven across disciplines such as labour studies, engineering, economics, and information systems. Variations in the underlying conceptual frameworks, techniques, and focal areas further complicate the requirement for integration in research and policy to guarantee a thorough understanding of the field's evolution.

2.3 Bibliometric analysis

Bibliometric analysis offers a systematic and replicable method for mapping the structure, dynamics, and intellectual foundations of this emerging research area. In this study, bibliometric analysis was carried out using the VOSviewer software program to quantitatively investigate publication patterns, determine the major contributors and authors, investigate notable thematic clusters, evaluate the patterns of co-citation, and analyse keyword structures (Amiri, Kushwaha and Singh 2023). By pinpointing the dominant discourses and new gaps that emerge, these methods give a wide perspective on how the academic community understands and treats innovation and modernisation within the AMI.

This bibliometric literature review focuses specifically on the innovation effects of the adoption of 4IR and 5IR technology in the AMI. This study aims to identify the critical factors that affect innovation and the innovation effects on the modernization of the AMI. Narrative reviews of the literature have been the usual approach of other literature reviews that have been conducted; although valuable, these reviews have not harnessed the power of bibliometric analysis that enable scalability and transparency (Dlamini and Kheswa 2023; Saah and Mbohwa 2025). The goal of anchoring this study in a bibliometric framework is fourfold:

a) to discover relevant factors influencing innovation and modernisation in AMIs that have adopted 4IR and 5IR technologies;
b) to inform the development of a theoretical model for subsequent hypothesis testing using SEM, specifically tailored to the innovation landscape of AMIs in developing economies;
c) to explore the challenges facing innovation and modernisation in the AMI in South Africa; and
d) to identify gaps in the existing literature on innovation and modernisation in AMIs, especially in developing economies such as South Africa.

2.3.1 Searching, identification, and analysis of data

To perform a literature review for the study, a systematic search of academic literature regarding the impact of recent industrial revolutions on the modernisation of the AMI was conducted using the Scopus database, which offers a more extensive citation and abstract search capability for peer-reviewed journals compared to other commonly used online scholarly databases such as Web of Science (WoS), Lens, Dimensions, and PubMed which are often employed to compile bibliometric analysis data for research purposes. For example, most of the publications in Scopus are available in WoS, but several publications in Scopus are not available in WoS. Additionally, Scopus was carefully chosen for this bibliometric study due to its wide-ranging multidisciplinary coverage, reliable citation data, and advanced analytical tools that support robust and accurate research impact assessment.

The resources utilised in this study include scholarly articles published during the period from 2020 to 2025, which saw the emergence of the 5IR attracting growing academic interest and application across various sectors. The publications for use in the bibliometric analysis were collected using a comprehensive sample strategy. The dataset includes bibliometric elements that are analysed, such as the publication title, author, abstract, keywords, publication year, publisher, journal, type of publication, and affiliations. The study utilised the following search strings with Boolean operators to extract relevant material from the Scopus database: “automotive manufacturing“ OR “automobile industry” AND “fourth industrial revolution” OR “4IR” OR “fifth industrial revolution” OR “5IR” OR “smart manufacturing” OR “digitalization” OR “human-robot collaboration” OR “human-machine collaboration” OR “human-machine cooperation” AND “innovation” OR “modernization” AND “automotive industry” OR “automobile industry” OR “automotive manufacturing” OR “automobile manufacturing” OR “car manufacturing”. The relative significance of these search phrases within the study was considered. The search was limited to articles, article reviews, and papers in conference proceedings published within the year range 2020 to 2025. Only documents in the English language were considered.

The search yielded 1697 documents suitable for inclusion in the final bibliometric analysis. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Rathee *et al.* 2023; Nyulas *et al.* 2025) were utilised in selecting and screening documents for the final bibliometric analysis, as shown in Figure 2.2 below.

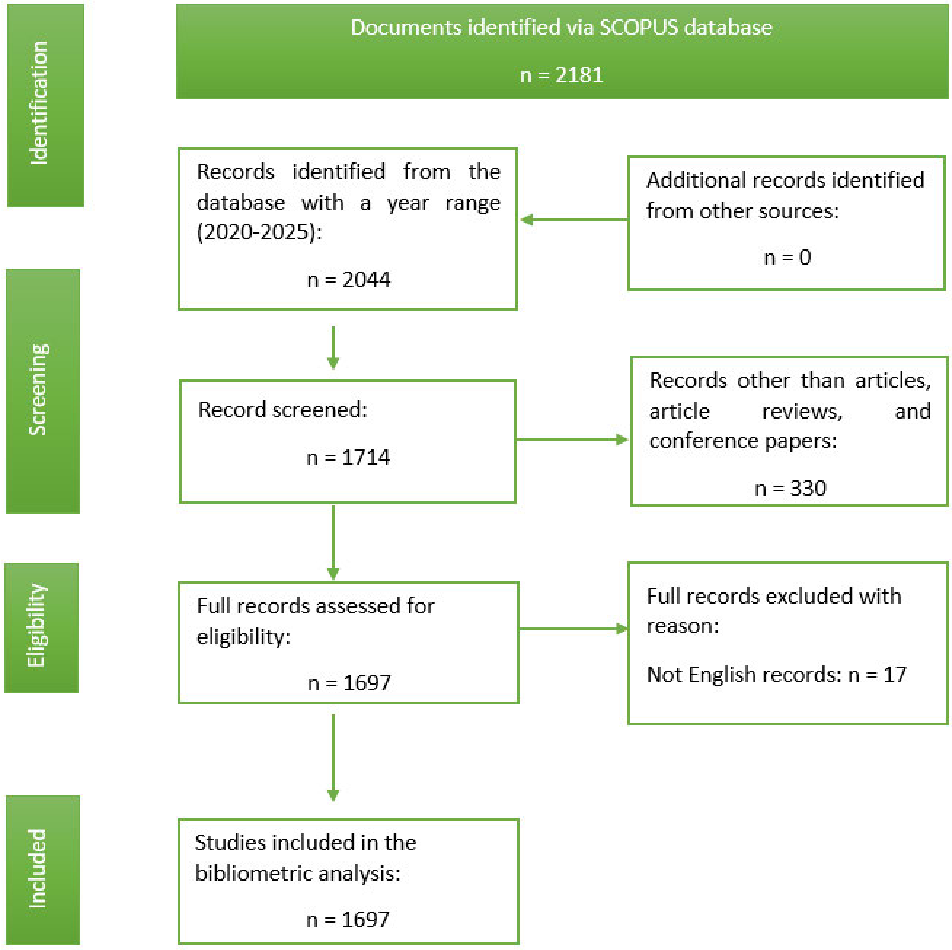

Figure 2.2: Study selection using Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines

Duplicates in the included papers were removed using OpenRefine, a free open-source data transformation and visualisation tool. Duplicate publications were not found. The VOSviewer software program was used to further analyse the papers. To create an objective bibliometric analysis and reduce the likelihood of bias, first and second-order indicators were integrated using VOSviewer.

2.3.2 Findings and discussion

This bibliometric literature analysis aims to inform the development of a theoretical model for subsequent hypothesis testing using SEM, specifically tailored to the innovation landscape of AMIs in developing economies, in addition to identifying factors influencing innovation in the AMI and outcomes of modernisation in the AMI. In order to fully capture what happens in the literature on the AMI from 2020, which is generally regarded as the beginning of the 5IR, to 2025, the bibliometric analysis identifies the most reputable authors and publishers, new subjects, strengths of regional collaboration, and the direction of the study field across multiple publications. The results of this analysis are presented in the subsections below in accordance with the goals of the study stated in Chapter One.

2.3.2.1 Distribution of publications by year

The number of publications on recent industrial revolutions from 2020—generally regarded as the year 5IR technology first emerged—to July 30, 2025, is displayed in Figure 2.3 below. There has been a discernible increase in research output over this time, particularly in fields closely associated with the 4IR and 5IR, according to the bibliometric profile of research publications published. From 100 articles in 2020 to 506 articles in 2024, with an additional 353 articles published in the first seven months of 2025, published articles exhibit a comparatively consistent growth curve during this time. With a noticeably steep upward trajectory since 2021, this rise suggests growing scholarly interest in the topic, potentially spurred by the revolutionary reactions resulting from the COVID-19 pandemic's effects and global technology advancements.

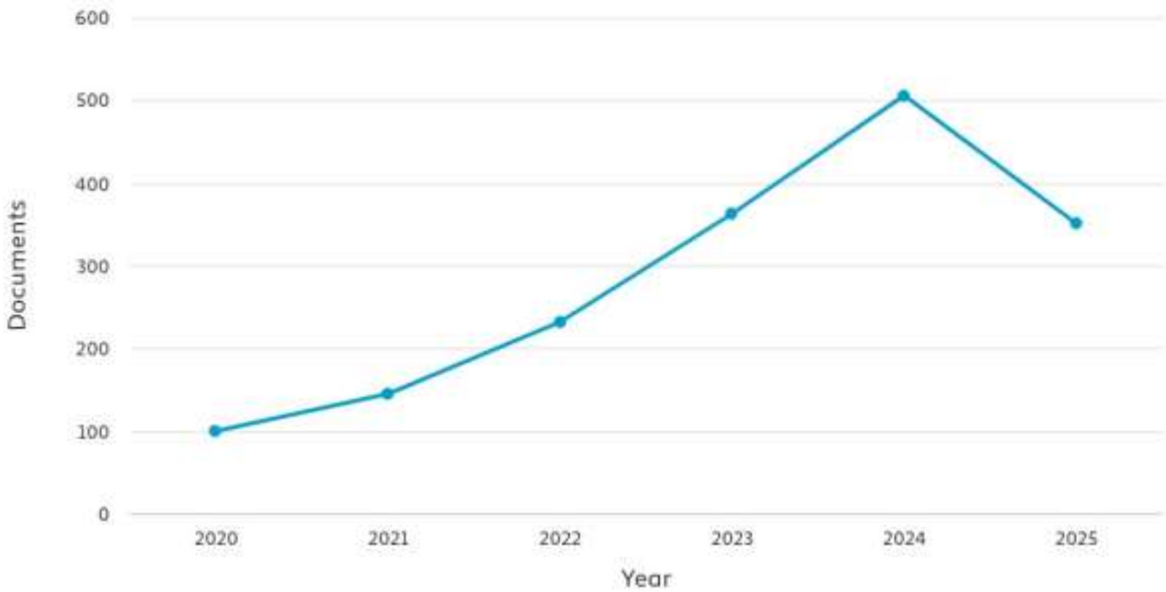

Figure 2.3: Distribution of publications by year

2.3.2.2 *Distribution of top five publication sources by year*

The bibliometric analysis of the top five publication sources from 2020 to 2025 demonstrates clear patterns in academic production related to the study's theme, as seen in Figure 2.4 below. A total of 91 relevant papers were published in *Sustainability Switzerland*, highlighting the crucial role of this journal in promoting studies on industrial transformation and sustainability. The *Journal of Cleaner Production* published 48 pertinent papers, and Business Strategy and the Environment published 36 pertinent papers. Both publications emphasise the strategic and environmental aspects of industrial revolutions. While *IEEE Transactions on Engineering Management* released 26 pertinent papers, highlighting the managerial and engineering aspects of the subject, *Technology Forecasting and Social Change* published 33 relevant papers, demonstrating a concentration on forecasting future technology developments. The chronological distribution of the publications is steadily increasing throughout different sources, particularly in *Sustainability Switzerland*, indicating an increasing level of scholarly interest in sustainability-focused industrial innovation. The multidisciplinary nature of the study is shown by this source-based analysis, which also identifies important journals that influence academic discussions in the field.

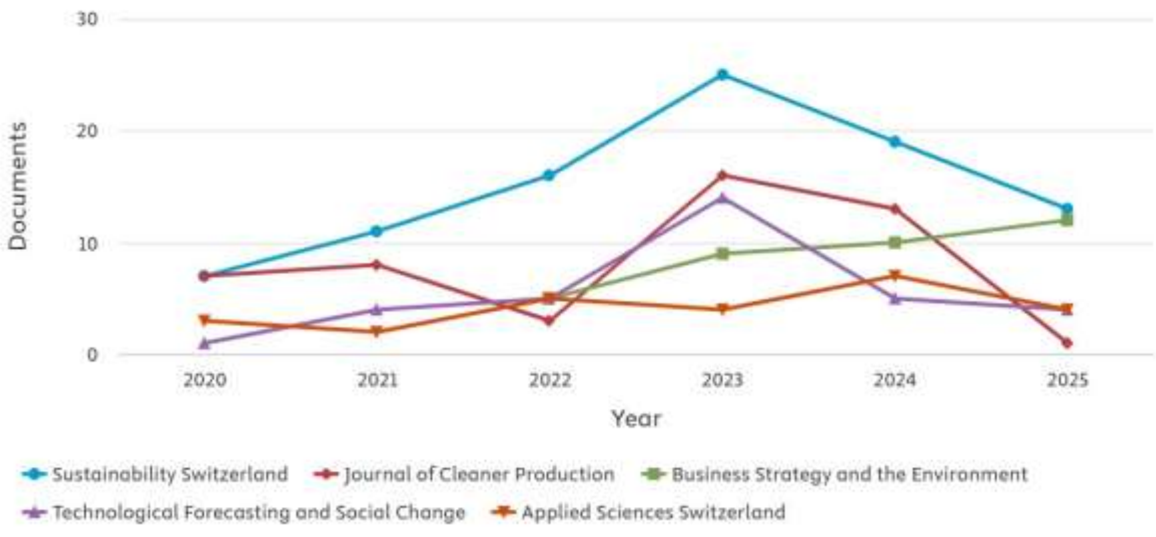

Figure 2.4: Distribution of top five publication sources by year

2.3.2.3 Distribution of top ten authors by publication count

As shown in Figure 2.5 below, the most prolific author impacting the development of exploration on the innovation impact of recent industrial revolutions on modernising the AMI during the indicated period is Garza-Reyes, who contributed 12 publications. Kumar and Luthra each contributed eight publications, showing continued scholarly engagement. Govindan, Gunasekaran, Krzywdzinski, Mangla, and Purwanto each contributed seven works, showing a substantial level of thematic or collaborative consistency. Anzolin and Behl each contributed six works.

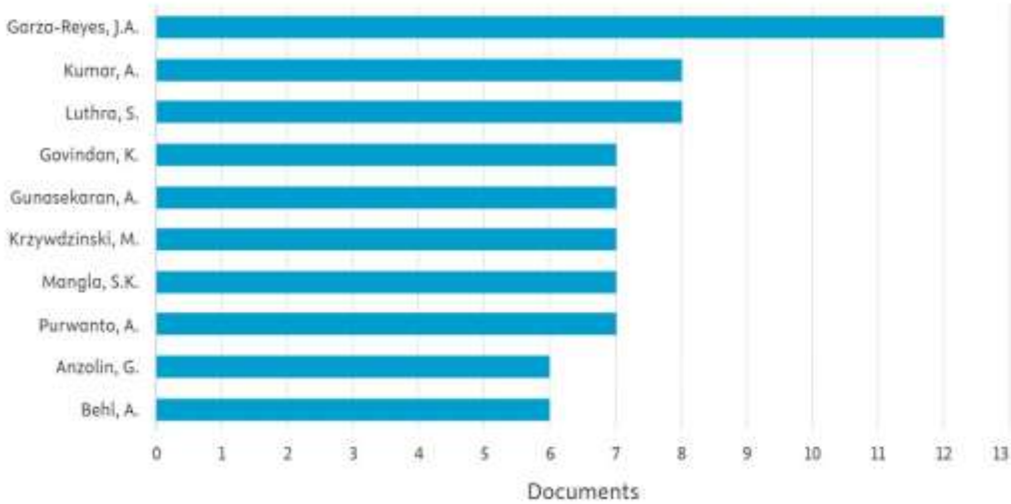

Figure 2.5: Distribution of top ten authors by publication count

This geographic distribution draws attention to a core set of powerful academics who are influencing the conversation and could be important nodes in networks of co-authorship or citations. Furthermore, their contributions may show leadership in certain areas like sustainable operations, digital transformation, or industrial innovation.

2.3.2.4 Distribution of top ten institutional affiliations by publication count

As shown in Figure 2.6 below, the bibliometric evaluation of institutional affiliations reflects an international and multi-sided research scenario.

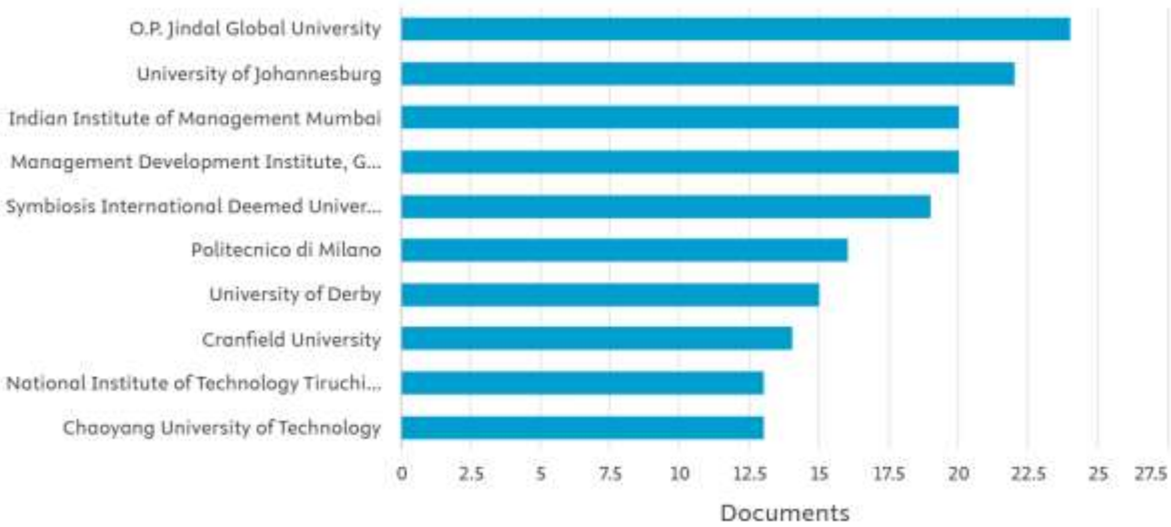

Figure 2.6: Distribution of top ten institutional affiliations by publication count

The two top-ranked institutions are O.P. Jindal Global University and the University of Johannesburg, indicating substantial regional research leadership on issues related to industrial transformation and sustainability. Institutions in India show a distinctly active involvement, with the Indian Institute of Management in Mumbai and the Management Development Institute in Gurgaon each contributing 20 papers and Symbiosis International Deemed University contributing 19 papers. European institutions that show extensive involvement include capable research organisations such as the highly esteemed Politecnico di Milano (16 papers), the University of Derby (15 papers), and Cranfield University (14 papers). Additional contributions from the National Institute of Technology Tiruchirappalli and Chaoyang University of Technology further highlight the international nature of the research field. These affiliations indicate the dominant institutional hotspots that act as nuclei for academic production and suggest possible international collaboration opportunities.

2.3.2.5 Distribution of top ten countries by publication count

India has the biggest scholarly production in this topic, with about 375 articles, according to the country-level bibliometric study, as seen in Figure 2.7 below. This highlights India's leading position in research on sustainability and industrial transformation. China has produced about 300 publications, indicating its strategic emphasis on policy-driven research and technological innovation. Western universities are actively involved in academia, as seen by the significant contributions from the United States of America (USA) (about 150 publications) and the United Kingdom (about 175 papers). Research communities in Europe and Southeast Asia are actively interested, as seen by the significant contributions from Malaysia (75 papers) and Italy (125 papers). About 75 publications are contributed by Germany and Australia, with slightly more than 50 papers each from France and Pakistan. This geographical distribution highlights the global nature of the research domain and suggests potential for cross-national cooperation as well as comparative research.

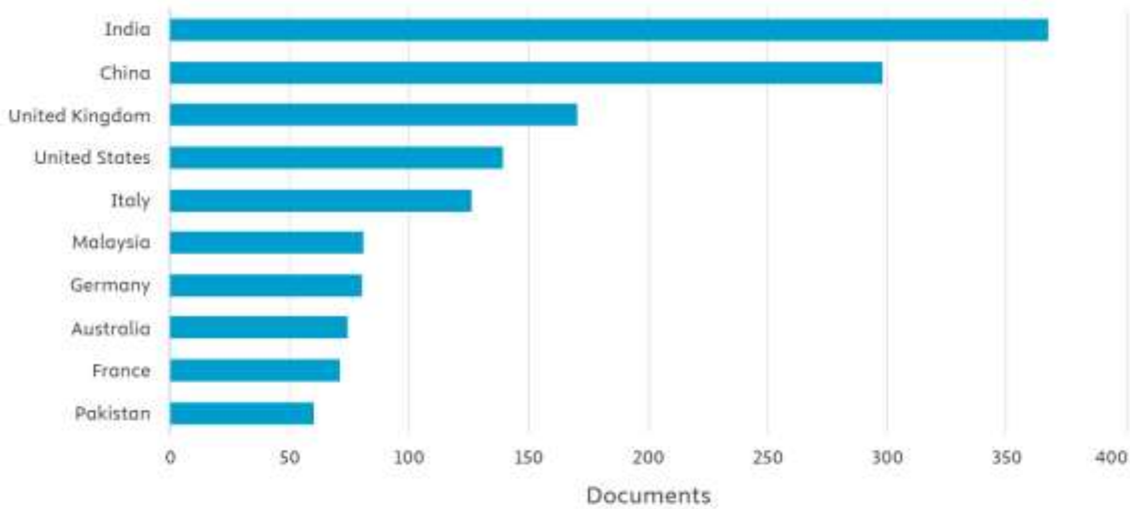

Figure 2.7: Distribution of top ten countries by publication count

2.3.2.6 Distribution of publications by type

As can be seen in Figure 2.8 above, peer-reviewed journal articles are the most prominent type of documents with 77.7% of the total documents published. The prevalence of this type of documents, representing an inclination toward original works based on the empirical and theoretical foundations, bears testament to the depth of research conducted and the rigorous scholarship of this field of study. Reviews make up the second type of documents at 11.5%, representing an emerging trend toward the consolidation of existing knowledge and agreement on the direction of future research endeavours. Conference proceedings make up the third type of documents at 10.8%, representing an active engagement with the scholarly community and the reporting of preliminary results of research endeavours. The prevalence of the first type of documents with regard to distribution signifies the maturity of the field of study.

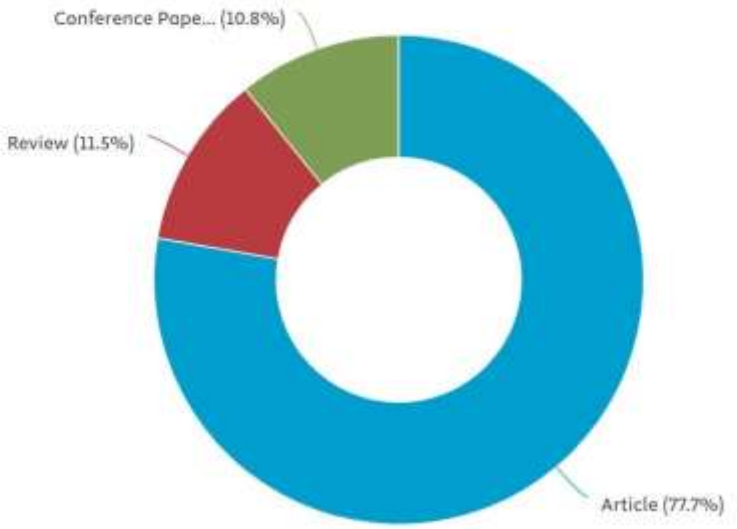

Figure 2.8: Distribution of publications by type

2.3.2.7 Distribution of publications by subject area

As shown in Figure 2.9 below, the distribution of publications by subject area reveals a complex research landscape. The most prevalent subject area is Business, Management, and Accounting, with 747 publications (19.5%); this highlights the strategic and organisational aspects of the process of industrial transformation. The crucial technological and computational underpinnings of the 4IR and 5IR are highlighted by the 612 papers (16.0%) in the Engineering subject area and the 504 publications (13.2%) in the Computer Science subject area. There are 405 publications (10.6%) in the Social Science subject area and 328 publications (8.6%) in the Environmental Science subject area, indicating a growing scholarly interest in the social and environmental effects of the changes brought about by the 4IR and 5IR. A focus on the operational, sustainable, and financial aspects of industrial transformation is evident in the results for the subject areas of Decision Sciences (7.0%), Energy (6.0%), and Economics, Econometrics, and Finance (4.8%). The results for the subject areas of Mathematics (3.2%) and Materials Science (1.8%) highlight the technical detail involved in the research landscape. The remaining 9.3% of publications fall in the “Other” category, which suggests extensive multidisciplinary engagement and consequently supports the complex and integrated nature of the research field.

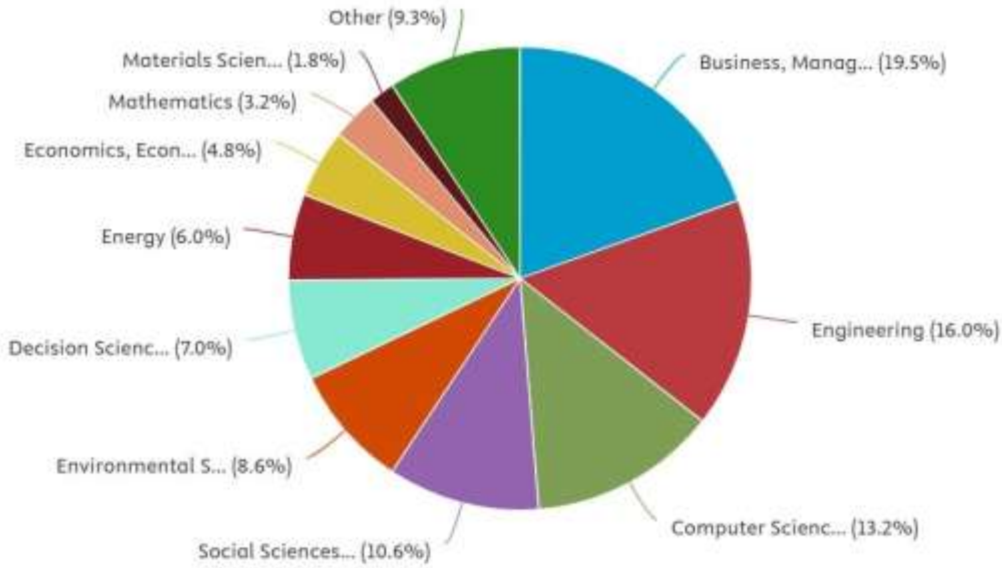

Figure 2.9: Distribution of publications by subject area

2.3.2.8 Citation map

Figure 2.10 below shows a citation map generated using VOSviewer. The citation map represents the research context and influence of the recent industrial revolutions. The size of each node, which represents a published work, directly corresponds to its frequency of citation; hence, larger nodes indicate a greater influence.

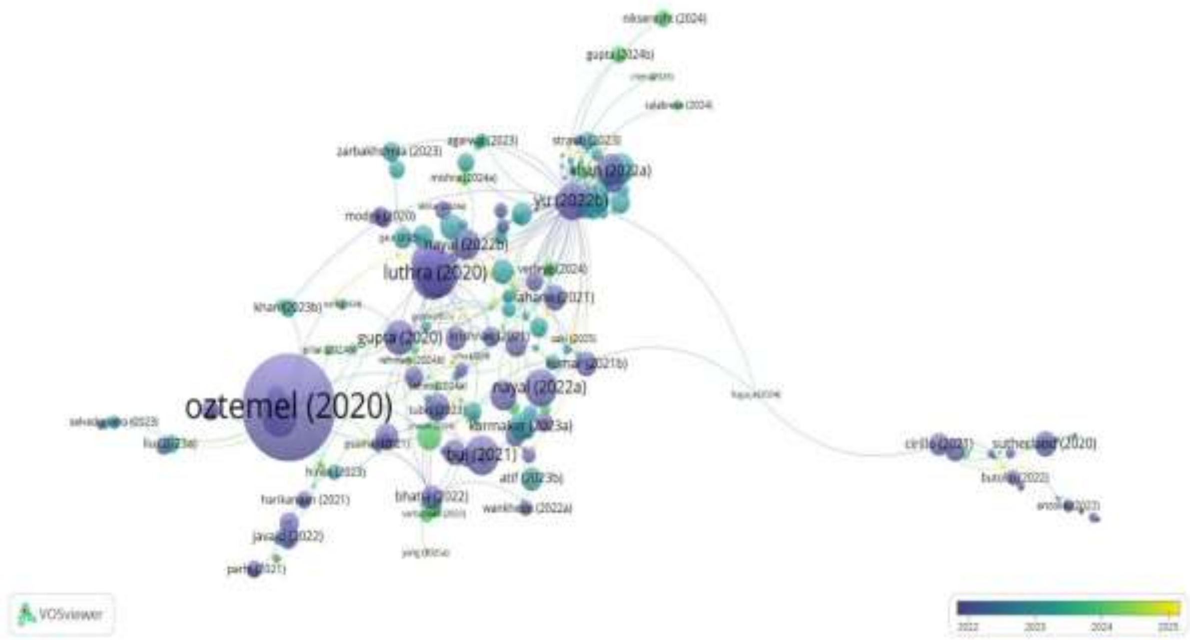

Figure 2.10: Citation map

Significantly cited studies, like Oztemel and Luthra's 2020 study, are depicted as building blocks that recur frequently throughout the network, emphasizing the vital role they play in laying the groundwork for subsequent research. Connections between citations are illustrated as connections between nodes, which show different study paths and literature emphases on connected topics. The node colours represent the citation years, which range from 2020 to 2025. In addition to indicating pioneering works, citation mapping helps to capture the growth and spread of knowledge in the field.

2.3.2.9 Co-citation network map

Figure 2.11 below shows a co-citation network map generated using VOSviewer. For authors with 20 or more citations, the total co-citation strength was computed. An author is represented as a node, and the size of a node indicates how many citations the author has received overall. A co-citation relationship is shown by a link between two nodes; the thickness of the link shows how frequently the authors are referenced together, indicating the strength of the co-citation relationship. The co-citation map illustrates the collaborative structures and intellectual environment relevant to research related to the 4IR and 5IR. Scholars appear in separate clusters depending on the number of co-citation occurrences between them, reflecting common research interests and thematic associations.

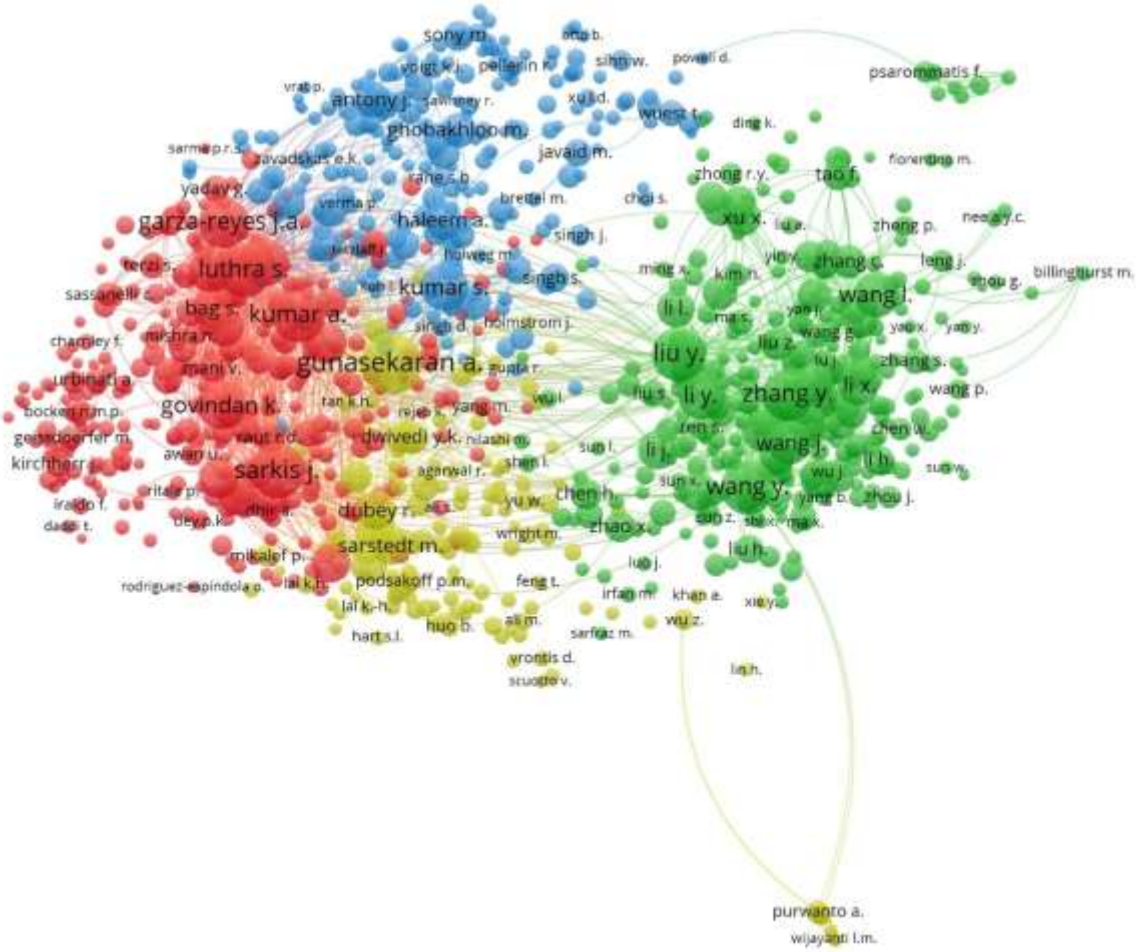

Figure 2.11: Co-citation network map

The red group, which includes Luthra, Kumar, and Garza-Reyes, is particularly interested in industry transformation strategy and sustainable supply chain management. These fields of study are represented in prestigious journals like the Journal of Cleaner Production and Environment and Business Strategy. In line with traditional research priorities, the blue group, which includes Sony, Choi, and Singh, represents research contributions in the fields of engineering, digital innovation, and risk management. The green group, including Zhang, Wang, and Li, focuses on computer science and engineering, particularly computational modelling and smart production research. The yellow group, including Dubey, Sarstedt, and Hair, focuses on themes associated with the circular economy and the environment, as well as national and subject-level analyses. The co-citation landscape thus emphasises the highly connected and complex nature of the research field.

2.3.2.10 Co-author network map

The co-author network map shown in Figure 2.12 below reflects a more emergent and diffuse scholarly landscape than highly dense mature research fields with relatively few and geographically dispersed connections.

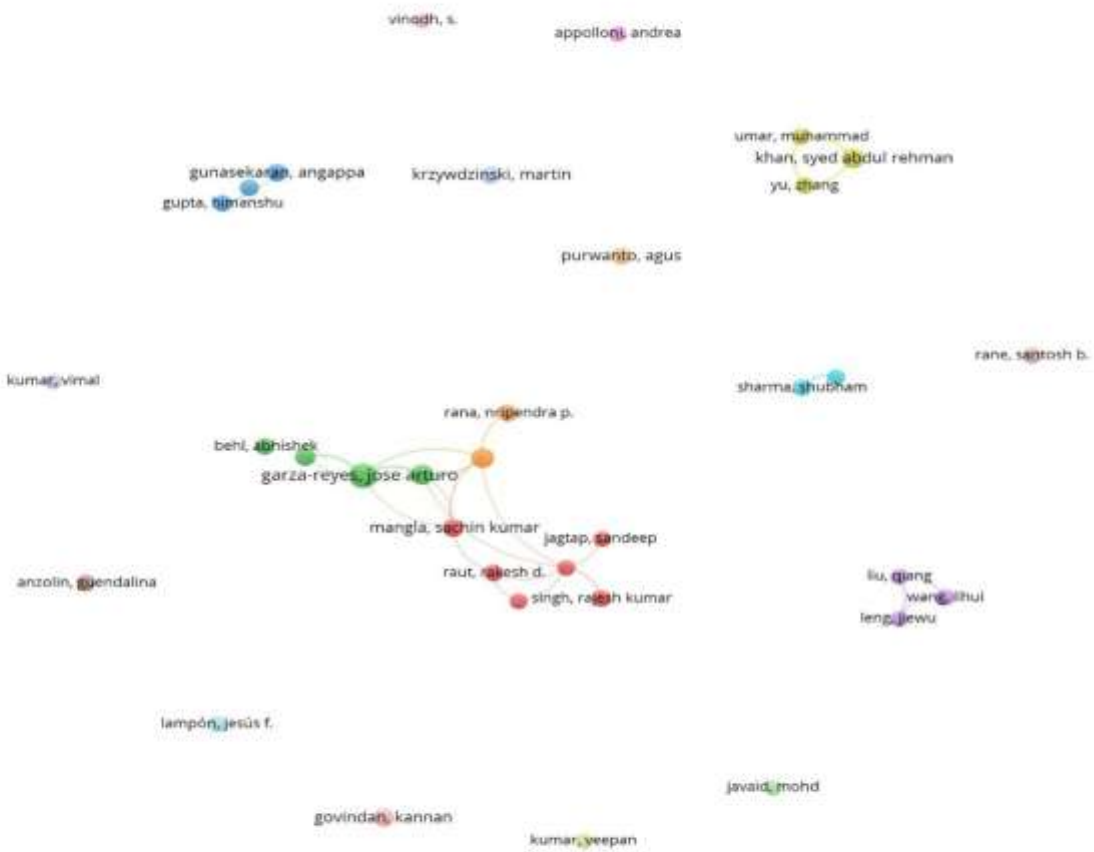

Figure 2.12: Co-author network map

The network topography suggests an emergent transdisciplinary field during its emergent phases, with Garza-Reyes as a bridging actor positioned close to the network core; ties extending over numerous author clusters indicate the researcher's role as an intellectual hub point between communities, offering cross-community knowledge flows. Clear regional research concentrations can be identified in South

Asia (Kumar, Gupta, Rana) and East Asia (Liu, Wang, Leng), detailing topographical research co-work patterns or common cultural academic research practices aligned to research methods. Emergent research areas are indicated by the peripheral nodes of Western and other European scholars (Krzywdzinski, Anzolin, Lampon).

The network's comparatively small number of connections per actor indicates that the area is expanding quickly and that new researchers are either creating citation patterns or representing a highly specialised field with fewer cross-citations as research foci stay specialised. Researchers like Purwanto and Sharma may serve as future boundary spanners who integrate currently divided research communities due to their between-region location, while some researchers' peripheral positioning indicates that there are plenty of opportunities to improve collaboration and theoretical integration in an emerging scholarly landscape.

2.3.2.11 Keyword map

An integrated and entwined network of activity at the nexus of Industry 4.0 technology, the need for sustainability, and specific applications like automotive production is revealed by the term map in Figure 2.13 below. Closely related words like machine learning, digital twins, intelligent manufacturing, and CPS define the technological underpinnings at the core of this network. These features demonstrate the contemporary literature's emphasis on time-based monitoring, data-driven automation, and intelligent systems that enable flexible and highly efficient manufacturing operations (Bag *et al.* 2021).

The thematic extensions derived from this technological core include all fields related to sustainability, the circular economy, and innovation, suggesting an increasing interest among scholars in the integration of digital transformation and sustainable objectives (Feroz, Zo and Chiravuri 2021; Javaid *et al.* 2022a). Agglomerations such as climate change, carbon emissions, and green innovation show an expanded comprehension of the sustainable potential of Industry 4.0 and its role in enhancing operational efficacy (Ghobakhloo *et al.* 2021; Jiang, Sakhare and Kaur 2021). Additionally, the incorporation of concepts like employment, servitization, and business models into theme developments relating to automobiles represents the socioeconomic sides of technological advancement. These phrases are linked to academic research on how digital technologies affect traditional manufacturing sectors in terms of employment and value generation (Bhatia and Kumar 2020; Llopis-Albert, Rubio and Valero 2021).

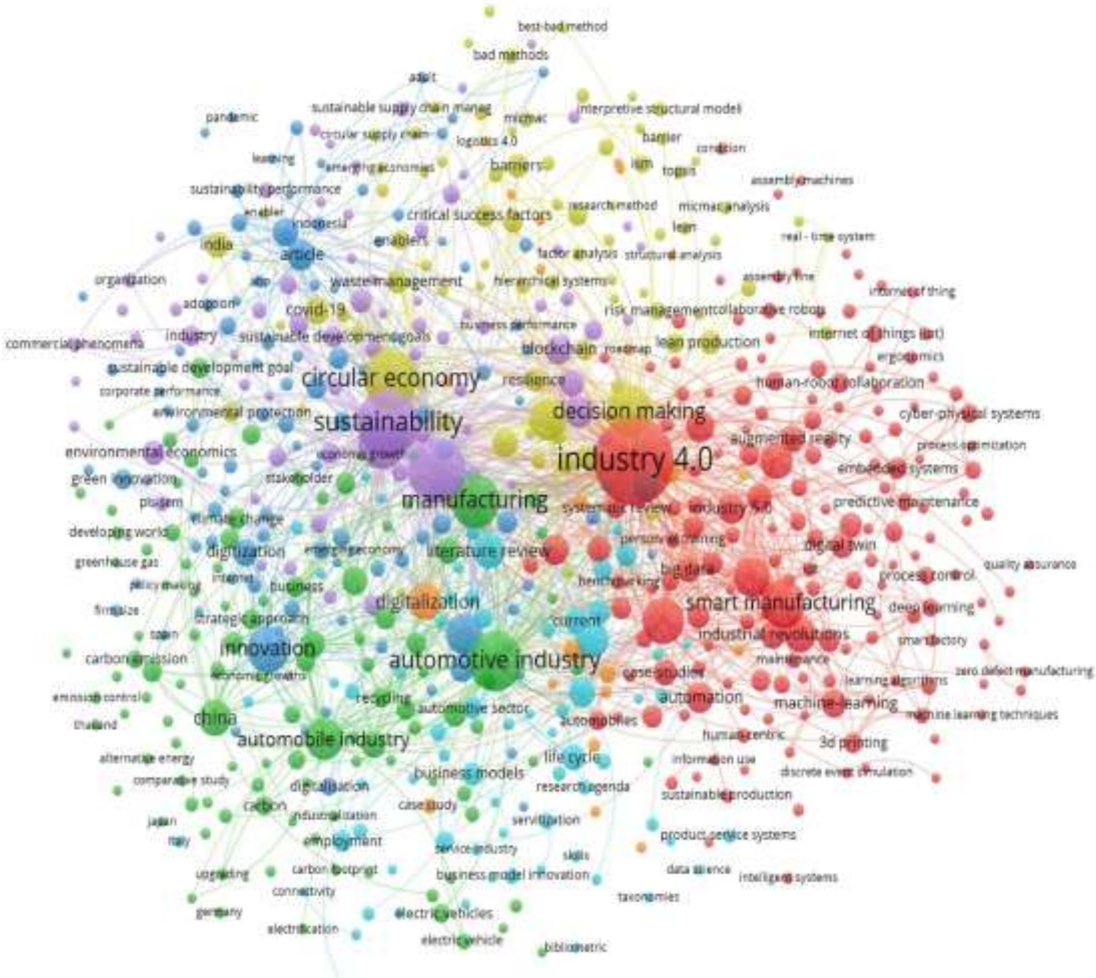

Figure 2.13: Keyword map

The introduction of methodological terms such as factor analysis, *Matrice d'Impacts Croisés Multiplication Appliquée á un Classement* (MICMAC) analysis, and decision making represents the increasing establishment of an academic discipline committed to studying implementation difficulties and success factors using systematic decision support systems (Vinodh, Wankhede and Muruganantham 2024). Overall, the map reflects a converging discourse in which technology adoption, environmental sustainability, and organisational adaptation are seen as mutually reinforcing components of industrial modernisation, consistent with emerging frameworks such as Industry 5.0 and socio-technical transition theory (Breque, De Nul and Petridis 2021).

2.4 Factors influencing the adoption of Fourth and Fifth Industrial Revolution technologies

2.4.1 Investment in Fourth and Fifth Industrial Revolution technologies

Investment in technologies that are applicable within the context of the 4IR and the 5IR is a very essential catalyst of innovation and modernisation within the AMI. Figure 2.13 above presents the keyword map that identifies the various linked clusters of research on smart manufacturing, the Industry 4.0 initiative, and the process of digitalisation that pertain directly to investments in capital-intensive technology. All the various clusters again point out the importance of financial investment as the key catalyst that heads the innovation transition process, with the development of complex capabilities that refer directly to the application of technologies that are more complex in nature, such as CPS, the IoT, AI, and collaborative robotics. Hossain *et al.* (2024) conclude that astute investments in complex systems bring the innovation transition from the conceptual towards the pragmatic in the form of modernisation, enhancing operational efficiency and product-innovation cycle rates accordingly. Further to this postulation, Ogunwole *et al.* (2023) and Kapoor (2024) demonstrate that the scale and concentration of investments of this sort determine the fate of new technologies in terms of whether they oust existing systems or co-exist successfully along with them, as well as modulating the eventual innovation impact of these technologies. Without adequate funding, the transition from theoretical innovation to practical modernisation becomes increasingly challenging, particularly in situations where resources are limited.

Investment is an important bridge that connects the aspirations of innovation with the tangible results of modernisation. Studies have shown that targeted investments in digital infrastructure, automation, and analytics improve organisational performance, support product customisation, and increase supply chain integrations (Atobishi, Moh’d Abu Bakir and Nosratabadi 2024; Sun 2024; Zhang, Xu and Ma 2023). This mediating role is aptly evidenced in bibliographic trends linking financial readiness with effective applications of predictive maintenance, digital twins, and real-time decision-making systems. Investment converts innovation strategies into tangible, value-creating activities, detaching them from their otherwise intangible and theoretical nature. It also serves as a moderating factor, exercising its impact on the strength and direction of the linkage between innovation and modernisation. Zhang, Xu and Ma (2023) assert that the scale and scope of investment can either incorporate technology advancements under existing paradigms or trigger transformative changes. Small investments allow incremental improvements through improved procedures, while high financial outlays support a drastic movement towards all-automated smart production networks (Cennamo *et al.* 2020). Such moderation is most significant in developing countries, where persistent financial and regulatory hurdles consistently affect the extent and speed of technology assimilation (Serumaga-Zake and van der Poll 2021).

The co-citation network map shown in Figure 2.11 above indicates vigorous intellectual links between studies that relate to financial planning, digital preparedness, and organisational performance, implying that budget decisions range from short-term economic needs to strategic considerations. Organisations must balance short-term expenses with long-term competitive sustainability, and policymakers play a pivotal role in enabling a conducive environment via tax concessions, subsidies, and public-private partnerships (Adebayo, Lulofs and Heldeweg 2023; Shi and Ge 2025). However, no empirical studies exist exploring the mediating and moderating roles played by investments on performance consequences associated with modernisation, and this demonstrates a significant gap in the existing literature.

2.4.2 Education in Fourth and Fifth Industrial Revolution technologies

Effective training and skill development play a major role in the AMI's adoption of technology and diffusion of innovation (DoI). In the keyword map displayed in Figure 2.13 above, education, training, and skills are significant key phrases, emphasizing the crucial role that human capital plays in guaranteeing the effective implementation of Industry 4.0 and 5.0 technologies. Studies have shown that a digitally literate workforce with learning adaptability and problem-solving skills is needed to exploit the opportunities of value creation offered by technologies related to the 4IR and 5IR, such as the IoT, AI, CPS, and cobots (Chaka 2023; Saniuk, Grabowska and Grebski 2022; Silva, J. *et al.* 2022). According to an empirical study by Zhu (2023), workers were completely prepared to interact with advanced technologies thanks to targeted training programs and varying degrees of technological integration, which also fostered an inventive culture inside automotive project teams. However, in situations where the required skills are missing, investments in advanced technologies may be squandered or rendered useless.

Education is a vital intermediary that bridges technological innovation and the effects of modernisation. It helps to bridge the gap between abstract knowledge and its practical application in industrial environments by providing employees with technical and cognitive abilities. For instance, communicative operators who operate automated vehicles and analysts who interpret data are integral to the efficient use of digital twins and predictive maintenance technologies (Lim *et al.* 2023). By fully enhancing the potential of technology through the incorporation of skilled labour, education plays a central mediating role that bridges innovation and modernisation. Education acts as a moderating influence in that it shapes both the rate and degree of learning and change within organisations (Ajayi and Udeh 2024). Li (2022) asserts that organisations with solid educational frameworks and regular upskilling programmes have a greater ability to adjust to technological upheavals and successfully embrace new technologies. In contrast, organisations with no regular upskilling programmes generally experience operational inefficiency, misalignment of staff, and inertia, which serve as barriers to modernisation (Morandini *et al.* 2023). The moderating impact of education is even more notable in countries with an underdeveloped economy, where the development of technical training programmes and educational infrastructure might lag behind rapid technological changes (Serumaga-Zake and van der Poll 2021).

The co-citation network map shown in Figure 2.11 above reveals a strong intellectual relationship between researchers involved in the analysis of the socio-technical aspects of industrial transitions, namely, Dubey, Sarkis, and Nayal. These scholars call for holistic systemic reforms involving changes in curricula within schools and colleges, industry-academia partnerships, and state-led programmes to improve digital literacy and ensure the alignment of workforce development with the changing needs of Industry 4.0 and 5.0 (Anurogo *et al.* 2023; Samuels and Pelser 2025). Nevertheless, even though these studies exist, the mediating and moderating effects of education on modernisation outcomes in the present era are still largely under-researched.

2.4.3 Management of Fourth and Fifth Industrial Revolution technologies

In the context of Industry 4.0 and 5.0, managerial techniques are crucial for managing innovation and directing the modernisation process in the automotive production sector. Leadership, management, and decision-making concerns stand up as crucial components, demonstrating their significance in connecting technical advancements to organisational needs, according to keyword mapping analysis. The 4IR and 5IR require an overarching approach in which digital transformation thrives on the interplay between agile governance and people-centric approaches, as opposed to previous industrial revolutions being largely driven by operational technology implementation (Sony and Naik 2020).

Management functions are intermediaries between innovation efforts and the results of modernisation. Resource allocations to emerging technologies such as the IoT, AI, and CPS are designed to use systematic approaches to increase efficiency, sustainability, and customer focus by setting up digital leadership and adaptive management systems (Sony and Naik 2020). The use of predictive analytics and advanced manufacturing technologies requires managerial intervention alongside technological deployments aimed at improving processes, controlling resources, and facilitating interdisciplinary approaches (Chatterjee *et al.* 2022; Zong and Guan 2024). A lack of managerial mediation regarding investment in specific technologies risks turning such investments into isolated efforts instead of integrating them into strategic organisational modernisation (Bajić *et al.* 2021; Serrano-Ruiz, Mula and Poler 2021). In addition, the functions of management act as a moderating factor that not only guides the effects of innovation and modernisation but also controls the intensity of their effects. Administrative and leadership approaches are central to determining measures of organisational preparedness, adaptability of reaction to shifts in cultures, and resilience in response to transformation (Prayag, Muskat and Dassanayake 2023; Zafar 2025). While rigid bureaucratic models might hamper advancement, proactive approaches to managing shifts and fluid decision-making models enable organisations to effectively manage challenges related to digital transformation. In the context of Industry 5.0, which combines automation with human-centric approaches encouraged through effective management, the importance of this moderating variable is central to attaining current-day modernisation that builds on social sustainability while maintaining employee morale (Ivanov 2022; Van Erp *et al.* 2024).

The co-citation network map shown in Figure 2.11 above reveals strong academic associations between studies on strategic management, digital maturity, and organisational performance, highlighting the consensus that management is not a marginal factor but a cornerstone in 4IR and 5IR evolution. However, empirical research quantifying management's mediating and moderating roles remains limited, particularly in emerging economies where structural and cultural barriers may amplify managerial influence. Addressing this gap is essential for developing frameworks for integrating leadership, technology, and human capital into cohesive modernisation strategies.

2.5 Factors influencing innovation in the automotive manufacturing industry

The transformation of the AMI under Industry 4.0 and 5.0 is driven by several innovation factors that determine the pace, scale, and success of technological adoption. These factors, which can be derived from the keyword co-occurrence map shown in Figure 2.13 above, include the cost of technology adoption, the availability of skilled labour, and support for technology infrastructure.

2.5.1 Cost of technology adoption

The economic effects of Industry 4.0 and 5.0 technology adoption are one of the main issues with the current development of the AMI. Keyword mapping analysis reveals a consistent level of academic concern regarding the economic implications of such adoption, which is captured by keywords such as investment, digital transformation, technological preparedness, and cost of implementation. These terms are consistently related to business approach and resource allocation and thus reflect the dominance of cost issues in the literature regarding industrial innovation.

The convergence of the IoT, AI, and CPS requires considerable initial investment in terms of hardware, software, and workforce training (Oztemel and Gursev 2020). In addition to these costs, the costs of cybersecurity infrastructure, system integration, and maintenance add to the total capital investment. Studies have shown that organisations need to assess their digital maturity before adopting such comprehensive changes since sudden adoption without proper preparation can cause operational downtime, losses that cannot be recovered, and inefficiencies (Haryanti, Rakhmawati and Subriadi 2023; Hortovanyi *et al.* 2023). This argument is supported by bibliometric analyses identifying eminent co-citation patterns between financial constraints and strategic readiness frameworks.

The challenges of acquiring funding in emerging economies, such as South Africa, are exacerbated by the substantial financial consequences of obtaining capital, insufficient governmental incentives, and restricted access to subsidised financing (Serumaga-Zake and van der Poll 2021). Unlike developed economies, where state assistance and tax advantages often act as principal catalysts of technology shifts, South African business faces formidable barriers inhibiting extensive technology adoption. Small and medium-sized enterprises (SMEs), which form the critical base of the supply chains of the AMI, find it difficult to justify the cost of sophisticated technology due to lower production volumes and profit margins.

The co-citation network map shown in Figure 2.11 above further clarifies the relationships between risk management research and related costs, implying, among other things, that cost factors are linked to market instability and technological uncertainty. Studies have asserted that collaborative strategies, including industry conferences and shared online forums, are likely to mitigate these issues through cost sharing among stakeholders (Li *et al.* 2024; Nayal *et al.* 2021; Vivona, Demircioglu and Audretsch 2022). A critical gap within the literature, evidenced by the absence of empirical data on the effectiveness of these models within emerging economies, highlights the need for further research on these dynamics.

2.5.2 Availability of skilled labour

The availability of skilled labour, particularly in the fields of automation and robotics, is one of the main drivers of innovation in the AMI. Key themes, including human-machine interaction, collaborative robotics, workforce preparation, and the labour market, are identified by the concept map displayed in Figure 2.13 above, highlighting conflicts between employment trends and technological advancement. Automation is a major component of Industry 4.0, which has the potential to significantly reduce reliance on human labour while also producing job losses. On the other hand, Industry 5.0 suggests a strategy that is focused on human talents, encouraging the fusion of technology and human abilities to foster innovation and increase operational effectiveness. Industry 5.0 emphasises the value of human inputs in the manufacturing process, with individuals with diverse skill sets serving as valuable resources (D'Souza and Tapas 2024; Ikenga and van der Sijde 2024; Oeij *et al.* 2024). While competitive advantage from cheap labour could result in late automation adoption in labour-surplus countries such as India and China, Industry 5.0 promises enhanced acceptance among the working population due to its emphasis on human-machine collaboration over replacement.

Incorporation of 4IR and 5IR technologies in the AMI poses a major threat in the form of labour displacement. As automation and robots increasingly take over jobs involving manual or repetitive tasks, job losses or shifts in the composition of the labour market could result (Dauth *et al.* 2021; Esguerra 2020). However, a German study found that while automation may reduce employment opportunities in manufacturing, it has led to the generation of new jobs within the services sector; in addition, individuals who are retained in manufacturing are often given new jobs that involve more advanced tasks, especially when they have complementary skills (Dauth *et al.* 2021). In the short to medium term, employment opportunities could increase if the skills possessed by workers are matched with emerging requirements in production, especially when new industries are located near existing ones. However, the shift towards EVs complicates this scenario. A study conducted by Cotterman *et al.* (2024) found that EV powertrain manufacture requires increased labour intensity compared with conventional internal combustion engines.

The 5IR highlights the essence of human-machine collaboration, striving to put the human factor back into manufacturing while ensuring less likelihood of total displacement of jobs because it harnesses advanced technology in combination with human innovation and flexibility (Fanoro, Božanić and Sinha 2021). Success in such collaborative settings requires an employee base with both technological and interpersonal skills, including communication and problem-solving skills (Chaka 2020). While the 4IR could increase labour displacement risks, the 5IR proposes an entirely human-centred framework that could help ease such difficulties because it emphasises collaboration between humans and machines.

Despite automation causing the obsolescence of some conventional jobs, incorporating 4IR and 5IR technologies in the automotive manufacturing sector can create an enormous number of new jobs. In addition to the use of smart factory concepts and digitalisation, the adoption of 4IR innovations has led to significant demand for programmers, mechatronics engineers, robotics technicians, data scientists, IoT experts, and smart system designing and maintenance experts (Jagannathan and Geronimo 2021; Jerman, Bach, and Aleksić 2020). In addition to higher-order technical skills, skills such as creativity, problem solving, flexibility, and willingness to keep updating knowledge concerning fast-changing technological trends are equally important for these jobs (Anshari, Almunawar and Razzaq 2021). The shift into the 5IR, with its focus on human-machine interaction, has been projected to drive the creation of jobs that amalgamate technological skills with people-oriented skills, such as collaborative robot attendants and human-machine interaction experts (Jerman, Bach and Aleksić 2020). The transformative process, besides boosting overall employment opportunities within the sector, serves as an engine driving expansion into other sectors such as information and communications technology (ICT), mobility services, and research and development (R&D) (Helmold 2021). To effectively prepare people for new jobs, especially in developing countries, large investments should be made in educating and training people in the labour market (Jagannathan and Geronimo 2021). Therefore, while automation results in job losses in specific sectors, the adoption of 4IR and 5IR technologies stimulates the creation of diversified, higher-order jobs within the automotive industry.

Workforce readiness is crucial for effectively applying 4IR- and 5IR-related technologies in the AMI; this requires whole-of-workforce programmes focused on both reskilling and upskilling to keep pace with rapidly changing job requirements (Li 2024; Verma and Venkatesan 2023). To create an organisational culture focused on lifelong learning, organisations should integrate training and continuing professional development as core components of strategy frameworks (Li 2024; Verma and Venkatesan 2023). In addition to the acquisition of technically oriented skills, workforce readiness incorporates essential soft skills such as creativity, problem-solving, and flexibility; these skills are increasingly important in the 5IR's human-centred, human-machine collaborative environments as well as in automation-intensive environments typical of the 4IR (Adegbite and Adeosun 2021; Verma and Venkatesan 2023). Empirical research undertaken within the AMI suggests that a large percentage of employees lack sufficient preparation, particularly in developing countries where digital competency and experience with sophisticated technology remain insignificant (Adegbite and Adeosun 2021; Carrillo, Vallejo, and Gomis 2022). Effective support mechanisms, flexible organisational dynamics, and effective leadership can enable employees to transition into new technology projects (Bahono 2023). By applying readiness review frameworks to determine current gaps and highlight specific areas where improvements could be made, organisations should be better placed to integrate new technologies seamlessly (Çınar, Zeeshan, and Korhan 2021; Wankhede and Vinodh 2022). In environments where intelligent manufacturing takes place, workforce readiness goes far beyond mere technological proficiency; it involves having an adaptable, flexible, continuously evolving, technology-capable workforce.

The findings of the co-citation analysis indicate significant associations between studies that analyse labour readiness and those researching digital transformation, thus validating that labour availability entails qualitative and quantitative dimensions. However, the successful implementation of these plans is significantly hindered by competency gaps in data analytics, robotic programming, and the incorporation of AI (Brauner, Murawski and Bick 2023). Taking these gaps into consideration, there is a need to undertake extensive re-skilling plans, joint training programmes, and strategic policy interventions to better prepare employees to counteract the challenges brought about by new technologies.

2.5.3 Infrastructure and technology support

The complexity and accessibility of technology paradigms play a major role in the emergence of innovation in the AMI. Terms like blockchain, IoT, cloud computing, smart factories, and digital platforms are included in the keyword map displayed in Figure 2.13 above, which emphasizes the need of developing skills related to Industry 4.0 and 5.0. The co-citation network map shown in Figure 2.11 above depicts notable academic input from researchers such as Wang and Liu, who have contributed significantly to the field of digital integration and smart manufacturing. This study highlights the extreme importance of strong infrastructure to support real-time data collection, analysis, and decision-making. Regional variations in infrastructure capability are key determinants of the speed of innovation propagation. While developing countries face issues related to connectivity, interoperability, and cybersecurity, economies with mature digital landscapes have a greater capability to embrace Industry 4.0 technologies (Raj *et al.* 2020). Additionally, the keyword map shown in Figure 2.13 above emphasises the critical importance of the use of cloud computing for scalable information management coupled with the application of blockchain technology to build transparency in the value chain, both of which form the bedrock of the modern AMI.

Progress in automotive innovation is largely the result of technological infrastructure improvements, including the advent of blockchain technology, cloud computing, and the IoT, among other enabling technologies. Industry 4.0 and 5.0 functionality is based on secure information processing, real-time information generation, and high-order decision-making ability, all of which depend heavily on resilient digital infrastructure. Differences in the standard of infrastructure between regions significantly determine the extent and the rate of innovation.

The IoT is fundamental to smart supply chains and smart factories in the AMI as it enables tracking, automation, and information-based manufacturing (Ahmed *et al.* 2022; Biot *et al.* 2025; Shahzad, Gherbi and Zhang 2022). Cloud-based technologies offer scalable solutions for storage, processing, and analysis of information, thus enabling the AMI to cope with the high volumes of information generated from activity and machinery monitoring (Al-Dulaimy *et al.* 2024; Pang, Chang and Wang 2022). Automotive technology innovation, automotive intelligence, intelligent mobility, and digital automotive service innovation are all heavily reliant on cloud computing, variable manufacturing processes, and big data analysis (Al-Dulaimy *et al.* 2024; Pang, Chang and Wang 2022). The usage of blockchain technology significantly enhances the security, transparency, and integrity of shared information across networks (Albshaier, Budokhi and Aljughaiman 2024; Fernando, Widjaja and Tan 2021; Shahzad, Gherbi, and Zhang 2022). The worldwide expansion of these technologies is being accelerated by their wide applicability, especially across IoT-edge-cloud networks with the added security and reliability provided by blockchain technology; while simultaneous usages of these technologies are driving the market towards future technological breakthroughs, the effectiveness of these solutions depends heavily on the availability of robust computing power, secure cybersecurity measures, and seamless interconnectivity between different devices and networks (Ahmed *et al.* 2022; Al-Dulaimy *et al.* 2024; Wei *et al.* 2024).

To overcome the limitations of single technologies, the AMI is increasingly embracing hybrid systems that combine cloud, edge, and blockchain technologies, thereby improving scalability, security, and operational efficiency. For instance, combining blockchain technology with cloud-edge computing reduces overhead on resources and optimises key management, thus making secure, private authentication and effective data sharing viable in transport structures (Gai *et al.* 2020; Mei *et al.* 2022; Zheng, Wu and Li 2023). Blockchain-based platforms are increasingly used in supply chain administration to create decentralised identity management systems for IoT devices and offer tamper-proof records, thus minimising information silos as well as enhancing stakeholder trust and transparency (Patwe and Phansalkar 2021; Subramanian and Thampy 2021; Wei *et al.* 2024). These hybrid systems facilitate high-throughput secure storage and subtle, dynamic access control, which are necessary for efficiently managing large amounts of multi-attribute data in supply chains in the automotive field (Li *et al.* 2023; Subramanian and Thampy 2021). The combination of blockchain with IoT and cloud technologies also strengthens security and privacy by reducing vulnerabilities such as data breaches, single points of failure, and unauthorised access, which are critical issues in the automotive industry's logistics and manufacturing spheres (Gai *et al.* 2020; Mei *et al.* 2022; Patwe and Phansalkar 2021). To actively combat cyberattacks in IoT-enabled systems, sophisticated intrusion detection and mitigation architectures that include blockchain and edge computing are being developed (Sharadqh *et al.* 2023). These integration trends are driving the development of secure, open, and efficient automotive operations in which hybrid architectures provide a solid foundation for continued innovation.

Geographic differences fundamentally influence the adoption of digital technologies in the automotive industry. Innovations can be swiftly and successfully adopted in areas with sophisticated digital ecosystems, robust infrastructure, and supportive regulations (Li, S. *et al.* 2025). In contrast, connectivity, interoperability, and cybersecurity difficulties are common in developing regions, impeding innovation and technology integration (Yi *et al.* 2023; Zhang, Van Gorp, and Kievit 2022). The quality of digital governance, the innovation environment, discrepancies in economic structures, different industrial foundations, and the existence of leading enterprises are the main causes of the disparities (Li, S. *et al.* 2025; Yi *et al.* 2023). However, with suitable investment and policy support, the deployment of hybrid and decentralised infrastructures, such as the integration of cloud computing, edge computing, and blockchain, is likely to close the gaps by providing scalable, secure, and flexible solutions (Du and Jian 2024; Yakimova and Pankova 2024). The acceleration of digital transformation is significantly dependent on the support provided by government institutions, along with the resilience of regional innovation systems. Regions showing accelerated growth typically benefit from policy support and cooperation between innovation networks, leading to positive spill-over effects (Du and Jian 2024; Liang, Fan and Wang 2025). Closing the regional divides to allow all regions to benefit from the opportunities offered by Industry 4.0 and 5.0 requires significant investment in infrastructure and technology coupled with the upskilling of staff, harmonisation of regulations, and the adoption of resilient, cooperative digital systems.

2.6 Outcomes of modernisation in the automotive manufacturing industry

The factors influencing innovation discussed in Section 2.5 above determine the feasibility of adopting Industry 4.0 and 5.0 technologies as well as organisational readiness for adopting these technologies. This section discusses the benefits that these technologies bring to the AMI. These include increased productivity, workforce upskilling, workforce income, and e-commerce promotion, each of which is evident in the keyword map shown in Figure 2.13 above.

2.6.1 Increased productivity

The capability to drastically improve productivity is often viewed as an important advantage of Industry 4.0 adoption in the AMI. Keywords often associated with sophisticated manufacturing and automation, such as optimisation, lean manufacturing, predictive maintenance, and efficiency, feature strongly in the keyword map shown in Figure 2.13 above. These keywords reveal a momentous focus on the intersection of improved operational efficiency and digital transformation (Kamble and Gunasekaran 2021; Sundarakani, Manikas and Gunasekaran 2024). Technologies related to Industry 4.0 and 5.0 enable end-to-end real-time monitoring, predictive analysis, and data-driven decision support, simultaneously eliminating waste, enhancing production line capability, and minimising downtime.

Morella *et al.* (2021) assert that manufacturers have the capability of gathering and interpreting data in real time at the machine level through the integration of CPS and IoT sensors. This technological integration helps organisations develop proactive maintenance plans and lower the chances of unforeseen downtimes. The integration of AI and machine learning algorithms helps improve dynamic scheduling and distribution of resources and thus makes manufacturing systems highly accommodating to changes in demand and disruptions in the supply system (Ding *et al.* 2023). These attributes mirror the lean principles of eliminating waste and maximising resource utilisation.

The co-citation network map shown in Figure 2.11 above indicates important intellectual links among researchers such as Luthra, Kumar, and Garza-Reyes, who have focused their efforts on the strategic adoption of digital technologies to improve productivity. Their contributions demonstrate that productivity improvements are linked not only to technology adoption but also to workforce capability, organisational culture, and redesign of processes (Aleca and Mihai 2025; Odebode and Ogunbayo 2025). For instance, the future success of efforts involving predictive maintenance programmes depends on the development of proper data governance structures and the utilisation of qualified staff who are in a position to interpret the results yielded. In addition, bibliometric analysis shows that productivity trends transcend conventional production contexts, having a major impact on customer interaction and supply chain management. Virtual networks allow end-to-end real-time visibility and lead time reduction while enhancing responsiveness to market changes (Yadav *et al.* 2020). These benefits come with the need to overcome cybersecurity threats and interoperability issues, areas that have not yet been well-scrutinised in the empirical literature.

2.6.2 Organisational support for upskilling

Workers must possess digital skills and abilities to enable seamless operation, maintenance, and innovation connected to cutting-edge technology as a result of the Industry 4.0 revolution and the new Industry 5.0 paradigm. The keyword map in Figure 2.13 above clearly illustrates the growing importance of human capital in technological advancement by discussing subjects like training, digital skills, collaborative robots, and human-machine collaboration, particularly in the Industry 5.0 cluster. While Industry 4.0 is primarily focused on optimisation and automation, Industry 5.0 introduces a human-driven model in which human imagination enhances machine accuracy, thus enabling mass customisation and sustainable manufacturing (Chen *et al.* 2024; Grosse *et al.* 2023).

This shift necessitates continual education and the development of new abilities, particularly in domains like cybersecurity, robotics programming, data analytics, and artificial intelligence. According to Nurova and Freze (2021), in order to obtain a competitive edge in the rapidly growing digital economy, organisations must enhance the capabilities of their personnel beyond technical competencies. Organisations' ability to use digital supply chain integration, predictive maintenance, and intelligent manufacturing systems effectively is largely dependent on their capacity to stay abreast of evolving technology developments (Okorie *et al.* 2023).

The significant work of academics who concentrate on the socio-technical dimensions of industrial change, such as Dubey and Sarkis, is highlighted in the co-citation network map seen in Figure 2.11 above. The results of these authors demonstrate the urgent need for institutional support, educational reform, and governmental actions to properly facilitate scaling efforts (Sony and Naik 2020). Governmental incentives, for instance, can encourage businesses to spend money on staff training, and connections between academic institutions and businesses are essential for aligning curricula with the evolving demands for technology skills. Programmes such as ICT learning, vocational training, and private-public collaborations are critical in remediating South Africa’s skills gap, which remains a significant barrier to the adoption of 4IR and 5IR technologies (Serumaga-Zake and van der Poll 2021).

However, enduring barriers still hamper the progression of such initiatives. SMEs often have limited financial means at their disposal, which are insufficient for significant investments in extensive training projects; staff reluctance may further exacerbate difficulties in the implementation of such initiatives. There is an absence of empirical research examining the long-term effects of upskilling projects on organisational resilience, staff satisfaction, and output (Mokgolo, Dikotla and Chigo 2024). To ensure that workforce development projects are aligned with the main goal of Industry 5.0, which is to balance technological advancement and human well-being, it is important to fill these gaps.

2.6.3 Workforce income growth

The effects of industrial development on labour compensation are multifaceted and diverse, with technological development creating a range of prospects as well as problems. Increased scholarly interest in the economic and social ramifications of

Industry 4.0 and 5.0 integration reflects these changes in labour market processes, including job displacement, economic effects, and income disparities. Automation and robotics are examples of technological advancements that can enhance productivity and reduce operating costs, but they can also widen economic disparities and create job insecurity, with unskilled workers most at risk (Stahler 2021).

Automation has the ability to boost efficiency, but if appropriate social safety measures and reskilling initiatives aren't taken, it could displace traditional jobs and potentially expand wage discrepancies (Jadhav and Banubakode 2024; Marguerit 2025). However, new and specialised jobs in specialised fields like data science, robotics engineering, and cybersecurity are now possible because of technological improvements (Jadhav and Banubakode 2024; Li et al. 2021). The necessity for inclusive innovation frameworks that strike a balance between technical advancement and economic growth is highlighted by this dualistic effect (Lee 2023). According to Adeniyi *et al.* (2024), in order to prevent negative effects on income and guarantee shared prosperity, industry and policymakers must implement proactive sector-wide measures such as wage protection acts, sectoral training programs, and labour market reforms.

The co-citation network map shown in Figure 2.11 above reveals important intellectual links among scholars such as Sarkis and Nayal who specialise in sustainability and human-oriented innovation, advocating for legal frameworks that integrate social considerations into digital transition policies. Their studies highlight the need to ensure fair compensation, secure social safety nets, and economic resilience frameworks to avoid subjecting susceptible labour segments to undue difficulties due to modernisation (Nayal *et al.* 2022). This approach has been complemented by the work-oriented Industry 5.0 philosophy, which focuses on the advancement of collaboration among humans and machines rather than on striving to achieve full automation, thus protecting job prospects along with improving the quality of work (Alves, Lima and Gaspar 2023).

Key questions remain regarding workforce income growth in the AMI. Few empirical studies measure the long-term income benefits of Industry 4.0 or 5.0 adoption across various workforce segments and geographical areas. Similarly, there is a lack of understanding of how effectively policy measures such as universal basic income, salary subsidies, and tax breaks reduce income disparity in highly technologically advanced manufacturing settings. Filling these gaps has the potential to connect industrial development with socially sustainable development and to encourage more inclusive economic development.

2.6.4 Promotion of digital commerce

A paradigm shift from dealership-centric models to digitally integrated ecosystems has been signalled by the advent of digital platforms and consumer-facing technology, which have fundamentally altered the automotive retail industry. Terms like e-commerce, digital platforms, customer experience, and car retail frequently co-occur in the keyword map displayed in Figure 2.13 above, indicating a growing emphasis on online engagement and service delivery in academia and industry. This change is in line with the larger Industry 4.0 concept, which advocates integrating digital technology not just into industrial operations but into every aspect of the value supply chain, including sales and post-sales services (Yadav *et al.* 2020).

In line with Industry 4.0 principles, the incorporation of sophisticated digital technologies boosts supply chains, streamlines inventory handling, and encourages greater customer interactivity. Virtual showrooms, personalisation plans, augmented reality configurators, and AI-powered suggestion systems are increasingly being used to overcome the hurdles of buying (Piromalis and Kantaros 2022). Automotive manufacturers are launching e-commerce sites to provide a comprehensive digital customer experience, integrating features such as real-time analytics, scheduling of predictive maintenance, and customised financing offers (Yadav *et al.* 2020). When aligned with production calendars to ensure that production matches actual demand, these technologies enable operational efficiencies as well as satisfying customers.

Bibliometric mapping reveals strong co-citation ties between digital transformation and supply chain innovation research, indicating the changing role of e-commerce from a marketing tool to a core aspect of industrial modernisation (Farfán Chilicaus *et al.*

2025). Interestingly, this differentiation leads to demand-pull manufacturing environments in which information exchange between configurators and manufacturing plants enables the instantaneous influence of online consumer behaviour on the manufacturing process (Ezeamii, Idoko and Ojochogwu 2025). In addition, there is a growing trend towards platformisation strategies such as OEM-managed portals, aggregator marketplaces, and mobility as a service (MaaS) platforms (Reischauer *et al.* 2024). Each of these strategies offers unique value propositions in terms of sustainability, convenience, and personalisation (Ding *et al.* 2023).

Despite the efforts undertaken, important gaps continue to exist. Inadequate evaluation of cybersecurity weaknesses in integrated sales networks undermines consumer confidence and data integrity (Fernandez de Arroyabe, Watson and Angelopoulou 2023). In addition, there has been a lack of scholarly focus on social sustainability, particularly the online marginalisation of rural demand and the progressive obsolescence of traditional dealership networks. Finally, there is a lack of empirical research on the environmental trade-offs of the conventional dealership model used in combination with online sales approaches. This research gap is particularly timely because of the added focus in Industry 5.0 on sustainability and sustainability-driven innovation.

2.7 Challenges facing innovation in the South African automotive manufacturing industry

Figure 2.14 below shows a keyword map generated using VOSviewer which reflects the context of the South African AMI. This keyword map focuses on the key local literature in order to identify key challenges facing innovation in the South African AMI.

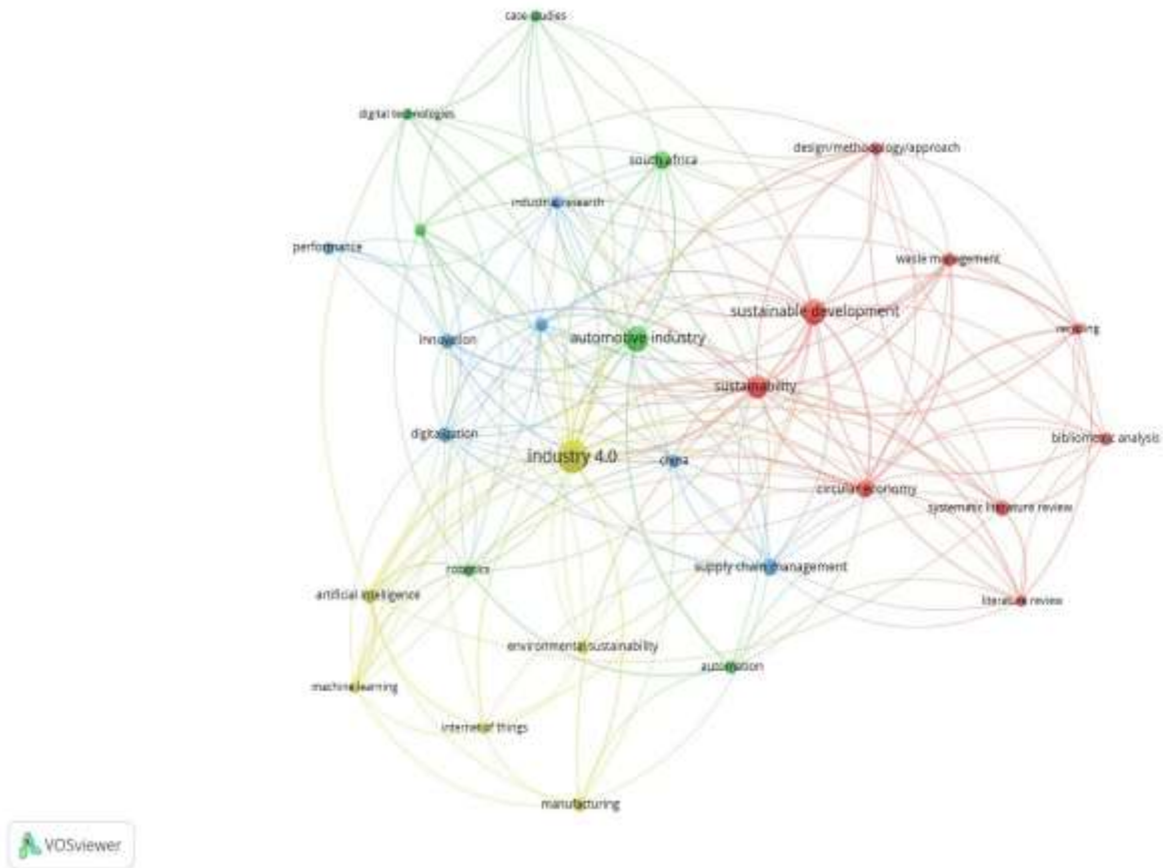

Figure 2.14: Contextual keyword map for the South African automotive manufacturing industry

The keyword map is based on 189 results that were extracted from the Scopus database using the following search strings with Boolean operators: “automotive manufacturing” OR “automobile industry” AND “fourth industrial revolution” OR “4IR” OR “fifth industrial revolution” OR “5IR” OR “smart manufacturing” OR “digitalization” OR “human-robot collaboration” OR “human-machine collaboration” OR “human-machine cooperation” AND “innovation” OR “modernization” AND “automotive industry” OR “automobile industry” OR “automotive manufacturing” OR “automobile manufacturing” OR “car manufacturing” AND “South Africa”. The contextual relevance of these search phrases within the study was considered. The search was limited to articles, article reviews, and papers in conference proceedings published within the year range 2020 to 2025.

The keyword map shows four core clusters that together represent the thematic extent of 4IR- and 5IR-related technologies and the current modernisation process in the

South African AMI. The most extensive cluster focuses on digital technology and Industry 4.0, with Industry 4.0 as the central node, co-occurring with terms such as automotive industry, innovation, digitalisation, and performance. This cluster points to a strong scholarly focus on the deployment of digital technologies, especially the IoT, CPS, and increased connectivity, as means to enhance innovation and performance in the South African AMI (Serumaga-Zake and van der Poll 2021). The presence of case studies, South Africa, and design/technology approach as co-occurring terms suggests that varied empirical and theoretical research is exploring local implementations of these technologies at different levels of impact (Alexander 2021).

The second cluster, focusing on AI and environmental sustainability, contains keywords such as AI, machine learning, manufacturing, automation, and environmental sustainability. The observed pattern features a significant focus on the use of analytics based on AI to optimise production procedures while also addressing environmental concerns (Piromalis and Kantaros 2022). The pairing of sustainability-oriented terminology with terminology relating to AI technologies suggests a growing tendency on the part of researchers to frame digital transformation as a tool to achieve increased productivity and environmentally friendly production mechanisms. However, the relatively lower occurrence of these terms as opposed to Industry 4.0 terminology suggests that the literature on the use of AI on a sustainability basis is in its infancy, underrepresented, and has yet to reach a level of maturity.

The third conceptual theme, focusing on sustainability and circular economy, includes terms such as sustainable development, circular economy, waste management, and life-cycle assessment. In response to global demands for material circularity and reduced carbon footprints, this field focuses on the increased interest in closed-loop technologies and material efficiencies in the AMI (Alexander 2021).

The fourth cluster, focusing on methodological and review-oriented research, includes methodologies such as literature review, bibliometric analysis, and systematic literature review. This cluster indicates a prevalent trend in the discipline towards a meta-analytical research perspective in which researchers explore the trajectory of subjects across studies and identify knowledge lacunas through systematic review approaches (Macpherson, Werner and Mey 2023). While the results from such research provide important insights relevant to the understanding of the field, they also highlight the limitation of experimental and longitudinal studies in supporting theoretical claims in practical, real-life settings. The appearance of both bibliometric analysis and systematic literature review as key terms in this field suggests that researchers ought to map gaps in existing knowledge and best practices by synthesising available information and critically examining proposed technologically innovative solutions. However, the literature tends to target equilibrium instead of examining direct correspondence between theoretical models and empirical data regarding cyclic approaches in practical applications within the automobile sector, especially in developing economies.

An integrated analysis of the keyword map shows that Industry 4.0 is positioned as a connecting factor among improvements in performance, sustainability needs, and technological adoption. The map clarifies the complex relationships among modernisation of the AMI and integrated digital technologies, AI-driven innovations, circular economy principles, and methodological acumen. However, it also reveals important gaps, particularly the absence of sound empirical analysis of current and future socio-technical changes in response to fast-changing market situations, as well as poor implementation of human-oriented Industry 5.0 principles (Alexander 2021; Serumaga-Zake and van der Poll 2021).

Despite the significant potential of 4IR and 5IR technologies to drive innovation and modernisation, several barriers continue to hinder their widespread adoption, especially in developing economies. These constraints are multifaceted, affecting technological readiness, workforce capacity, organisational strategy, and institutional policy environments.

2.7.1 Cost barriers

One of the major hurdles in the implementation of 4IR and 5IR technologies is high initial expenditure. SMEs are the driving force of rapidly growing economies, but many of them are unable to mobilise funding for digitalisation. Automation, AI, robotics, and integration of CPS are so costly that most SMEs find these expenditures prohibitive, particularly if return on investment is remote or uncertain (Macpherson, Werner and Mey 2023). Limited fund exposure, limited common investment platforms, and limited budgetary incentives for the purchase of technology all add to the financial strain faced by SMEs (Amirova, Osadchij and Stepanova 2024).

2.7.2 Infrastructural deficiencies

Digital infrastructure is a fundamental enabler of the implementation of 4IR and 5IR technologies, but its uneven geographical distribution is problematic, particularly in sub-Saharan Africa. South Africa's ICT infrastructure, despite being relatively well-developed, is still characterised by uneven broadband, smart grid, and industrial IoT networks (Moeletsi 2021). Such infrastructural deficiencies are a major hurdle for businesses in peri-urban and rural industrial hubs, including manufacturers of vehicle accessories and small parts, hindering them from implementing Industry 4.0 and 5.0-related technologies. Inadequate digital infrastructure hinders essential features of Industry 4.0 and 5.0 paradigms such as real-time information exchange, predictive maintenance, and remote manufacturing operations (Sun 2025).

2.7.3 Skills shortages

A shortage of appropriately skilled labour is a widely recognised barrier to the adoption of 4IR and 5IR technologies. The effective use of technologies such as AI, digital twins, and automated systems requires a digitally literate and technically trained workforce. However, many emerging economies, including South Africa, face severe gaps in science, technology, engineering, and mathematics education, as well as limited training in advanced manufacturing technologies (Ayinde, Adedeji and Ajayi 2024; Nyagadza *et al.* 2022). A lack of coordinated industry-university partnerships further exacerbates these skills gaps. Without continuous upskilling and reskilling programmes, technological transformation risks increasing labour market exclusion rather than fostering inclusive industrial growth.

2.7.4 Organisational readiness

Apart from technical and infrastructural constraints, organisational factors also play a critical role in mediating technology adoption. Many firms suffer from resistance to change, internal inertia, and limited digital leadership. Bhuiyan (2024) emphasises that a lack of strategic vision, weak top management commitment, and inadequate change management mechanisms can prevent firms from aligning technological adoption with broader organisational goals. Additionally, many manufacturers lack a formal digital strategy, making it difficult to prioritise and sequence investments in 4IR and 5IR technologies. This lack of readiness is particularly evident in firms that operate under legacy systems or hierarchical governance structures, which are ill-suited for agile, digitally enabled environments (van der Poll 2024).

These factors are more pronounced in the South African context due to structural imbalances, legacy exclusion, and divergent policies. Unequal access to education and digital technology exacerbates the digital divide, which limits the beneficiaries of industrial transformation (Sheik 2023). Inconsistent alignment between national and regional policies often hinders coordinated investment support for infrastructure, digital competencies, and finance for SMEs (Macpherson and Werner 2025). Without corrective action to address these structural limitations, the transformative potential of the 4IR and 5IR to unleash sustainable, inclusive development remains largely unfulfilled.

2.8 Challenges facing modernisation of the South African automotive manufacturing industry

The global AMI operates within a highly dynamic and competitive environment in which digital transformation has emerged as both a necessity and a challenge. In emerging markets such as South Africa, the transition towards 4IR and 5IR technologies is being undertaken against the encompassing backdrop of structural economic constraints, changing policy regimes, and growing global pressures. These external forces dictate the pace, scale, and strategic direction of technology adoption in the industry.

2.8.1 *Global competition*

The South African AMI, including OEMs and Tier-1 suppliers, is constantly faced with the challenge of catching up with competitors from more technologically advanced economies. Multinational competitors gain a competitive edge by leveraging economies of scale, which lower per-unit production costs, and by using integrated digital platforms and current technology, resulting in a faster time-to-market for new products (Avenyo, Bell and Nyamwena 2024; Gaffley and Pelser 2021). Automotive manufacturing across East Asia, Europe, and the Americas is automated through enhanced digital sophistication, data-driven supply management, and real-time customer responsiveness (Papulová, Gažová and Šufliarský 2021). Comparatively, South African manufacturers are faced with high unit production costs, limited automation capacity, and limited global integration. These challenges not only affect global competitiveness but also discourage investments in new technologies that might have no short-term benefits in a pricing-sensitive market (Sindhwani *et al.* 2022).

2.8.2 *Supply chain disruptions*

The COVID-19 pandemic revealed the vulnerability of global supply chain networks, particularly for industries that rely on just-in-time supply chain networks and sophisticated cross-border procurement networks. Supply lines for strategic parts such as semiconductors were shut off by border closures, lockdowns, and shipping congestion, causing the shutdown of manufacturing units and leading to revenue gaps (Figueira-De-Lemos *et al.* 2024). Following the pandemic, geopolitics and protectionism have continued to disrupt the supply of finished goods and materials (Mykyta 2025). To ensure supply chain resilience, the use of 4IR and 5IR technologies such as blockchain for supply chain transparency, AI for demand forecasting, and the IoT for asset monitoring is becoming imperative (Fanoro, Božanić and Sinha 2021). However, the investment capacity of South African firms is limited by inadequate infrastructure, finance, and technology (Obokoh *et al.* 2024). While digital transformation enhances agility and responsiveness, a lack of modernisation leaves firms vulnerable to future disruptions (Jeza and Lekhanya 2022).

2.8.3 Policy uncertainty

Policy instability is a major constraint on long-term strategic investment in the South African automotive sector. While the South African Automotive Masterplan (SAAM) 2035 outlines an ambitious vision for deepening localisation, expanding employment, and promoting technological upgrading, its implementation has been inconsistent (Nurhayanti *et al.* 2025; Sibuyi 2021). Fluctuating tax incentives, delays in subsidy disbursements, and unclear implementation timelines often discourage firms from making long-term capital investments in digital infrastructure (Noombo and Mwange 2024). Moreover, conflicting objectives across industrial, trade, and education policies result in misalignment between workforce development programmes and the actual technological needs of the industry (Mbuyazi, Mazenda and Mmakola 2025). This policy fragmentation contributes to uncertainty about the regulatory environment for automation, data protection, and ethical AI deployment, further slowing the adoption of 4IR and 5IR innovations (Adelowotan 2021).

2.8.4 Capital intensity

Automotive manufacturing is inherently capital-intensive, requiring sustained investment in physical infrastructure, advanced machinery, R&D, and regulatory compliance. Key areas requiring substantial and ongoing investment include robotics, sensor technologies, EV production lines, and emission reduction systems to meet increasingly stringent environmental standards (Nguvava 2024; Zi *et al.* 2025). For firms operating within tight margins, especially those dependent on export rebates or fluctuating foreign demand, the high upfront costs of 4IR and 5IR technologies can be prohibitive (Fanoro, Božanić and Sinha 2021; Nguvava 2024). Even when firms recognise the long-term efficiency gains offered by digital upgrades, they may be prevented from implementing these technologies by limited internal funding, high interest rates, and restricted access to development finance (Anzolin 2024). As a result, strategic investment decisions are often deferred or scaled down, weakening the competitiveness and sustainability of the sector in the long term (Macpherson, Werner and Mey 2023).

The current economic challenges emphasise the importance of a unifying policy framework that aligns digital transformation objectives with overall industrial development planning. For a policy to be effective, beyond visionary objectives, a foundation of sustainable incentives, inter-sector alignment, and capacity building must be laid (Görçün *et al.* 2024). A carefully integrated industrial strategy involving infrastructure development, upgrading of skills, and integration of SMEs can reduce adoption expenditures, manage risk more proactively, and induce wide participation in the digital economy (Nayan 2025). Synchronisation of technology adoption with industrial policy is vital for achieving global competitiveness and, even more significantly, for ensuring the long-term sustainability and development of the South African AMI (Anzolin 2024).

2.9 Gaps in the literature

Regarding the innovation impact of 4IR and 5IR technologies on the modernisation of the AMI, there are gaps in the research, particularly in developing nations like South Africa. AI, the Internet of Things, robots, additive manufacturing, and human-machine cooperation are examples of 4IR and 5IR technologies that have revolutionised the AMI and could have significant economic ramifications. There are substantial gaps in our understanding of the entire range of economic repercussions, despite increased scholarly attention. Three basic shortcomings in the current literature are addressed in this study; each is covered separately below.

2.9.1 Emerging economy emphasis

Current 4IR and 5IR technology research is largely grounded in advanced economies such as the European Union and the USA, with little attention to specific contextual issues in emerging economies such as infrastructure shortfalls, skills shortages, and dispersed policy regimes (Ayentimi 2020; Lambrechts, Sinha and Marwala 2020; Lee, Malerba and Primi 2020; Nyagadza *et al.* 2022; Tomás-Miquel, Maldonado-Gómez and Vicedo 2025). While the 4IR offers unprecedented opportunities for industrial upgrading and incorporation into global value chains, emerging economies are faced with shortfalls in digital infrastructure, access to frontier technologies, and the availability of workforce training, which may limit their full utilisation of these opportunities (Lee, Malerba and Primi 2020; Nyagadza *et al.* 2022). Policy incoherence and the absence of concerted approaches hinder technology adoption and dissemination in these environments (Ayentimi 2020; Vergara 2024). Scholars have called for anticipatory, context-sensitive policy interventions and investment in the development of skills to address these challenges (Tomás-Miquel, Maldonado-Gómez and Vicedo 2025; Vergara 2024). Furthermore, since the current evidence is mostly conceptual or based on secondary data, many studies have called for more empirical and longitudinal research with particular reference to the economic and social impacts of the 4IR and 5IR in emerging economies (Nyagadza *et al.* 2022; Tomás-Miquel, Maldonado-Gómez and Vicedo 2025). To guarantee that the advantages of digital transformation are inclusive and sensitive to the reality of emerging countries, it is imperative to address these flaws.

2.9.2 Sustainability metrics beyond circular economy rhetoric

While studies on circular economy and sustainability abound, there is a remarkable lack of quantitative studies exploring digital enablers, digital twins, and the impact of blockchain-based traceability on material use, energy intensity, and carbon emission reductions across an entire vehicle life cycle. A comprehensive review of international literature indicates that while digital twins have the potential to model life-cycle scenarios at a system level, they often fail to provide environmental performance insights after implementation within mass-production settings (Piromalis and Kantaros 2022). Although there has been research on sustainability in the South African context, this has largely concentrated on municipal landfill disposal of end-of-life products and evaluation of supply chain environmental performance without exploring appropriate 4IR data-driven optimisation strategies for disassembly and remanufacturing (Alexander 2021). In addition, existing studies have not measured returns on expanded digitalisation alongside power consumption requirements of data centres and cloud computing, leading to an extensive gap within life-cycle assessments related to net-zero production centres.

2.9.3 Comprehensive modernisation indicators

Research in 4IR and 5IR technologies is characteristically rather narrowly concerned with enhancing productivity, with substantial neglect of the broader economic impacts of these technologies, such as workforce upskilling, income growth, and catalysis of digital commerce (Gorski *et al.* 2022; Gorski *et al.* 2023; Li 2024). Research has shown that lifelong learning and the development of digital capabilities are crucial for both individual and organisational success in the emerging industrial era, and that reskilling and upskilling are urgently needed to equip people for quickly changing job requirements (Gorski *et al.* 2023; Katunga, Keating and Mange 2024; Rotatori, Lee and Sleeva 2020; Samuels and Pelser 2025). Nevertheless, little empirical study has been done on how these measures lead to real income advantages and better employment quality, particularly in developing countries (Katunga, Keating, and Mange 2024; Wong *et al.* 2020). Similarly, the significance of digitalisation in generating new digital commerce and entrepreneurial opportunities and how this could result in equitable economic expansion has not been adequately examined in the research now under publication (Gorski *et al.* 2022; Samuels and Pelser 2025). Furthermore, obstacles like a lack of comprehensive training frameworks, reluctance to change, and resource constraints make it difficult to realise the interconnected advantages of digitalisation, particularly in places like South Africa (Katunga, Keating and Mange 2024).

2.9.4 Small and medium-sized enterprises and Tier-N supplier-centric perspectives

The main international discourse relating to Industry 4.0 primarily involves OEMs. The specific set of challenges and limitations experienced by smaller manufacturers, particularly their limited financial resources, lack of experienced personnel, and relatively inferior technological infrastructure, is rarely discussed. A similar lacuna has been found in terms of the adoption of cost-effective, modular strategies for participating in the 4IR by Tier-2 and Tier-3 component manufacturers in South Africa (Alexander 2021; Serumaga-Zake and van der Poll 2021). Serumaga-Zake and van der Poll (2021) also highlight the lack of customised 4IR strategic roadmaps designed specifically for SMEs in developing nations. Without such customised roadmaps, smaller manufacturers could be at risk of being excluded from current value chains and thus not achieving the productivity and quality improvements available to larger OEMs. Furthermore, there is a scarcity of reliable information worldwide regarding the availability of shared service centres, alternative funding, and comprehensive technology roadmaps to assist SMEs in controlling the investment risks associated with implementing 4IR technologies.

2.9.5 Human-centric innovation and socio-technical integration

Industry 4.0's effects on the AMI have been thoroughly examined, but Industry 5.0, a more recent paradigm that emphasises employee well-being, collaborative intelligence, and synergistic human-machine interactions, has received relatively less attention in South Africa and around the world (Alexander 2021; Serumaga-Zake and van der Poll 2021). Research conducted in South Africa has mostly concentrated on 4IR-related technologies, like automation, artificial intelligence, and the Internet of Things, without taking into account the significant organisational shifts and socio-technical procedures required to support human-centric applications of these technologies (Alexander 2021). Similarly, there are yet few international studies that offer long-term empirical evidence on how the application of affective AI and collaborative robots affects worker satisfaction, skill development routes, and job design in the AMI (Serumaga-Zake and van der Poll 2021). There are significant information gaps regarding efficient workforce upskilling techniques, change management models, and ergonomics in human-robot collaboration due to the dearth of mixed-method case studies examining Industry 5.0 pilot programs, particularly in emerging economies.

2.9.6 Methodological and geographic biases

Bibliometric analyses show a strong methodological bias towards systematic reviews and bibliometric studies; however, empirical, contextual studies of socio-organisational processes relevant to the transitions involved in the 4IR are relatively rare. Research methods such as action research, ethnography, and longitudinal field experiments are less frequently employed (Alexander 2021; Fernandez de Arroyabe, Watson and Angelopoulou 2023). Also largely underrepresented in global academia are studies of large emerging market areas, including Africa, Southeast Asia, and Latin America, mainly owing to an over-reliance on contributions from China, Europe, and North America. This geographical bias limits understanding of the impact of local labour law trends, institutional development, and issues in the energy sector on AMI modernisation paths globally.

While global interest in 4IR and 5IR technologies is growing, studies that are particularly focused on the South African AMI are rare, despite its predominance in national industrialisation and productive output (Serumaga-Zake and van der Poll 2021; Sutherland 2020). The AMI is a major contributor to South Africa's GDP, employment, and foreign exchange earnings, but its digital transformation path has not been extensively studied (Anzolin 2024; Avenyo, Bell and Nyamwena 2024). Recent studies on the exposure of South Africa's AMI to 4IR technologies have often been limited to initial explorations into the prospects versus the limitations of these technologies. A study conducted by Lorenz and Kraemer-Mbula (2021) which investigated the adoption of 4IR-related technologies, including the IoT, intelligent sensors, and 3D printing, by the AMI and mining machinery vendors in South Africa found that adoption was confined to a few market leaders, with SMEs falling behind due to infrastructural and skills limitations.

A study conducted by Alexander (2021) highlighted a bias in the diffusion of 4IR technologies among firms in the automotive and mining machinery manufacturing industries; the study found that while firms were adopting 4IR technologies, this innovation was fragmented and not integrated with policy frameworks or sectoral digital plans. Such gaps can be filled by focusing on areas such as connectivity, workforce-related issues, and access to finance, which are critical for the effective integration of 4IR and 5IR technologies. The South African AMI faces additional challenges with integrating new technologies due to structural issues such as supply chain disintegration, globalisation, and unclear policies (Nurhayanti *et al.* 2025). This scenario calls for specific studies that not only capture technology adoption but also assess the resultant economic implications for productivity, income generation, and digital trade.

This study addresses these gaps by employing a quantitative approach to examine the innovation impact of 4IR and 5IR technologies on the modernisation of the South African AMI, focusing on measurable modernisation outcomes such as increased productivity, organisational support for upskilling, workforce income growth, and digital commerce promotion. The study contributes empirical evidence to a field that has been largely dominated by conceptual and qualitative analyses. It also offers insights into how technology adoption can be strategically aligned with national development goals and industrial policy.

2.10 Chapter summary

This chapter has reviewed the relevant literature to provide a broad understanding of the innovation impact of 4IR and 5IR technology adoption on the modernisation of the AMI. It began with a brief overview of the five industrial revolutions, followed by the findings and discussion of the bibliometric analysis. Factors influencing 4IR and 5IR technology adoption, factors influencing innovation in the AMI, outcomes of modernisation in the AMI, and challenges facing innovation and modernisation in the South African AMI were then discussed. Finally, the chapter examined gaps in the literature.

The next chapter provides a concise examination of the theories underpinning this study's examination of the innovation impact of the adoption of 4IR and 5IR technologies on the modernisation of the AMI.

CHAPTER THREE

THEORETICAL FOUNDATION

3.1 Introduction

Innovation in the AMI is increasingly driven by the adoption of advanced technologies associated with the 4IR and 5IR. As discussed in Chapter Two, key factors influencing innovation include the cost of technology adoption, the availability of skilled labour, and infrastructure and technology support. Modernisation refers to the transformation of manufacturing processes and workforce capabilities to meet contemporary demands. In the AMI, modernisation is reflected through increased productivity, workforce upskilling, income growth, and e-commerce promotion. The 4IR and 5IR represent transformative periods in technological advancement characterised by the integration of CPS, AI, and human-centric innovation. In the AMI, these revolutions are reshaping production paradigms, organisational structures, and strategic capabilities.

The previous chapter provided an overview of the existing body of knowledge. To provide a comprehensive foundation for understanding the innovation impact of adopting recent industrial revolution technologies on the modernisation of the AMI, this chapter synthesises the following key theoretical frameworks: the TOE framework, the DoI theory, the RBV, the HCT, the socio-technical systems (STS) theory, the dynamic capabilities theory (DCT), and the digital transformation theory (DTT). Each of these theoretical frameworks is discussed in detail below.

3.2 Technology-organisation-environment framework

The TOE conceptual framework, which was developed in 1990 by Louis G. Tornatzky and Mitchell Fleischer, is used to understand the determinants of adoption of technological innovation in an organisation. The model assumes that adoption is contingent on three interlinked contexts: technological, organisational, and environmental (Jensen 2021); it provides a comprehensive lens for understanding the dynamics between these contexts. The TOE framework posits that innovation adoption is determined by technological readiness (including cost and infrastructure), organisational capabilities (such as skilled labour), and external environmental pressures. In the AMI, the high costs of adopting automation, robotics, and AI can hinder innovation unless offset by supportive infrastructure and skilled human capital.

3.2.1 Technological context

The technological context refers to the external and internal technologies to which an organisation has ready access. It includes the capabilities of existing technologies, the technology infrastructure, and the perceived value of adopting new technologies. Factors such as technology readiness and ICT consultation service quality influence how easily and efficiently an organisation can adopt new technologies (Dlamini and Gratsa 2022; Melo, Luft and Rocha 2021).

3.2.2 Organisational context

The organisational context refers to the character and assets of the organisation itself. This includes the size of the organisation, its culture, and the quality of its management team. Senior management commitment and an effective ICT management team are crucial factors in the success of technology integration projects (Li, D. *et al.* 2025; Melo, Luft and Rocha 2021; Pradifera *et al.* 2022). Organisational readiness to implement new technology is also likely to influence the overall decision-making process regarding adoption (Dlamini and Gratsa 2022).

3.2.3 Environmental context

The environmental context refers to external factors that have the potential to influence the ability of the organisation to adopt new technologies. These factors include competitive pressure, the socio-cultural environment, government incentives, and the support of trading partners and suppliers (Melo, Luft and Rocha 2021). Organisations must consider such external factors when making technology adoption decisions since these factors have the potential to introduce either challenges or opportunities in the technology adoption process (Li, D. *et al.* 2025).

The TOE model has been applied extensively to examine technology adoption in various industries, showing its flexibility and usefulness in understanding technology adoption dynamics in organisational settings (Malik *et al.* 2021).

3.3 Diffusion of innovation theory

The DoI theory, which supplements the TOE framework, describes how innovations proliferate both inside and outside organisations (Rogers 2003). Adoption rates of innovations greatly depend on factors such as compatibility, complexity, and relative advantage. For example, inadequately trained personnel and poor infrastructure can hinder large-scale adoption of EV technology due to its cost and complexity.

Everett M. Rogers was central to crafting the concept of DoI, which is a key paradigm for explaining how new ideas and technologies spread within and between social systems. According to Rogers (2003: 5), diffusion is “the process by which an innovation is communicated over time through certain channels among the members of a social system”. This theoretical model is of particular value in environments shaped by 4IR- and 5IR-related technologies, which are known to instigate far-reaching changes and uncertainty within social and organisational settings.

The DoI theory asserts that five inherent characteristics of innovations significantly impact their adoption: relative advantage, compatibility, complexity, trialability, and observability. These characteristics are closely related to the five phases of the innovation-decision process model: knowledge, persuasion, decision, implementation, and confirmation (Chauhan, Gupta and Goyal 2022; Raman *et al.* 2024). In addition, mass communication and interaction channels are crucial in reducing the uncertainty associated with an innovation.

The DoI theory is useful for understanding the adoption of 4IR and 5IR technologies such as AI, the IoT, robotics, and human-centred innovations in various sectors. In addition, it highlights the role of organisational structures, innovation champions, and opinion leaders in facilitating or hindering the adoption process. The DoI theory, which originated in a rural context, has been described as having limited applicability to advanced, highly integrated technologies and has been criticised for its failure to account for the social construction of technology, network economies, and institutional governance; researchers have proposed more advanced models that integrate these aspects (Alka'awneh, Abdul-Halim and Saad 2025; Bhattacharyya and Shah 2021). García-Avilés (2020) extends the DoI model to include media organisations, putting greater emphasis on digital convergence and the interactivity of complementary audiences that drive the DoI. Since the 5IR emphasises sustainable and human-centred innovation, it is only fitting that the DoI theory be redeveloped to include elements of post-adoption dynamics, inter-organisational diffusion, and group adoption behaviours. The complexity, interactivity, and regulatory environments of contemporary technological ecosystems necessitate the use of integrative models.

3.4 Resource-based view

The RBV is a well-known theoretical model that explains how an organisation leverages its internal resources to gain and maintain a competitively favourable position. This model, which proposes that leveraging unique internal resources is an important source of innovation (Barney 1991), emerged as an extension of studies led by Wernerfelt in 1984 asserting that the performance of firms, which are heterogeneous due to their unique mixture of resources, is determined by how their resources are distributed and utilised. When utilised efficiently, advanced technologies and an experienced workforce provide strategic competitive advantages.

The RBV, which asserts that a sustainable competitive advantage can be achieved through resource accumulation and the strategic leveraging of distinctive assets, represents a major theoretical development within strategic management. To provide competitive advantage, resources must possess the attributes of being valuable, rare, inimitable, and non-substitutable: valuable resources enable organisations to exploit opportunities or manage threats; rare resources are those not held by competing firms; inimitable resources are difficult to replicate due to factors such as causal ambiguity, social complexity, or distinctive history; non-substitutable resources cannot be substituted for by alternatives (Barney 1991). The accumulation of resources that possess these attributes helps organisations to develop lasting strategic advantages. These long-lasting competitive advantages are built on Ricardian rents that emanate from resource market imperfections (Sun, Chen and Mei 2024).

The RBV is particularly relevant in the context of the 4IR and 5IR. Emerging technologies such as the IoT, robotics, AI, and human-centric technologies are responsive and adaptive to changing demands in the marketplace (Zheng and Yuan 2025). The RBV suggests that, while ownership of resources is important, their functionality is more important; in the context of the 4IR and 5IR, the ability to integrate and recontextualise complementary or co-specialised resources for new applications is crucial in developing new competencies (Zheng and Yuan 2025). In addition, it is important to consider the dynamic nature of resources and their life cycle, which is influenced by fluctuations in the environment, scientific breakthroughs, and strategic moves made by competitors (Amariles and Baquero 2023; Li, D. *et al.* 2025).

The RBV considers managerial skills to be a critical internal resource. Managers are seen as enactors who recognise possibilities, reorganise resources, and modify their strategies in response to both internal capabilities and external challenges (Do *et al.* 2021). This viewpoint is consistent with the dynamic character of the 4IR and 5IR, in which modernisation requires strategic innovation and agility.

Despite its conceptual strength, the RBV has been criticised for several methodological issues. One such issue is a tendency towards tautological reasoning since the RBV defines resources as valuable in relation to their performance outcomes (D'Oria *et al.* 2021). In addition, the RBV struggles to quantify intangible assets, such as organisational routines, culture, and expertise, that are essential to innovation. Furthermore, empirical testing is complicated by the diverse resource configurations and strategic situations of different firms. While the RBV's perspective is firm-centric, the broader perspective of the innovation systems theory highlights the importance of systemic and institutional support, such as government grants and cooperation with industry, in fostering an environment that aids in building up innovation ecosystems within industries such as the AMI.

Nevertheless, the RBV is an important paradigm for studying how the AMI can exploit industrial technologies emanating from the 4IR and 5IR to revitalise their process operations, reinforce their competitive advantages, and achieve sustainable long-term growth. With its emphasis on strategic resource administration, as well as its recognition of the importance of manager flexibility and resource building, the RBV forms an important foundation for the conceptual framework underpinning this study. In addition, it provides a robust perspective for studying how companies develop and adapt their strategies when confronted with novel technologies in the current 4IR and 5IR environment.

3.5 Human capital theory

The HCT explains the relationship between education, training, and economic outcomes (Becker 1962). Workforce upskilling due to the adoption of 4IR and 5IR technologies, such as AI-driven diagnostics and smart manufacturing, enhances productivity and leads to higher income levels (Hwang and Kim 2021). This is particularly relevant in the transitioning of traditional roles to technology-enabled roles in the AMI. The HCT, which is based on Becker’s (1962) concept of human capital, posits that human capital, which is defined as knowledge, skills, health, and other inputs invested to raise productivity, is the source of economic growth and development. Just as companies invest in physical assets, individuals also invest in training and education to enhance productivity and income; this investment is measured in the form of increased income (Becker 1962). The HCT was further developed by Schultz (1964), who emphasised that investment in humans is the greatest source of economic growth and that education is the greatest investment in human capital. The theory has since been extensively studied and tested empirically by several experts.

3.5.1 The individual as capital

Human capital is the collective value of the abilities, knowledge, and skills that contribute to the economic productivity and value of an individual in the labour market (Shiksha 2025). Such capital includes formal education as well as experiential learning obtained through work experience, occupational mobility, and employer-funded courses (Jibir, Abdu and Buba 2022). Human capital impacts an individual's employability, wages, and contribution to economic growth (Wirajing, Nchofoung and Etape 2023).

3.5.2 Importance of education

Education is the foundation of human capital formation. It prepares human beings to engage in society and in the workforce, enhancing their employability as well as their health (Wirajing, Nchofoung and Etape 2023). Educational expenditure at the primary, secondary, and tertiary levels has been linked to scientific, technological, and innovation developments that boost national and international economic competitiveness (Shiksha 2025). In addition, as former United Nations Secretary-General Kofi Annan has noted, education has an even greater significance as a fundamental tool for building peace and social solidarity (Shiksha 2025).

3.5.3 Learning organisations and mobility

Organisations with an HCT-aligned strategy value continuous learning and staff improvement. More than 80% of occupational mobility is due to a change of employer and, since losing staff is undesirable, organisations must create well-defined opportunities for advancement as well as in-house training programmes for skills development (Robinson and Pope 2023). Providing such opportunities increases staff commitment as well as addressing labour market unpredictability.

3.5.4 Evaluating potential

Many leading firms have shifted their recruitment strategies to prioritise potential and transferable skills over work experience (Bestová and Krestová 2024; Khandelwal and Chairman 2019). Such strategies involve designing customised tests to establish the required capabilities that would be critical for the performance of specific roles (Karam *et al.* 2020). They also enable a transparent approach to career development in which existing staff can be assessed in terms of their growth potential rather than in terms of their current roles (Khandelwal and Chairman 2019; Tsani *et al.* 2023).

3.5.5 Task-specific human capital

Task-specific human capital, as theorised by economists Michael Waldman and Robert Gibbons, emphasises the development of skills to perform particular tasks in the labour market (Walter and Lee 2022). This theory posits that the value of skills obtained in a particular occupation can be realised in a variety of contexts, emphasising flexibility as well as the transferability of skills in optimising human capital (Holland 2019). This perspective is beneficial for both employees and organisations because it provides a framework for career planning and assists organisations to optimise their capabilities (Holland 2019; Walter and Lee 2022).

3.6 Socio-technical systems theory

Emery and Trist's (1960) STS theory suggests that there is a need for a synergistic relationship between advanced technological systems and human factors. To achieve efficiency in modernisation processes, it is imperative for advanced systems to be operated by highly skilled workers (Sony and Naik 2020). For instance, the effectiveness of a smart factory system depends not only on appropriate technology but also on skilled workers who can understand and interpret the data (Jerman, Bach and Aleksić 2020). The STS theory is a broad approach that outlines the dynamics between social and technological elements in the design and implementation of systems. Developed at the Tavistock Institute, this approach emerged from the idea that successful systems need to take into consideration the interactions between people, processes, and technology to improve technical performance and meet the needs of users (Sony and Naik 2020).

The STS theory is particularly relevant in the context of the 4IR and 5IR, where rapid technological advancements need to be incorporated into intricate organisational and social contexts. The theory supports systems that adjust to changing social settings and human requirements rather than requiring people to adjust to inflexible technological frameworks (Münch *et al.* 2022). Important tenets of the STS theory include human-centred design, which prioritises trust, usability, and user satisfaction; adaptability, which ensures resilience and relevance in changing environments; and participatory design, which actively involves stakeholders at all levels in system design (Böhme and Graf-Pfohl 2025; Herrmann 2024). While conceptually sound, traditional STS approaches such as ETHICS and QuickETHICS have practical limitations due to the challenges of managing large datasets, their incompatibility with fast-paced and costly development cycles, and the difficulty of converting abstract socio-technical ideas into workable system designs (Baxter and Sommerville 2011). These difficulties are especially noticeable in industries undergoing rapid digital transition during the 4IR and 5IR, such as the AMI. Ngowi and Mvungi (2018) offer a workable framework that integrates the STS theory with modern engineering techniques to overcome these drawbacks. This framework incorporates soft systems methodology for stakeholder involvement and contextual inquiry, object-oriented analysis and design for modular and scalable system modelling, and agile development for iterative, user-driven design.

By bridging the gap between theory and practice, this integrated approach improves the applicability of the STS theory in intricate, technologically demanding situations, enabling businesses to create systems that are not only technologically advanced and innovative but also ethically and socially responsible. In the context of the 4IR and 5IR, which emphasise ethical AI and human-machine collaboration, the STS theory, particularly in its updated form, provides important insights into how innovation can be used to promote both operational excellence and human well-being.

3.7 Dynamic capabilities theory

Teece, Pisano and Shuen's (1997) DCT posits that organisations must continuously integrate, reorganise, and reorient their resources to sustain their competitiveness. In the AMI, modernisation focuses on improving the ability to satisfy consumer needs, achieve environmental sustainability, and counteract digital disruption. The DCT originated in response to the RBV's failure to explain how companies prosper in environments that are changing rapidly. While the RBV focuses on possession of valuable, rare, inimitable, and non-substitutable resources, the DCT centres on those abilities that help organisations reconfigure, integrate, and upgrade their resource bases to achieve sustainable competitiveness (Teece, Pisano and Shuen 1997).

In the context of the 4IR and 5IR, the DCT provides an important lens through which to analyse how organisations transform and reconfigure in response to changes in technology. Current economic debates drawing on this theoretical framework are divided into two major schools of thought. Teece, Pisano and Shuen (1997) describe dynamic capability as an organisation's expertise in reconfiguring internal and external resources within changing environments, thus enhancing strategic renewal and adaptability. In contrast, Eisenhardt and Martin (2000) frame dynamic capabilities as distinctive organisational and strategic routines that help companies exploit novel configurations of resources in changing market environments. This differentiation highlights the fluidity of the conceptualisation of dynamic capabilities, as Bleady, Ali and Ibrahim (2018) note in their systematic assessment of 53 empirical studies; of these studies, 41.5% endorsed Teece's description, 20.75% agreed with the interpretation of Eisenhardt and Martin, and the remainder used composite or customised definitions.

Despite a lack of consensus on a universal definition of the DCT, it is operationalised by three fundamental dimensions: sensing, which refers to the activity of perceiving threats and opportunities in the external environment; seizing, which refers to mobilising resources to exploit value; and transforming, which refers to the rearrangement of organisational configurations and assets to stay relevant (Teece 2007). These dimensions are particularly significant in the AMI, in which innovations related to the 4IR and 5IR, such as AI, the IoT, robotics, and human-centric innovations, necessitate continuous and increasingly frequent transformations and adaptability on the part of firms (Ghosh *et al.* 2021). In this scenario, the DCT enables assessment of how organisations react to disruptive technologies and their ability to stay adaptive and competitive in changing market landscapes (Al-Khatib *et al.* 2023).

The DCT is a crucial part of the theoretical framework underpinning this study because it promotes a comprehensive view of modernisation in 4IR and 5IR contexts by highlighting adaptation, learning, and renewal. The study uses the DCT as a guide to analyse the strategic agility and innovation potential of automotive firms experiencing digital transformation. By emphasising both the possession of important resources and the methods by which they are dynamically handled, the study integrates the RBV with the DCT.

3.8 Digital transformation theory

The DTT is a conceptual framework that provides a strong foundation for understanding how digital technologies restructure organisational forms, strategic approaches, and value-creating processes. This framework involves a deliberate and comprehensive rethinking and restructuring of organisational practices and stakeholder interactions, reaching far beyond digitisation and digitalisation. Vial (2019) describes digital transformation as an intricate phenomenon that integrates computing, communications, connectivity, and information technologies to achieve deep changes in organisations; it is therefore a central component of modern strategic management. Key characteristics of digital transformation include strategic change, technology integration, business model innovation, and organisational development (Bechchar, Soulhi and Akourri 2025; Llopis-Albert, Rubio and Valero 2021; Proff, Proff and Sommer 2021).

Digital transformation impacts every phase of the strategic management process, from the analysis of internal and external environments to strategy development, execution, assessment, and refinement (Warner and Wäger 2019). This ongoing and flexible cycle enables businesses to adjust their strategy orientation in response to competition pressures and technological advancements (Gouveia *et al.* 2024). In addition to enriching internal processes, digital transformation extends its influence to the broader societal, political, and economic contexts.

In the context of the AMI, the transformative effects of the 4IR and 5IR are redefining conventional business models. In line with an overall shift towards digitalisation, the AMI is increasingly using digital channels to deliver personalised service, real-time information, and experiential experiences to vehicle buyers (Bechchar, Soulhi and Akourri 2025). Digital transformation enables contemporary restructuring of AMI sales and service paradigms through digital car showrooms, online configuration, and digital stores.

The DTT is crucial for analysing how organisations change as a result of automation, intelligent systems, and human-machine cooperation in the context of the 4IR and 5IR (Noble *et al.* 2022). By highlighting the revolutionary potential of digital technologies and their role in promoting strategic agility, innovation, and modernisation throughout the AMI, the DTT enhances other theoretical perspectives in this study.

3.9 Theoretical integration and relevance to the study

The theoretical perspectives outlined in this chapter provide a strong foundation for studying the effects of 4IR and 5IR technology on modernisation and innovation in the AMI. These theoretical lenses offer different approaches to studying the complexities surrounding technological changes. The RBV provides a strategic lens to examine how organisations effectively utilise their internal resources, while the DCT offers insight into how organisations respond to changing circumstances in order to maintain their competitiveness (Barney 1991; Teece, Pisano and Shuen 1997). These theoretical frameworks highlight the fundamental role of managerial flexibility and resource reconfiguration in dealing with the disruptive nature of 4IR and 5IR technologies, such as robotics, AI, and the IoT.

The STS theory proposes a design approach that emphasises human interaction and inclusivity, thus addressing the key challenge of optimising both human and technological elements (Ngowi and Mvungi 2018). In line with the tenets of 5IR philosophy, this viewpoint highlights the need to utilise technologies in an equitable, just, and sustainable way. The DTT further develops this idea by showing how technology adoption can revitalise organisational forms, value-creating processes, and business models (Rêgo *et al.* 2022; Vial 2019). The DTT is particularly applicable in the AMI, where operational environments are being restructured with revolutionary technologies such as digital twins, IoT-powered smart manufacturing, and virtual showrooms.

The TOE framework provides a structured approach for studying the internal and external enablers and inhibitors of technology adoption. This framework places 4IR and 5IR innovations within the broader context of organisational preparation, information technology infrastructure, and external environmental influences (Tornatzky and Fleischer 1990). This contextual approach is reinforced by the HCT, which highlights the need for workforce skills to catalyse productive change. Investment in education, training, and digital literacy is vital in sustaining modernisation, as the implementation of 4IR and 5IR technologies requires new and different skill sets (Becker 1962).

The blending of these theoretical frameworks provides an integrated and multidivergent paradigm of innovation adoption, which forms the basis of this study. This paradigm enables analysis of transformation in the AMI through deliberate resource allocation, responses to state-of-the-art technologies, socio-technical system arrangements, and human resource development. In addition, it ensures that the study investigates complexities that arise from the adoption of 4IR and 5IR technologies and their impact on the strategies, operations, and human resources of organisations.

The theoretical frameworks underpinning this study operate at different analytical levels, giving rise to important tensions that shape the conceptual model. The RBV adopts a firm-centric perspective focused on internal capabilities, such as investment capacity, managerial competence, and workforce skills, while the TOE framework emphasises ecosystem-level determinants, including technological readiness, infrastructure support, and external pressures. HCT further contributes a people-centred lens by highlighting workforce competencies and upskilling as prerequisites for effective technology absorption. These perspectives are synthesised and extended through the Support-Driven Capabilities and Innovation Theory (SCIT), developed in this study, which integrates internal capabilities, workforce development, and technological support structures into a unified pathway for modernisation. TOE informs the study's adoption drivers (costs, labour availability, infrastructure), RBV informs the capability-based mediators (investment, education, management), HCT informs hypotheses related to upskilling and workforce income, and SCIT provides the overarching logic that links support, capabilities, and modernisation outcomes. This integration provides the theoretical foundation from which the hypotheses were derived and clarifies the reasoning behind both the direct and mediated relationships tested in the study.

3.10 Chapter summary

This chapter has discussed the theories underpinning this study's examination of the innovation impact of the adoption of 4IR and 5IR technologies on the modernisation of the AMI. The following theories were examined: the TOE framework, the DoI theory, the RBV, the HCT, the STS theory, the DCT, and the DTT. Thereafter, the chapter discussed the integration of these theories and their relevance to the study.

The following chapter outlines the methodology of the study.

CHAPTER FOUR

RESEARCH METHODOLOGY

4.1 Introduction

The theories underpinning this study's examination of the innovation impact of the adoption of 4IR and 5IR technologies on the modernisation of the AMI were outlined in Chapter Three. The current chapter outlines the methodologies employed in this study. Firstly, the chapter explains the philosophical framework that underlies the study, followed by a discussion of the research design and approach. Thereafter, the conceptual model and hypotheses are discussed, as well as the target population and sampling procedures employed. The tools and procedures utilised for data collection are elucidated, as well as the procedures used to ensure validity and reliability. The chapter then examines the mitigation of bias and the study's ethical considerations, followed by a discussion of the data analysis techniques used in the study. The chapter concludes with a summary.

4.2 Philosophical paradigm underpinning the study

A paradigm refers to the fundamental belief system or worldview that guides the researcher in various aspects, including methodology and ontological and epistemological principles (Park, Konge and Artino Jr 2020). While there is some debate about the number of major philosophical paradigms, Alharahsheh and Pius (2020) argue that two contrasting constellations of beliefs exist regarding the generation of valid and applicable knowledge: positivism and constructivism (or the interpretive paradigm). Kankam (2019) asserts that the paradigms of positivism and interpretivism serve as comprehensive frameworks for conducting research. These two general paradigms are discussed in turn below.

4.2.1 Positivist paradigm

The positivist paradigm, which is frequently associated with quantitative research, is a research strategy that concentrates on empirical reality and objective truth (Karupiah 2022). It is founded on the assumptions that reality can be seen and measured and that personal prejudices should not influence scientific investigation (Park, Konge and Artino Jr 2020). This paradigm has been applied extensively to determine cause-and-effect relationships and to test predetermined hypotheses in numerous disciplines, including the social sciences, accounting, and education.

The foundation of positivism is realism, which is premised on the idea that reality is independent and objective. Dualist and objectivist epistemology assumes that knowledge is value-free and objective and that the researcher and the study material are distinct (Karupiah 2022).

4.2.2 Constructivist (interpretive) paradigm

The constructivist paradigm provides a scaffold that emphasises the dynamic role of individuals in building knowledge through their interactions and experiences with the world (Park 2023). This paradigm is utilised in a variety of fields, including psychology, education, and international relations, where it confronts customary objectivist approaches by placing its focus on subjective understanding and social interactions (Kumatongo and Muzata 2021). Constructivism suggests that comprehension is not submissively received but dynamically built by the learner in a lively and context-dependent process.

This study adopts the positivist research paradigm. Adherents of this paradigm hold the belief that accurate knowledge can be obtained through observation and experimentation. Consequently, positivists typically employ the scientific method as a means of generating knowledge (Park, Konge and Artino Jr 2020).

4.3 Research design and strategy

A research design refers to a comprehensive plan or blueprint outlining the execution of a research study, encompassing the operationalisation of variables to enable measurement, the selection of a sample of interest, the collection of data to serve as the foundation for hypothesis testing, and the analysis of results (Bougie and Sekaran 2019). Various designs exist, including causal research, explanatory research, experimental research (such as field experiment, controlled experiment, and quasi-experiment), descriptive research (such as case study, naturalistic observation, and survey), and correlational research designs (such as case-control study and observational study) (Hair Jr, Page and Brunsveld 2019).

This study employs a correlational research design with a cross-sectional time dimension. Correlational research design uses a quantitative research approach to examine the relationship between variables without manipulation. Its purpose is to provide answers to questions regarding the interrelatedness of variables (Miksza *et al.* 2023). This particular form of design is frequently utilised in correlational research where the major purpose is to identify conditions or associations already present (Istiara, Hastomo and Indriyanta 2023). Correlational data are generally obtained by employing methods such as surveys and observation. Surveys are effective in gathering data on individuals' experiences, beliefs, and attitudes (Istiara, Hastomo and Indriyanta 2023). Observational methods can involve video recording or experience sampling, during which participants report what they are experiencing at the time (Ogomegbunam 2023). Correlational research offers rich data on both the direction and strength of relationships between variables, although causality cannot be established.

4.4 Research approach

Research approaches, which occupy a position that is one level lower than research paradigms within the research process, tend to align themselves with a specific paradigm (Dubey and Kothari 2022). In order to address the hypotheses of the study, a quantitative research approach was adopted. Quantitative research serves as a means to examine objective theories by exploring the relationships among variables (Mohajan 2020). These variables can subsequently be measured, typically using instruments, so that numerical data can be analysed through the application of statistical procedures (Washington *et al.* 2020). The final report, once transcribed, adheres to a structured format that comprises an introduction, a literature review, a theoretical framework, a methodology, findings, and arguments.

Quantitative research is characterised by deductive methodologies within the research paradigm, designed to validate, invalidate, or substantiate pre-existing theoretical frameworks. This category of research necessitates the quantification of variables and the examination of inter-variable relationships, with the objective of unveiling patterns, correlations, or causal associations (Leavy 2022).

A deductive methodology was adopted for this study. Deductive methodologies employ empirical observation and analysis to test established theories or hypotheses. In this study, hypotheses regarding the interlinkages between 4IR and 5IR technology adoption and its economic implications were developed based on a review of the literature. Data collected by means of a survey were then used to test these hypotheses. This methodology was considered suitable for this study as it enabled systematic verification of theoretical hypotheses and added to the current knowledge base of 4IR and 5IR technologies.

4.5 Conceptual model and hypothesis development

The study proposes the conceptual model shown in Figure 4.1 below. The model is grounded in the theoretical frameworks outlined in Chapter Three, namely, the TOE framework, the DoI theory, the RBV, the HCT, the STS theory, the DCT, and the DTT.

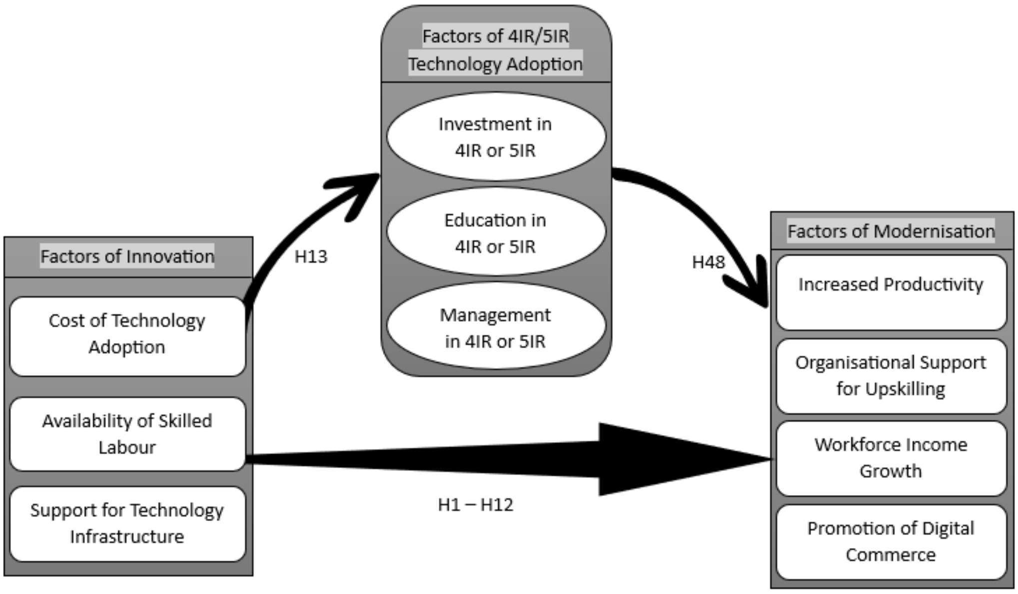

Figure 4.1: Conceptual model

As shown in the conceptual model above, the hypotheses are categorised in terms of direct and mediated relationships. The hypotheses are set out below.

4.5.1 Direct relationships

H1 to H12 are direct relationships which have been tested in the literature in multiple fields by various authors over the years.

H1: There is a relationship between the cost of technology adoption and increased productivity (Timilsina and Malla 2023; Wei and Lu 2024).

H2: There is a relationship between the cost of technology adoption and organisational support for upskilling (Fiorello *et al.* 2022; Omar and Weilbach 2025).

H3: There is a relationship between the cost of technology adoption and workforce income growth (Kumar *et al.* 2023; Zhau and Li 2024).

H4: There is a relationship between the cost of technology adoption and the promotion of digital commerce (Costantino and Pietroforte 2006; Knezevic, Skrobot and Pavic 2021).

H5: There is a relationship between the availability of skilled labour and increased productivity (Benito and Young 2025; Karimi, Taylor and Goodrum 2017).

H6: There is a relationship between the availability of skilled labour and organisational support for upskilling (Czako and Murauskaite-Bull 2021; Jamal, El Nemar and Sakka 2025).

H7: There is a relationship between the availability of skilled labour and workforce income growth (Kahne and Mabel 2010; Nagurney 2022).

H8: There is a relationship between the availability of skilled labour and the promotion of digital commerce (Abueva 2013; Cheng and Liu 2024).

H9: There is a relationship between support for technology infrastructure and increased productivity (Aleca and Mihai 2025; Li, Li and Ren 2023).

H10: There is a relationship between support for technology infrastructure and organisational support for upskilling (Pedota, Grilli and Piscitello 2023; Wahab, Rajendran and Yeap 2021).

H11: There is a relationship between support for technology infrastructure and workforce income growth (Feng, Dai and Zhang 2025; Shen, Chen and Ruan 2025).

H12: There is a relationship between support for technology infrastructure and the promotion of digital commerce (Damayanti *et al.* 2024; Shou, Jia and Yu 2024).

4.5.2 Novel mediation relationships

H13 to H48 are novel mediation relationships.

H13: There is a relationship between the cost of technology adoption and investment in 4IR and 5IR technologies that leads to increased productivity.

H14: There is a relationship between the cost of technology adoption and investment in 4IR and 5IR technologies that induces organisational support for upskilling.

H15: There is a relationship between the cost of technology adoption and investment in 4IR and 5IR technologies that leads to workforce income growth.

H16: There is a relationship between the cost of technology adoption and investment in 4IR and 5IR technologies that promotes digital commerce.

H17: There is a relationship between the cost of technology adoption and education in 4IR and 5IR technologies that leads to increased productivity.

H18: There is a relationship between the cost of technology adoption and education in 4IR and 5IR technologies that induces organisational support for upskilling.

H19: There is a relationship between the cost of technology adoption and education in 4IR and 5IR technologies that leads to workforce income growth.

H20: There is a relationship between the cost of technology adoption and education in 4IR and 5IR technologies that promotes digital commerce.

H21: There is a relationship between the cost of technology adoption and management of 4IR and 5IR technologies that leads to increased productivity.

H22: There is a relationship between the cost of technology adoption and management of 4IR and 5IR technologies that induces organisational support for upskilling.

H23: There is a relationship between the cost of technology adoption and management of 4IR and 5IR technologies that leads to workforce income growth.

H24: There is a relationship between the cost of technology adoption and management of 4IR and 5IR technologies that promotes digital commerce.

H25: There is a relationship between the availability of skilled labour and investment in 4IR and 5IR technologies that leads to increased productivity.

H26: There is a relationship between the availability of skilled labour and investment in 4IR and 5IR technologies that induces organisational support for upskilling.

H27: There is a relationship between the availability of skilled labour and investment in 4IR and 5IR technologies that leads to workforce income growth.

H28: There is a relationship between the availability of skilled labour and investment in 4IR and 5IR technologies that promotes digital commerce.

H29: There is a relationship between the availability of skilled labour and education in 4IR and 5IR technologies that leads to increased productivity.

H30: There is a relationship between the availability of skilled labour and education in 4IR and 5IR technologies that induces organisational support for upskilling.

H31: There is a relationship between the availability of skilled labour and education in 4IR and 5IR technologies that leads to workforce income growth.

H32: There is a relationship between the availability of skilled labour and education in 4IR and 5IR technologies that promotes digital commerce.

H33: There is a relationship between the availability of skilled labour and management of 4IR and 5IR technologies that leads to increased production.

H34: There is a relationship between the availability of skilled labour and management of 4IR and 5IR technologies that induces organisational support for upskilling.

H35: There is a relationship between the availability of skilled labour and management of 4IR and 5IR technologies that leads to workforce income growth.

H36: There is a relationship between the availability of skilled labour and management of 4IR and 5IR technologies that promotes digital commerce.

H37: There is a relationship between the support for technology infrastructure and investment in 4IR and 5IR technologies that leads to increased productivity.

H38: There is a relationship between support for technology infrastructure and investment in 4IR and 5IR technologies that induces organisational support for upskilling.

H39: There is a relationship between support for technology infrastructure and investment in 4IR and 5IR technologies that leads to workforce income growth.

H40: There is a relationship between support for technology infrastructure and investment in 4IR and 5IR technologies that promotes digital commerce.

H41: There is a relationship between the support for technology infrastructure and education in 4IR and 5IR technologies that leads to increased productivity.

H42: There is a relationship between the support for technology infrastructure and education in 4IR and 5IR technologies that induces organisational support for upskilling.

H43: There is a relationship between the support for technology infrastructure and education in 4IR and 5IR technologies that leads to workforce income growth.

H44: There is a relationship between the support for technology infrastructure and education in 4IR and 5IR technologies that promotes digital commerce.

H45: There is a relationship between support for technology infrastructure and management of 4IR and 5IR technologies that leads to increased productivity.

H46: There is a relationship between support for technology infrastructure and management of 4IR and 5IR technologies that induces organisational support for upskilling.

H47: There is a relationship between support for technology infrastructure and management of 4IR and 5IR technologies that leads to workforce income growth.

H48: There is a relationship between support for technology infrastructure and management of 4IR and 5IR technologies that promotes digital commerce.

SEM, a technique which allows several interactions of latent elements to be explored simultaneously, is employed in the testing of the hypotheses of the study. SEM is particularly appropriate due to the complexity of the theoretical model and the necessity for the testing of direct and indirect effects on organisational, technological, and human constituents.

4.6 Target population

Determining the scope and aim of the project is largely dependent on the target population, which comprises the full collection of items or components that are important to the research endeavours (Abhinav 2023). Because they include the precise data that the project plans to collect and analyse, these items or components are considered pertinent to the research study (Daruhadi and Sopiati 2024). The target population for this study comprises automotive manufacturing firms registered under NAACAM and NAAMSA. Within these firms, the respondents consisted of chief technology officers, heads of digital transformation, chief information officers, heads of R&D, and operations managers of automotive manufacturers in South Africa. These respondents were selected because they hold direct responsibility for technology adoption, operational transformation, and strategic decision-making related to 4IR and 5IR integration. The sampling frame was drawn from the NAACAM and the NAAMSA, with a population of 210 NAACAM and 48 NAAMSA manufacturers.

4.6.1 Sampling procedures

Sampling involves strategically selecting a limited number of subjects or units from a larger pool, known as the population, for the purpose of using them as the basis for making estimates or projections of some unknown data, scenarios, or outcomes for the entire population (Lohr 2021). There are two general categories of sampling techniques: probability and non-probability; each serves a particular purpose in a research study (Mishra and Alok 2022). In some cases, researchers prefer to employ both techniques jointly, thereby developing a mixed sampling design (Nayak and Singh 2021).

Probability sampling, as the name suggests, is an unbiased and random selection process where the likelihood of an element being chosen is determined a priori by the researcher (Berndt 2020). Probability sampling relies on a systematic and indiscriminate procedure in which every population element has a non-zero probability of being included in the sample and the probability of selection is known (Bairagi and Munot 2019). Probability sampling methods generally take large samples to maximally represent the target population they are drawn from (Lohr 2021). Some common methods of probability sampling are simple random sampling, systematic sampling, stratified sampling, and cluster sampling (Mishra and Alok 2022).

Non-probability sampling, on the other hand, does not assign probabilities to the elements within the population and therefore does not ensure random selection (Rahman 2023). As a result, any conclusion based on a non-probability sample cannot definitively be generalised to the whole population (Dubey and Kothari 2022). Interestingly, non-probability sampling techniques tend to be applied where probability sampling is not possible or where the research objectives place greater emphasis on aspects other than representativeness (Mellenbergh 2019). Convenience sampling, judgmental sampling, and quota sampling are some of the popularly employed non-probability sampling techniques (Kumar 2022).

A sampling technique is selected on the basis of various considerations such as research objectives, available resources, and the level of representativeness required. Probability sampling techniques offer a systematic and unbiased foundation, with the guarantee that every element has a known opportunity to be chosen, while non-probability sampling techniques offer flexibility and convenience but with limitations on generalisability (Nayak and Singh 2021). Researchers must balance these concerns carefully and choose the sampling technique that best fits their research aims to achieve valid and reliable results.

This study used a census sampling technique in which the entire population defined in the sampling frame was covered in the research. The census sampling technique was used to avoid sampling error and to achieve full representation of the targeted population at firm-level, while purposive sampling was used at the respondent level to ensure that only appropriately knowledgeable and experienced individuals contributed to the study. The census approach ensured that the study included a broad range of automotive firms, from large multinational firms to small local firms. By covering the entire population, the study aspired to obtain a more representative and generalisable understanding of the innovation impact of 4IR and 5IR technology adoption on the modernisation of the South African AMI.

4.7 Data collection tools and procedures

Data collection refers to the systematic process of acquiring and assessing information pertaining to variables of interest. This process is conducted in a meticulous manner to facilitate the answering of research questions, the testing of hypotheses, and the evaluation of outcomes (Taherdoost 2021). There are two principal approaches for obtaining information regarding a particular situation, individual, issue, or phenomenon: primary data collection and secondary data collection (Pandey and Pandey 2021). Primary data is obtained through quantitative data collection techniques, while secondary data is obtained through qualitative data collection procedures.

The quantitative data collection method involves the acquisition of numerical data by employing structured questionnaires or observation guides in order to gather primary data from individuals (Bairagi and Munot 2019). The data collected through this method can cover a wide range of aspects, including opinions, beliefs, attitudes, lifestyles, behaviours, and background information such as age, gender, education level, and income level (Bougie and Sekaran 2019). Quantitative survey data gathering can be divided into three broad categories: self-completion, interviewer completion, and observation.

On the other hand, qualitative data collection entails the gathering of non-numerical data by means of various approaches such as observation, the conducting of one-on-one interviews, and the facilitation of focus groups (Bougie and Sekaran 2019). The approaches employed for qualitative data collection encompass a range of methods, including observation, ethnographic research, content analysis, interviews, and projective techniques (Bell, Bryman and Harley 2022).

In this study, quantitative survey data was gathered by means of a standardised questionnaire designed to collect information on various factors influencing innovation, such as availability of skilled labour and organisational support for upskilling, as well as modernisation outcomes, such as productivity levels and income growth. The survey was aimed at chief technology officers, heads of digital transformation, chief information officers, heads of R&D, and operations managers of automotive manufacturers. The survey comprised closed-ended questions employing a 5-point Likert scale to quantify degrees of agreement, together with demographic questions to determine respondent characteristics. The survey was conducted online in an effort to ensure maximum reach and optimum data collection.

4.7.1 Questionnaire design

The questionnaire was designed for readability, with very brief statements designed to be easy to understand. This was intended to make the questionnaire more appealing to the respondents and to increase their willingness to contribute to the study. The questionnaire was designed to assess the innovation impact of 4IR and 5IR technologies on the modernisation of the AMI and was based on the bibliometric literature review presented in Chapter Two. The measurement items were adapted from peer-reviewed studies. The adaptation process for the items ensured that the essence and content of the questions were retained and that they were aligned with the context of the study. Some sentences and words were revised to fit the context and ensure clear understanding of the questions asked. No translation was required as the original questions were in English and were in line with the context of this study.

The questionnaire (see Annexure D) consisted of 48 items and was divided into four sections, which measured the following themes:

a) Section 1: Demographic information – 6 items (Hughes *et al.* 2022)
b) Section 2: 4IR and 5IR technology adoption – 7 items (Shahzad *et al.* 2023)
c) Section 3: Factors influencing innovation – 15 items: cost of technology adoption (Lai, Sun and Ren 2018); availability of skilled labour (Somfula and Zhanda 2023); support for technology infrastructure (Lai, Sun and Ren 2018)
d) Section 4: Modernisation outcomes – 20 items: increased productivity (Dalenogare *et al.* 2018; Müller, Buliga and Voigt 2018); workforce income growth (Ghobakhloo and Fathi 2019); organisational support for upskilling (Shahzad *et al.* 2023; Somfula and Zhanda 2023); promotion of digital commerce (Alsulaimani and Islam 2022; Yong and Huipeng 2022)

Sections 2, 3, and 4 of the questionnaire employed a 5-point Likert-type scale with the following representations: 1 = strongly disagree; 2 = disagree; 3 = neutral; 4 = agree; and 5 = strongly agree. The main reason for choosing this style of questioning was that a Likert scale is simple to read and understand. Since completion of the questionnaires was not very time-consuming, many organisations participated in the study without hesitation, as indicated by the high response rate achieved. In addition, the questionnaire data was simple to code and analyse.

Each section of the questionnaire is described in turn below.

4.7.1.1 Section 1: Demographic information

Respondents were asked to provide information regarding their age group, gender, education level, current position, duration of working experience in the automotive manufacturing sector, and the type of automotive sector in which they were currently working.

4.7.1.2 Section 2: Fourth and Fifth Industrial Revolution technology adoption

Respondents were asked to rate their level of agreement with various statements related to the adoption of 4IR and 5IR technologies in their organisations.

4.7.1.3 Section 3: Factors influencing innovation in the automotive manufacturing industry

Respondents were asked to rate their level of agreement with statements regarding the following factors influencing innovation: cost of technology adoption, availability of skilled labour, and support for technology infrastructure.

4.7.1.4 Section 4: Outcomes of modernisation of the automotive manufacturing industry

Respondents were asked to rate their level of agreement with statements regarding the following outcomes of modernisation: increased productivity, organisational support for upskilling, workforce income growth, and promotion of digital commerce.

4.7.2 Measurement scale

The questionnaire used a combination of nominal and interval scales. The use of each type of scale in the questionnaire is discussed in turn below.

4.7.2.1 Nominal

A nominal scale is used to allocate subjects to particular groups or categories. These groups are assigned different code numbers, which serve as simple and convenient category labels with no intrinsic value other than to assign respondents to one or two non-overlapping or mutually exclusive categories (Bougie and Sekaran 2019: 200).

Nominal scales were used in the study questionnaire to capture information in Section 1, which comprises items relating to respondent demographics.

4.7.2.2 Interval

An interval scale allows certain arithmetical operations to be performed on the data collected from respondents. This enables the computation of the means and the standard deviations of the responses regarding the variables. The responses are ranked under categories from “strongly disagree” to “strongly agree” in relation to the statements in the questionnaire (Bougie and Sekaran 2019: 200).

Interval scales were used in the study questionnaire to capture information in Sections 2, 3, and 4. All items in these sections were measured on a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree).

4.7.3 Administration of questionnaire

The respondents were informed about the aim of the study, and the questionnaire was distributed electronically to allow the respondents to complete it at their own convenience, in the comfort of their homes or offices, and at their own desired pace.

4.8 Validity and reliability

In this section, the techniques used to ensure the instrument’s validity and reliability are examined in detail.

4.8.1 Validity

The concept of validity refers to the extent to which a research or test mechanism effectively measures what it was originally intended to measure or the level of success with which the research or test mechanism achieves its intended purpose (Dubey and Kothari 2022). Validity is often classified into four categories: criterion-related validity, content validity, face validity, and construct validity. Criterion-related validity refers to the extent to which a measurement instrument accurately correlates with a specified external criterion (Kumar 2022); content validity refers to the degree to which a measurement instrument adequately covers all aspects of the concept that it was designed to measure (Nayak and Singh 2021); face validity involves the establishment of a logical connection or correlation between each individual item or question present within the measurement instrument and the predefined objectives of the study (Allen, Robson and Iliescu 2023); construct validity is a statistical concept that evaluates whether a measurement instrument accurately measures the abstract concept it is designed to assess (Mata-López *et al.* 2021).

In this study, content validity was assessed by expert review to confirm that the questionnaire items sufficiently described and measured the desired constructs for the innovation impact of the adoption of 4IR and 5IR technologies on the modernisation of the AMI. Construct validity was assessed to confirm that the questionnaire adequately measured the theoretical constructs under study. Criterion validity was assessed to confirm the predictive ability of the questionnaire in relation to modernisation outcomes.

4.8.2 Reliability

If a research tool demonstrates consistency and stability and is therefore capable of making accurate predictions, it is classified as reliable (Bougie and Sekaran 2019). The level of reliability of an instrument is directly proportional to the extent of its consistency and stability (Sürücü and Maslakci 2020). Information can be deemed reliable if the results obtained from carrying out research on different groups of respondents, under similar conditions, are replicable (Shaked *et al.* 2019). In this study, a pilot test and Cronbach’s alpha coefficient were used to ensure reliability. Each test is discussed in turn below.

4.8.2.1 Pilot test

Piloting refers to conducting a small-scale test in order to identify potential concerns and feedback for improvement (Lu and Zhang 2023). A pilot test is a screening test prior to the fine-tuning of processes, tools, or systems for mass implementation in order to achieve effectiveness, efficiency, and feasibility of the final product or process (Ambalavanar *et al.* 2024). It is used in the R&D process in various disciplines.

A pilot test for this study was conducted on 10 automotive manufacturers. This pre-testing helped to identify potential concerns about the clarity of the questions, understanding, and response trends. This ensured that the questions accurately measured the intended concepts. The pilot test resulted in several minor refinements aimed at improving clarity and ensuring that the measurement items aligned effectively with the study constructs. These refinements included simplifying wording in items that respondents found ambiguous, adjusting the sequence of selected questions to enhance logical flow, and modifying a small number of statements to improve alignment with the underlying latent variables. No structural changes were made to the constructs themselves; rather, the adjustments focused on improving readability and ensuring that respondents interpreted each item consistently. These refinements strengthened both face validity and internal reliability prior to full-scale data collection.

4.8.2.2 Cronbach's alpha coefficient

Cronbach's alpha is a measure of the internal consistency of a set of questionnaire items and is generally applied within the fields of social science, education, psychology, and biomedical studies (Zakariya 2022). Cronbach's alpha tests the strength of the interrelatedness of items in a scale, providing an estimate of its internal consistency (Kotian, Varghese and Motappa 2022). An accepted minimum for the value of Cronbach's alpha is 0.70 (Karakaya and Alparslan 2022).

In this study, the internal consistency of the questionnaire was assessed using Cronbach's alpha coefficient, providing a statistical measure of the reliability and cohesiveness of the questionnaire items.

4.9 Description of the sample

The study involved a total of 258 participants (N = 258). The questionnaire was electronically distributed to the respondents, and 221 responses were captured, giving a response rate of 85.66%. This excludes the 10 respondents who had participated in the pilot test. The responses from the pilot test were used to improve the language and technical aspects of the structured electronic questionnaire (Ashahril, Isa and Anwar 2023). The Cronbach's alpha coefficient statistical test was used to establish the reliability of the structured electronic questionnaire, with the scores ranging from 0.808 to 0.942. Based on the recommendations of Karakaya and Alparslan (2022), which suggest that internal consistency values greater than 0.70 are acceptable, the measuring instrument was deemed reliable.

The reliability statistics for the pilot test are shown in Table 4.1 below.

Table 4.1: Pilot test reliability statistics

Variable	Cronbach's alpha	Items per variable	Mean	Standard deviation	Cronbach's alpha if item is deleted
4IR/5IR_Tech_Adoption	0.942	7	2.9643	0.64703	0.948
					0.922
					0.926
					0.945
					0.920
					0.924
					0.941
Adoption_Cost	0.876	5	3.5200	0.74356	0.854
					0.819
					0.864
					0.840
					0.861
Labour_Avail	0.936	5	2.0200	0.77431	0.943
					0.904
					0.913
					0.913
					0.934
Tech_Infrastructure	0.808	5	2.0200	0.77431	0.778
					0.715
					0.733
					0.810
					0.797
Productivity	0.941	5	3.8600	0.79470	0.915
					0.922
					0.945
					0.908
					0.945
Upskilling	0.941	5	3.8600	0.79470	0.915
					0.922
					0.945
					0.908
					0.945
Workforce_Income	0.921	5	3.3400	0.65354	0.957
					0.911
					0.890
					0.868
					0.868
Digital_Commerce	0.855	5	2.5000	0.83400	0.818
					0.918
					0.779
					0.772
					0.807

4.10 Elimination of bias

Systematic error can distort the measurement process and impact the overall study progress, impacting validity (Pandey and Pandey 2021). To achieve dependability and credibility, a study must eliminate bias in order to accurately reflect and depict the features of the target population, resulting in detailed and authentic conclusions (Nayak and Singh 2021).

This study used email-based surveys, which prevented researchers from influencing respondents' views and avoided the risk of interviewer bias.

4.11 Ethical considerations

Ethics play a significant role in regulating research activities by safeguarding the dignity of participants and the integrity of the data collected (Ichendu 2020). Ethical issues must be considered to prevent interference and the possibility of misleading data (Suri 2020). Ethical considerations require researchers to prioritise the need for justice and respect and the avoidance of injury to participants (Bougie and Sekaran 2019). Researchers need to ensure informed consent, maximum confidentiality and anonymity, and gatekeepers' approval (Dubey and Kothari 2022).

In addition to ensuring the ethical standards mentioned above and clarified in the subsections below, this study adhered to the ethical guidelines provided by Durban University of Technology. For the purpose of acquiring ethical approval for this study, draft copies of the informed consent form, the data collection tools, and the letter of information for participants were sent to the relevant university committee for approval. After ethical approval had been obtained, approval was requested from the gatekeepers, namely, the NAACAM and the NAAMSA, prior to data collection from their constituent firms.

4.11.1 Informed consent

Confirmation of informed consent is essential when engaging in research activities. Informed consent ensures that a participant willingly and knowingly provides their approval, fully comprehending the scope of the research and its expectations (Dubey and Kothari 2022). In order for informed consent to be granted, it is imperative that all pertinent information relating to the study is readily accessible to the participants. Furthermore, the participants must volunteer their involvement without any form of coercion or deception (O'Sullivan *et al.* 2021).

In this study, a letter of informed consent was issued to the participants. In addition, a letter of information informed the participants fully of the aim and nature of the study and that the study was being conducted for research purposes.

4.11.2 Participant safety

A study is obligated not to inflict any damage or harm on participants; if the likelihood of harm exists or if participants might suffer any form of disturbance, convincing reasons for this should be offered (Ichendu 2020). The infliction of damage or harm may take the form of bodily harm, stress, anxiety or uneasiness, invasion of privacy, or social disadvantage (Dubey and Kothari 2022). The researcher needs to take into consideration all the implications of the study and evaluate whether the benefits outweigh the risks; if the risks are greater, then the study must be revised (Clark *et al.* 2021).

In this study, respondents were made aware that participation was entirely voluntary and that they could withdraw at any time before submitting the questionnaire without penalty or consequence. Contact information for the researcher and supervisory team was provided to allow for any concerns to be addressed. Before beginning the survey, participants were presented with a detailed letter of information and consent form outlining the purpose, risks, and benefits of the study. Submission of the questionnaire implied consent to participate. The questionnaire was designed to exclude sensitive personal or demographic questions that were unrelated to the objectives of the study. All items focused on the innovation impact of the adoption of 4IR and 5IR technologies on the modernisation of the AMI.

4.11.3 Anonymity and confidentiality

When an individual's identity cannot be linked to specific responses, anonymity is achieved. In the event that anonymity cannot be guaranteed, the researcher must consider concealing the identities of the participants by safeguarding their personal information (Dougherty 2021). The preservation of anonymity and confidentiality is of utmost importance in research, as participants will only disclose private information when they are confident that it will be protected (Arca and Hewett 2023).

In this study, all research materials and data were handled with strict confidentiality throughout the study and after its completion. In accordance with standard research practices and institutional requirements, the collected data will be retained for five years after the completion of the study. During this retention period, digital data will be stored in encrypted format on a password-protected computer and backed up on a secure cloud storage system with two-factor authentication, accessible only to authorised research team members. Physical documents will be kept in a locked filing cabinet in a secure office and will be accessible only to the principal researcher. All data collected has been anonymised, meaning that any identifying information (such as names, contact details, or specific job titles) has been removed or replaced with codes to ensure that individual participants cannot be identified from the data.

4.12 Data analysis

The process of data analysis involves the conversion of raw data into relevant knowledge that will provide the greatest utility for an institution (Bougie and Sekaran 2019). Data analysis is a crucial process for researchers to extract knowledge and answers from data (Goniwada 2023). It includes verifying the correctness and validity of data, conducting the relevant analysis processes, and verifying the conclusions (Sayal 2023). Data analysis identifies trends, relationships, and patterns within the data, providing useful knowledge (Resch and Brenzel 2023). It allows for the establishment of conclusions, the improvement of processes, the improvement of efficiency, and the facilitation of support processes across various industries (Abu-Mahfouz 2022). In data analytics, processes such as pre-processing, statistical analysis, quantitative metrics, and uncertainty assessment are applied to gain insight from quantitative data (Thompson 2022). Data analysis plays a crucial role in supporting conclusions, informing future activities, and improving the decision-making process across various industries by providing valuable insights.

In this study, the data was analysed using quantitative methods with the aim of clarifying how the innovation impact of the adoption of 4IR and 5IR technologies contributes to the modernisation of the AMI. IBM Statistical Package for the Social Sciences (SPSS) Statistics version 30 and Amos version 31 were used to conduct the data analysis.

4.12.1 Descriptive statistics

Descriptive statistics summarise and describe the general features of a dataset. They enable the organisation and presentation of data in a logical and meaningful manner without making conclusions beyond the data itself (Wienclaw 2021). Descriptive statistics are fundamental for understanding the characteristics of a dataset, providing a foundation for further analysis.

This study used frequency distributions to summarise the demographic data. This provided an overall summary of the characteristics of the sample and the distribution of responses across various categories, helping to identify normal response patterns.

4.12.2 Inferential statistics

Inferential statistics enable researchers to make generalisations about a large population by studying a smaller, representative sample. Inferential analysis uses inductive reasoning to draw general conclusions about a population from sample data, enabling the study of cause-and-effect relationships and the evaluation of hypotheses (Kushwahak 2020). Inferential statistics are used in various fields, such as the social sciences, health studies, and applied linguistics, to draw conclusions beyond the dataset under investigation (Yoo 2022).

In this study, hypotheses were evaluated and correlation analysis was used to examine the relationships between different variables. For instance, the influence of the adoption of 4IR and 5IR technologies on productivity and workforce income was analysed, and notable correlations between variables were observed. Linear regression analysis showed the strength and nature of the interrelationship between the dependent variables and the independent variables. This technique showed the predictive strength of the independent variables towards the desired consequences.

4.12.3 Factor analysis

4.12.3.1 Exploratory factor analysis

Exploratory factor analysis (EFA) is a statistical technique that has been widely utilised in the social sciences for the discovery of latent relationships between observed variables. It is also used for data dimensionality reduction and assessment of scales (Trendafilov and Hirose 2022). EFA helps to identify latent variables, or factors, that explain the correlations among a set of observed variables; it can be used with different types of variables, including continuous, binary, ordinal, and mixed data (Watkins 2021). In this study, EFA was used to identify the underlying factors or dimensions that influence the adoption of 4IR and 5IR technologies and its implications. This statistical method grouped related response patterns from the study into fewer, more meaningful latent factors.

4.12.3.2 Confirmatory factor analysis

CFA is a statistical technique used to test whether or not a hypothesised model is supported by collected data (Štiglic, Budler and Watson 2023). As a part of SEM, CFA is used to confirm the degree to which observed variables measure underlying latent variables or constructs (Verma and Verma 2023). CFA and SEM played complementary roles in strengthening the rigour and depth of this study. CFA rigorously tested the factor structure identified through EFA by evaluating the presumed relationships between observed indicators and latent constructs, thus confirming whether the suggested dimensions reasonably reflected the data. Through the utilisation of fit indices, such as the root mean square error of approximation (RMSEA), the comparative fit index (CFI), and the Tucker-Lewis Index (TLI), CFA tested the measurement model's adequacy, reliability (composite reliability (CR)), and validity (convergent and discriminant), thus rendering the constructs psychometrically sound as well as theoretically consistent.

4.12.4 Structural equation modelling

SEM is a quantitative technique used to test complex relationships between observed variables and latent variables (Hair *et al.* 2021). It enables researchers to test and validate theoretical models, making it particularly useful in advanced quantitative research (Jobst, Bader and Moshagen 2023). SEM goes beyond analysing observed variables by integrating the measurement model with the structural model to test hypothesised causal relationships between latent variables.

This study utilises SEM to test the hypotheses. SEM was selected as the preferred analytical methodology for several reasons. Firstly, it displays a robust capacity to examine complex relationships among latent constructs and observed variables. The ability of SEM to consider both direct and indirect effects in one comprehensive model makes the tool particularly suitable for studies based on multiple theories (Sathyanarayana and Mohanasundaram 2025), such as the RBV, the DCT, the DTT, and the TOE framework. This ability is essential to investigate the innovation impact of the adoption of recent industrial revolution technologies on the modernisation of the AMI, where organisational agility, technological preparedness, and human capital are constantly intermixed factors. Secondly, SEM enables researchers to combine confirmatory factor analysis (CFA) with structural measurement models, including path analysis. This methodology enables the simultaneous estimation of hypothesised relationships in terms of direction and magnitude, as well as evaluation of the validity and reliability of the constructs (Harris and Gleason 2022). SEM is a powerful statistical method of modelling constructs through multiple indicators, which is especially relevant considering that the study is focused on constructs that are not observable and are therefore latent variables, such as innovation capability, digital maturity, and strategic alignment (Sathyanarayana and Mohanasundaram 2025). Finally, SEM is useful in dealing with model fit indices, multicollinearity, and measurement error, all of which are crucial to establishing the validity and generalisability of results in empirical research (Vispoel, Lee and Chen 2025).

SEM was selected due to its methodological rigour as well as its compatibility with the theoretical complexity and empirical goals of the investigation. It permits a thorough examination of how different organisational, technological, and environmental elements interact to affect the results of digital transformation, innovation, and modernisation in the AMI.

The choice of SEM is motivated by the complexity of the study's conceptual model, which incorporates multiple latent variables, numerous direct and indirect pathways, and several theoretically grounded mediators. SEM is uniquely suited for such analyses because it simultaneously tests measurement models and structural relationships, accounts for measurement error, and evaluates the fit of the overall theoretical model. Alternative multivariate techniques such as multiple regression, path analysis, and MANOVA lack the ability to model latent constructs or evaluate mediated effects within a unified analytical framework. Given the multidimensional nature of the TOE, RBV, HCT, and SCIT-based relationships tested in this study, SEM offers the methodological rigour required to validate both the measurement and structural components of the model.

4.13 Chapter summary

This chapter has outlined the methodologies employed in exploring the innovation impact of recent industrial revolution technology adoption on the modernisation of the AMI. Firstly, the chapter discussed the philosophical framework that underlies the study. Thereafter, the research approaches and design were discussed, and the conceptual framework and hypotheses of the study were presented. The chapter then focused on the target population and the sampling procedures employed. Thereafter, the tools and procedures utilised for data collection were discussed, as well as the procedures used to ensure the validity and reliability of these tools. The chapter then examined the mitigation of bias and the study's ethical considerations, followed by a discussion of the data analysis techniques used in the study.

The results of the study are presented in the next chapter.

CHAPTER FIVE

RESULTS

5.1 Introduction

The research methodology adopted for this study was discussed in the previous chapter. This chapter presents and analyses the findings of the study. The chapter begins by presenting and analysing the descriptive statistics of the dataset. Thereafter, the chapter presents the findings of the analysis of the innovation impact of 4IR and 5IR technology adoption on the AMI, including demographic data, EFA, reliability analysis, correlations analysis, CFA, SEM, and hypothesis testing. The chapter concludes with a summary.

5.2 Descriptive statistics of respondents

The descriptive analysis of the dataset reveals a well-distributed and statistically sound foundation for further inferential testing. As shown in Table 5.1 below, the means for items range between 2.21 and 3.51, indicating that the dataset displays adequate variability across items, with no evidence of floor or ceiling effects, and is therefore suitable for subsequent parametric analysis. Such use offsets central tendency bias and enhances interpretability in results (Field 2024). Standard deviations range between 0.51 and 2.41, with most clustering around 1.4, which shows there is a moderate spread around the mean. Such a level of dispersion is desirable in questionnaire survey research because it shows diversity in views while not taking a volatile form (Pallant 2020). Values for variances ranging between 0.260 and 1.794 support standard deviations equally and show no signs of extreme values or clustering for any variable, further substantiating the assumption of an even keel and dependable distribution in the data. These indicate a perfectly symmetrical platykurtic distribution, or responses evenly spread but flatter than a normal distribution. Most items in the dataset fall within the acceptable ranges of ±2 for skewness and ±7 for kurtosis, indicating no substantial deviations from normality (Byrne 2010; Hair *et al.* 2010). The mean values generally fall between 2.2 and 3.5, reflecting mid-range distributions without clustering at extreme response categories. These characteristics confirm that the dataset is well-behaved and appropriate for the subsequent SEM procedures. These trends show that the items are neither extremely homogeneous nor excessively random, yielding sensitivity for statistical testing.

Table 5.1: Descriptive statistics

Constructs	Mean	Std. Dev	Variance	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
4IR/5IR Technology Adoption							
Invest_4IR5IR1	2.92	1.246	1.553	0.118	0.164	-.930	0.326
Invest_4IR5IR2	2.98	1.300	1.691	0.046	0.164	-1.079	0.326
Invest_4IR5IR3	3.11	1.287	1.655	-0.045	0.164	-1.077	0.326
Educa_4IR5IR2	2.95	1.262	1.593	0.053	0.164	-1.005	0.326
Educa_4IR5IR1	3.05	1.282	1.642	-0.024	0.164	-1.050	0.326
Manage_4IR5IR	2.96	1.284	1.648	-0.001	0.164	-1.103	0.326
Cost of Technology Adoption							
A_Costs1	3.21	0.702	0.493	-.235	0.164	-0.808	0.326
A_Costs2	3.17	0.692	0.479	-.242	0.164	-0.904	0.326
A_Costs3	3.21	0.678	0.459	-.289	0.164	-0.830	0.326
A_Costs4	3.19	0.690	0.476	-.276	0.164	-0.889	0.326
A_Costs5	3.22	0.673	0.453	-.288	0.164	-0.808	0.326
Availability of Skilled Labour							
Labour1	3.51	0.528	0.278	.236	0.164	-1.327	0.326
Labour2	3.48	0.576	0.332	0.170	0.164	-0.536	0.326
Labour3	3.49	0.510	0.260	0.131	0.164	-1.737	0.326
Labour4	3.48	0.560	0.314	-0.136	0.164	-0.768	0.326
Labour5	3.49	0.536	0.287	-0.312	0.164	-1.158	0.326
Support for Technology Infrastructure							
Infra1	2.92	0.734	0.539	0.129	0.164	-1.128	0.326
Infra2	2.92	0.788	0.621	0.145	0.164	-1.373	0.326
Infra3	2.84	0.769	0.592	0.167	0.164	-1.040	0.326
Infra4	2.91	0.720	0.519	0.137	0.164	-1.058	0.326
Infra5	2.90	0.768	0.590	-0.010	0.164	-0.897	0.326
Increased Productivity							
Productivity1	2.67	0.656	0.430	0.359	0.164	-0.612	0.326
Productivity2	2.70	0.683	0.467	0.296	0.164	-0.609	0.326
Productivity3	2.76	0.706	0.499	0.135	0.164	-0.590	0.326
Productivity4	2.69	0.692	0.479	0.173	0.164	-0.463	0.326
Productivity5	2.74	0.675	0.456	0.274	0.164	-0.682	0.326
Organisational Support for Upskilling							
Org_Supp1	3.18	1.340	1.794	-0.095	0.164	-1.178	0.326
Org_Supp2	2.67	0.656	0.430	0.359	0.164	-0.612	0.326
Org_Supp3	2.70	0.683	0.467	0.296	0.164	-0.609	0.326
Org_Supp4	2.76	0.706	0.499	0.135	0.164	-0.590	0.326
Org_Supp5	2.69	0.692	0.479	0.173	0.164	-0.463	0.326
Workforce Income Growth							
W_Income1	2.23	0.598	0.358	0.001	0.164	-0.222	0.326
W_Income2	2.21	0.582	0.338	-0.058	0.164	-0.336	0.326
W_Income3	2.23	0.590	0.349	-0.103	0.164	-0.426	0.326
W_Income4	2.23	0.569	0.324	-0.026	0.164	-0.343	0.326
W_Income5	2.25	0.593	0.351	-0.135	0.164	-0.487	0.326
Promotion of Digital Commerce							
E_Comm1	3.14	2.38	0.556	0.309	0.006	0.164	-0.699
E_Comm2	2.99	2.39	0.574	0.330	-0.138	0.164	-0.639
E_Comm3	3.05	2.41	0.562	0.316	0.043	0.164	-0.650
E_Comm4	2.96	2.35	0.605	0.366	-0.102	0.164	-0.410
E_Comm5	2.86	2.36	0.559	0.313	-0.127	0.164	-0.766
Valid N (listwise)							

The dataset features strong distributional features, which enjoy ample equilibrium and variability to support parametric statistical analysis. Therefore, the data are suitable for advanced statistical analysis such as factor analysis, regression analysis, and correlation.

5.3 Data analysis

5.3.1 Demographic data of respondents

The demographic distribution of respondents is summarised in Table 5.2 below.

Table 5.2: Demographic profile of respondents

Characteristics	Category	Frequency	Percent %
Age	18-25	0	0.0%
	26-30	1	0.5%
	31-35	7	3.2%
	36-40	39	17.6%
	41-45	78	35.3%
	46-50	52	23.5%
	51+	44	19.9%
Gender	Male	194	87.8%
	Female	27	12.2%
Qualification	High School	3	1.4%
	Higher certificate	6	2.7%
	Diploma	42	19.0%
	Bachelor's Degree	113	51.1%
	Honours Degree	15	6.8%
	Master's Degree	41	18.6%
	PhD or equivalent	1	0.5%
Position	Chief Technology Officer (CTO)	6	2.7%
	Head of Digital Transformation	1	0.5%
	Chief Information Officer (CIO)	2	0.9%
	Head of Research and Development (R&D)	6	2.7%
	Operations/Plant/General Manager	148	67.0%
	Director/Managing Director	40	18.1%
	Technology Officer/Related Position	17	7.7%
	R&D	1	0.5%
Experience	1 – 5	21	9.5%
	6 – 10	33	14.9%
	11 – 15	64	29.0%
	16 – 20	58	26.2%
	21+	45	20.4%
Sector	Personal use vehicle manufacturers	0	0.0%
	Light Commercial Vehicle (LCV) Manufacturers	0	0.0%
	Medium and Heavy Commercial Vehicle (MCV and HCV) Manufacturers	5	2.3%
	Automotive Component Manufacturers	209	94.6%
	Original Equipment Manufacturers (OEMs)	7	3.2%

The majority of respondents are in the age group of 41-50 years; 35.3% of respondents are in the age group of 41-45 years, and 23.5% are in the age group of 46-50 years, indicating a mature and experienced workforce. The gender distribution is predominantly male (87.8%), with only 12.2% female respondents, indicating a statistically significant gender imbalance in the surveyed sample. The gender distribution indicates a markedly male-dominated respondent group. While this reflects the current composition of the AMI's technical and managerial workforce, it also signals a constrained talent pipeline for digital manufacturing roles. More than half (51.1%) of respondents possess a Bachelor's degree, and 25.9% possess a postgraduate qualification, indicating that most respondents are highly educated. With regard to employment roles, the majority (67.0%) of respondents are operations, plant, or general managers, followed by directors or managing directors (18.1%), indicating that the perspectives of senior managers are represented. With regard to experience levels, 29.0% of respondents have between 11 and 15 years of experience, 26.2% have between 16 and 20 years of experience, and 20.4% have 21 or more years of experience, indicating that most respondents possess a strong, in-depth understanding of the AMI. The near-universal majority (94.6%) of respondents represent the automotive component manufacturing sector, with much smaller proportions representing OEMs (3.2%) and medium and heavy commercial vehicle manufacturers (2.3%). Therefore, the demographic data indicates that the findings of the study are based on the experience of highly experienced and educated professionals who are predominantly employed in the automotive component manufacturing sector.

5.3.2 Exploratory factor analysis

The presence of correlations among variables is a prerequisite for factor analysis. Two main statistical tests, the Kaiser-Meyer-Olkin Measure of Sampling Adequacy (KMO) and Bartlett's test of sphericity, are used to assess this correlation. The KMO value typically ranges from 0 to 1, with a value exceeding 0.6 suggesting that the dataset is suitable for factor analysis (Sun, Zhang and Liu 2025). The null hypothesis of Bartlett's test states that the observed correlation matrix is equal to the identity matrix, suggesting that the observed matrix is not factorable. Therefore, rejecting the null hypothesis indicates appropriateness for factor analysis.

For this dataset, as shown in Table 5.3 below, the KMO value is 0.922 (greater than 0.6), and Bartlett's test rejects the null hypothesis, confirming that the sample data used in this study are suitable for factor analysis.

Table 5.3: Kaiser-Meyer-Olkin Measure of Sampling Adequacy and Bartlett's test results

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.922
Bartlett's Test of Sphericity	Approx. Chi-Square	10222.702
	df	820
	Sig.	<.001

The scree plot for the factor analysis is shown in Figure 5.1 below. Eight factors display eigenvalues greater than 1, while the eigenvalues of all other factors are below 1, aligning with the variance explanation results. During the factor selection process, 33 indices were excluded after completing the principal component analysis (PCA), leaving eight indices. Ultimately, the goal of dimensionality reduction was achieved.

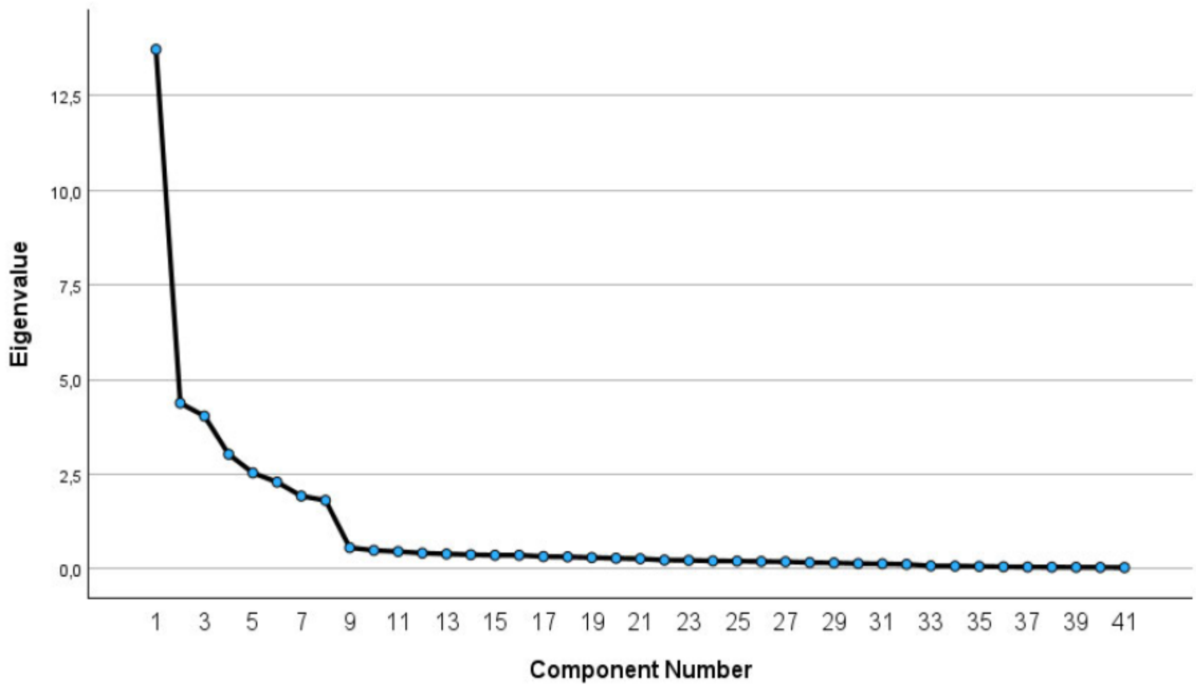

Figure 5.1: Scree plot for factor analysis

The total variance indicates the extent to which the extracted factors, following dimensionality reduction, account for the original variables. As shown in Table 5.4 below, eight factors with eigenvalues greater than 1 were extracted, and the cumulative variance contribution rate of these eight factors after dimensionality reduction is approximately 82%, demonstrating a high level of information integrity.

Table 5.4: Total variance explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	13.722	33.469	33.469	13.722	33.469	33.469	5.548	13.532	13.532
2	4.379	10.679	44.149	4.379	10.679	44.149	4.740	11.561	25.093
3	4.034	9.839	53.988	4.034	9.839	53.988	4.255	10.379	35.472
4	3.026	7.380	61.368	3.026	7.380	61.368	4.188	10.215	45.687
5	2.534	6.181	67.549	2.534	6.181	67.549	3.805	9.280	54.966
6	2.290	5.584	73.133	2.290	5.584	73.133	3.782	9.224	64.190
7	1.922	4.688	77.821	1.922	4.688	77.821	3.743	9.130	73.321
8	1.808	4.409	82.230	1.808	4.409	82.230	3.653	8.909	82.230
Extraction Method: Principal Component Analysis.									

Table 5.5 below shows the rotated component matrix reflecting the PCA with Varimax rotation. The PCA identified eight distinct components, each having a coherent set of correlated variables. The factor analysis yielded a stable and interpretable solution, and the rotation scheme converged at seven iterations. Eight unique components materialised, each reflecting a stable and theoretically significant construct for the South African AMI.

Component 1, representing 4IR and 5IR technology adoption, consists of the variables *Invest_4IR5IR1* to *Invest_4IR5IR3*, *Educate_4IR5IR1* and *Educate_4IR5IR2*, and *Manage_4IR5IR*, with loadings ranging from 0.878 to 0.890. This implies a strong latent factor that captures attitudes toward workforce readiness and labour availability, both of which are fundamental ingredients for technology-driven manufacturing.

Component 2, representing increased productivity, consists of the variables *Productivity1* to *Productivity5*, with loadings ranging from 0.908 to 0.922. This dominant factor indicates that there are tangible productivity improvements that respondents link with organisational and technological changes.

Component 3, representing the costs of technology adoption, consists of the variables *Costs1* to *Costs5*, with loadings ranging from 0.862 to 0.898. High loadings indicate cost as a persistent influence on the adoption of new technologies and possibly a deterrent to such adoption.

Component 4, representing support for technological infrastructure, consists of the variables *Infra1* to *Infra5*, with loadings ranging from 0.864 to 0.884. This component indicates the significant interplay between infrastructure facilitating digital transformation and operational efficiency optimisation.

Component 5, representing organisational support for upskilling, consists of the variables *Org_Supp1* to *Org_Supp5*, with loadings ranging from 0.766 to 0.805. This component highlights the essential role of internal support systems in enabling workforce development.

Component 6, representing the availability of skilled labour, consists of the variables *Labour1* to *Labour5*, with loadings ranging from 0.795 to 0.852. This component indicates the crucial role of human capital in the use of new technologies.

Component 7, representing workforce income growth, consists of the variables *W_Income1* to *W_Income5*, with loadings ranging from 0.754 to 0.797. The stable loadings highlight income-based outcomes of organisational and technological developments.

Component 8, representing the promotion of digital commerce, consists of the variables *Digi_Comm1* to *Digi_Comm5*, with loadings ranging from 0.783 to 0.817. This component highlights the industry's interaction through digital channels and e-commerce models as part of its digitalisation effort, as well as its strategic direction towards advanced industrial technologies.

Table 5.5: Rotated component matrix

	Component							
	1	2	3	4	5	6	7	8
Invest_4IR5IR1	0.888							
Invest_4IR5IR2	0.883							
Invest_4IR5IR3	0.878							
Educa_4IR5IR1	0.890							
Educa_4IR5IR2	0.879							
Manage_4IR5IR	0.886							
Cost_Adopt1			0.898					
Cost_Adopt2			0.896					
Cost_Adopt3			0.884					
Cost_Adopt4			0.862					
Cost_Adopt5			0.869					
Labour1						0.834		
Labour2						0.795		
Labour3						0.852		
Labour4						0.836		
Labour5						0.840		
Infra1				0.869				
Infra2				0.864				
Infra3				0.884				
Infra4				0.867				
Infra5				0.873				
Productivity1		0.919						
Productivity2		0.915						
Productivity3		0.908						
Productivity4		0.910						
Productivity5		0.922						
Org_Supp1					0.789			
Org_Supp2					0.786			
Org_Supp3					0.792			
Org_Supp4					0.805			
Org_Supp5					0.766			
W_Income1							0.791	
W_Income2							0.791	
W_Income3							0.797	
W_Income4							0.754	
W_Income5							0.787	
Digi_Comm1								0.783
Digi_Comm2								0.789
Digi_Comm3								0.817
Digi_Comm4								0.794
Digi_Comm5								0.816
Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.								
a. Rotation converged in 6 iterations.								

5.3.3 *Reliability analysis*

Reliability was measured using Cronbach's alpha. Cronbach's alpha values of 0.7 or higher indicate acceptable internal consistency (Karakaya and Alparslan 2022). As shown in Table 5.6 below, all key constructs show high internal consistency, substantiating the overall fitness of the measurement tool.

Table 5.6: Reliability statistics

Variable	Cronbach's Alpha	N of Items	Cronbach's Alpha if item is deleted
4IR/5IR Technology Adoption	0.991	6	0.989
			0.989
			0.989
			0.989
			0.989
			0.988
Cost of Technology Adoption	0.946	5	0.931
			0.930
			0.935
			0.935
			0.937
Availability of Skilled Labour	0.906	5	0.884
			0.890
			0.881
			0.884
			0.885
Support for Technology Infrastructure	0.942	5	0.930
			0.930
			0.926
			0.931
			0.923
Increased Productivity	0.984	5	0.981
			0.981
			0.981
			0.980
			0.981
Organisational Support for Upskilling	0.933	5	0.916
			0.915
			0.921
			0.914
			0.921
Workforce Income Growth	0.916	5	0.901
			0.893
			0.892
			0.904
			0.897
Promotion of Digital Commerce	0.894	5	0.881
			0.877
			0.868
			0.866
			0.861

The Cronbach's alpha scores for almost all constructs, namely, *4IR/5IR Technology Adoption* ($\alpha = 0.991$), *Increased Productivity* ($\alpha = 0.984$), *Cost of Technology Adoption* ($\alpha = 0.946$), *Support for Technology Infrastructure* ($\alpha = 0.942$), *Organisational Support for Upskilling* ($\alpha = 0.933$), *Workforce Income Growth* ($\alpha = 0.916$), and *Availability of Skilled Labour* ($\alpha = 0.906$), exceed the established benchmark for excellent reliability ($\alpha \geq 0.90$) (Taber 2018), while the score for the remaining construct, *Promotion of Digital Commerce* ($\alpha = 0.894$), is within the established range for good reliability (0.80 to 0.90). In broad terms, high reliability scores for all constructs indicate that the data is internally consistent and robust enough for further statistical analysis.

5.3.4 Correlation analysis

The Pearson correlation matrix shown in Table 5.7 below provides insightful information on the relationships between the adoption of 4IR and 5IR technologies and various socioeconomic variables, including technology adoption costs, labour availability, infrastructure support, productivity, workforce upskilling, workforce income, and the expansion of digital commerce. The correlation analysis highlights significant and notable relationships between the adoption of 4IR and 5IR technologies and key constructs representing innovation factors and modernisation outcomes in the South African AMI.

Table 5.7: Pearson correlations

	4IR/5IR Adoption	Adoption Costs	Labour Availability	Infrastructure Support	Increased Productivity	Workforce Upskilling	Workforce Income	Digital Commerce
4IR/5IR Adoption	1							
Adoption Costs	-0.360**	1						
Labour Availability	0.246**	0.010	1					
Infrastructure Support	0.277**	-0.010	0.006	1				
Increased Productivity	0.429**	-0.206**	0.282**	0.248**	1			
Workforce Upskilling	0.572**	-0.289**	0.294**	0.263**	0.409**	1		
Workforce Income	0.506**	-0.269**	0.195**	0.390**	0.355**	0.489**	1	
Digital Commerce	1	-0.360**	0.246**	0.277**	0.429**	0.572**	0.506**	1
**. Correlation is significant at the 0.01 level (2-tailed).								

The construct *4IR/5IR Adoption* has significant positive links with *Workforce Upskilling* (r = 0.572, $p < 0.01$), *Workforce Income* (r = 0.506, $p < 0.01$), and *Increased Productivity* (r = 0.429, $p < 0.01$). These links suggest that increased adoption of advanced technologies goes hand in hand with increased skills development, higher incomes, and improved organisational performance. These results confirm broader industrial policy goals in South Africa that emphasise digital transformation as a pathway towards greater competitiveness and inclusive growth.

In addition, *4IR/5IR Adoption* has positive associations with *Infrastructure Support* ($r = 0.277$, $p < 0.01$) and *Labour Availability* ($r = 0.246$, $p < 0.01$), indicating that effective adoption of 4IR and 5IR technologies is dependent upon enabling fundamentals in the form of capable human capital and technology infrastructure. These results highlight that digital transition is not an independent process but an integral component of broader system capacities.

Conversely, *Adoption Costs* exhibits negative relationships with all outcome measures, such as *Increased Productivity* ($r = -0.206$, $p < 0.01$), *Workforce Upskilling* ($r = -0.289$, $p < 0.01$), and *Workforce Income* ($r = -0.269$, $p < 0.01$). These findings emphasise the deterrent effect of cost on achieving digital transformation benefits. In the South African context, where access to capital and financial resources is uneven and constrained, these findings highlight the necessity of targeted support instruments for alleviating cost pressures associated with technology adoption.

The constructs *Labour Availability*, *Infrastructure Support*, and *Workforce Upskilling* have significant intercorrelations with *Workforce Income* and *Increased Productivity*, implying a synergistic association between workforce preparation, infrastructure, and performance outcomes. *Workforce Upskilling* has positive intercorrelations with *Workforce Income* ($r = 0.489$, $p < 0.01$) and *Increased Productivity* ($r = 0.409$, $p < 0.01$), emphasising the need for ongoing learning and development as an essential factor in industrial prosperity. In the social sciences, Pearson's r values between 0.30 and 0.50 are generally regarded as moderate, whereas values greater than 0.50 are regarded as strong (Turney 2024).

5.3.5 Confirmatory factor analysis

The results of the tests of the measurement models, shown in Table 5.8 below, indicate high construct validity and internal consistency for all latent constructs. The constructs have CR values ranging between 0.894 and 0.991, all of which are greater than the standard threshold of 0.70 (Baharum *et al.* 2023), indicating that the internal consistency of the items is very high. Similarly, the average variance extracted (AVE) values range between 0.629 and 0.946, all of which exceed the threshold of 0.50 (Baharum *et al.* 2023), indicating that convergent validity is adequate.

Table 5.8: Measurement model testing

Constructs	Loadings	CR	AVE	MaxR(H)
4IR/5IR Technology Adoption		**0.991**	**0.946**	**0.991**
Invest_4IR5IR1	0.967			
Invest_4IR5IR2	0.975			
Invest_4IR5IR3	0.969			
Educa_4IR5IR1	0.974			
Educa_4IR5IR2	0.975			
Manage_4IR5IR	0.977			
Cost of Technology Adoption		**0.946**	**0.779**	**0.947**
Cost_Adopt1	0.897			
Cost_Adopt2	0.907			
Cost_Adopt3	0.872			
Cost_Adopt4	0.875			
Cost_Adopt5	0.860			
Availability of Skilled Labour		**0.907**	**0.661**	**0.908**
Labour1	0.829			
Labour2	0.789			
Labour3	0.839			
Labour4	0.809			
Labour5	0.797			
Support for Technology Infrastructure		**0.942**	**0.764**	**0.944**
Infra1	0.861			
Infra2	0.863			
Infra3	0.880			
Infra4	0.857			
Infra5	0.909			
Increased Productivity		**0.984**	**0.927**	**0.985**
Productivity1	0.960			
Productivity2	0.964			
Productivity3	0.957			
Productivity4	0.970			
Productivity5	0.963			
Organisational Support for Upskilling		**0.933**	**0.736**	**0.934**
Org_Supp1	0.873			
Org_Supp2	0.876			
Org_Supp3	0.830			
Org_Supp4	0.874			
Org_Supp5	0.835			
Workforce Income Growth		**0.916**	**0.687**	**0.918**
W_Income1	0.808			
W_Income2	0.853			
W_Income3	0.858			
W_Income4	0.792			
W_Income5	0.831			
Promotion of Digital Commerce		**0.894**	**0.629**	**0.899**
Digi_Comm1	0.729			
Digi_Comm2	0.761			
Digi_Comm3	0.802			
Digi_Comm4	0.823			
Digi_Comm5	0.846			

The items measuring the construct *4IR/5IR Technology Adoption* demonstrate good psychometric qualities. The CR value (0.991) and AVE value (0.946) for this construct indicate that the items are reliable indicators of adopting these technologies. The factor loadings for the items relating to investment in 4IR and 5IR technologies (0.967, 0.975 and 0.969), education in 4IR and 5IR technologies (0.974 and 0.975), and management of 4IR and 5IR technologies (0.977) indicate robust reliability. The results confirm the multidimensionality of technology adoption, highlighting investment, education, and management as key facets of digital transformation.

The constructs relating to factors influencing innovation in the AMI, namely, *Availability of Skilled Labour*, *Cost of Technology Adoption*, and *Support for Technology Infrastructure*, all demonstrate high reliability and validity. In particular, the construct *Availability of Skilled Labour* (CR = 0.907, AVE = 0.661, MaxR(H) = 0.908, loadings > 0.78) reflects the precision with which labour availability is being captured. The high reliability of the constructs *Cost of Technology Adoption* (CR = 0.946, AVE = 0.779) and *Support for Technology Infrastructure* (CR = 0.942, AVE = 0.764) confirms that both financial investment and infrastructure support are key enablers of innovation in the AMI. These findings are in line with research evidence highlighting the application of human capital and infrastructure to digital transformation (Tajuddin 2025).

The constructs relating to outcomes of modernisation of the AMI, namely, *Increased Productivity*, *Organisational Support for Upskilling*, *Workforce Income Growth*, and *Promotion of Digital Commerce*, have good measurement properties. The values for the constructs *Increased Productivity* (CR = 0.984, AVE = 0.927, loadings > 0.95) and *Workforce Income Growth* (CR = 0.916, AVE = 0.687, loadings > 0.79) indicate that these concepts are measured reliably. The high reliability of the construct *Organisational Support for Upskilling* (CR = 0.933, AVE = 0.736) merits its use in the 5IR context, where human-machine cooperation is crucial. The construct *Promotion of Digital Commerce* (CR = 0.894, AVE = 0.629) is also robust, with loadings ranging from 0.729 to 0.846 indicating moderately high reliability. This construct represents the extent to which businesses are embracing and integrating digital channels and e-commerce, which is one of the key outcomes of modernisation of the AMI. The MaxR(H) values, which indicate the upper bound of reliability, are all consistent with the CR values, further validating the stability of the constructs.

The adequate reliability and validity of the scale confirms that these constructs are suitable for further structural modelling. Item factor loadings for all the constructs are satisfactory, indicating that the measurement framework is robust, well-defined, and reliable for measuring the essential dimensions relevant to the innovation impact of recent industrial revolutions on the modernisation of the AMI.

The model fitness statistics shown in Table 5.9 below provide strong evidence of goodness of fit of the observed data with the hypothesised structural model.

Table 5.9: Confirmatory factor analysis model fitness measures

Measure	Estimate	Threshold	Interpretation
χ^2	857.471	--	--
DF	751.000	--	--
$\chi^{2/DF}$	1.142	Between 1 and 3	Excellent
CFI	0.989	> 0.95	Excellent
SRMR	0.035	< 0.08	Excellent
RMSEA	0.025	< 0.06	Excellent
PClose	1.000	> 0.05	Excellent

The ratio of the chi-square index (χ^2 = 857.471) to the degrees of freedom (DF = 751) is 1.142, which is well within the acceptable range of between 1 and 3, showing low discrepancy and hence good fit for the model (Gao *et al.* 2023). The CFI (0.989) is well above the minimum threshold for excellent fit (0.95), showing that the model fits the data much better than could be expected of a baseline null model. The standardised root mean square residual (SRMR) value (0.035) is below the recommended maximum threshold of 0.08 (Hamidkholgh, Mirzaei and Nemati-Vakilabad 2025), showing low levels of residual and therefore excellent fit. Similarly, the RMSEA value (0.025) is below the maximum threshold of 0.06, further showing that the model is a close approximation of the actual figures. The PClose value (1.000), testing the null hypothesis of RMSEA ≤ 0.05, is well above the minimum threshold of 0.05 (Butt, Khan and Baig 2025), further showing the fit of the model as excellent. These indices confirm that the structural model's proposed theoretical relationships are statistically consistent with the observed data.

Table 5.10 below provides evidence of the discriminant validity of the constructs measured in the measurement model. Discriminant validity is established where each construct's square root of the AVE (diagonal elements) is greater than the correlation between it and all of the other constructs (off-diagonals), known as the Fornell-Larcker criterion (Agnes and Muthupandi 2024; Silva 2023).

Table 5.10: Discriminant validity

Variables	Commerce	4IR/5IR Adoption	Adoption Costs	Labour Availability	Increased Productivity	Infrastructure Support	Workforce Upskilling	Workforce Income
Commerce	**0.793**							
4IR/5IR Adoption	0.364	**0.973**						
Adoption Costs	-0.095	-0.372	**0.882**					
Labour Availability	0.266	0.255	0.004	**0.813**				
Increased Productivity	0.331	0.428	-0.213	0.299	**0.963**			
Infrastructure Support	0.281	0.292	-0.010	0.004	0.265	**0.874**		
Workforce Upskilling	0.441	0.594	-0.299	0.319	0.428	0.283	**0.858**	
Workforce Income	0.380	0.527	-0.288	0.198	0.379	0.429	0.526	**0.829**

All the constructs in the model meet the Fornell-Larcker test. For example, the square root of the AVE for the construct *4IR/5IR Adoption* (0.973) is greater than its correlations with other constructs, such as *Workforce Upskilling* (r = 0.594), *Workforce Income* (r = 0.527), and *Increased Productivity* (r = 0.428). Similarly, the square root of the AVE for the construct *Workforce Upskilling* (0.858) is greater than its correlations with other constructs, such as *Workforce Income* (r = 0.526) and *Infrastructure Support* (r = 0.283). The discriminant validity of the construct *Adoption Costs*, with a square root of AVE (0.882) greater than its correlations with all other constructs in the model, including *Increased Productivity* (r = -0.213) and *Workforce Upskilling* (r = -0.299), supports the conclusion that cost perceptions are empirically different from constructs of performance and capability.

The matrix establishes that each construct represents a distinctive aspect of the overall landscape of digital transformation and labour dynamics in the South African AMI. The separateness of the constructs lends support to the validity of the measuring model and provides a solid basis for further structural modelling and testing of hypotheses.

The final measurement model, as shown in the structural equation graph in Figure 5.2 below, clearly illustrates the latent constructs and the observed indicators with standardised factor loadings, inter-construct relationships, and evidence of the model's adequacy. The latent constructs are measured with several indicators, and most of the factor loadings are well above the threshold of 0.50, indicating strong construct-to-item relationships (Razali 2023).

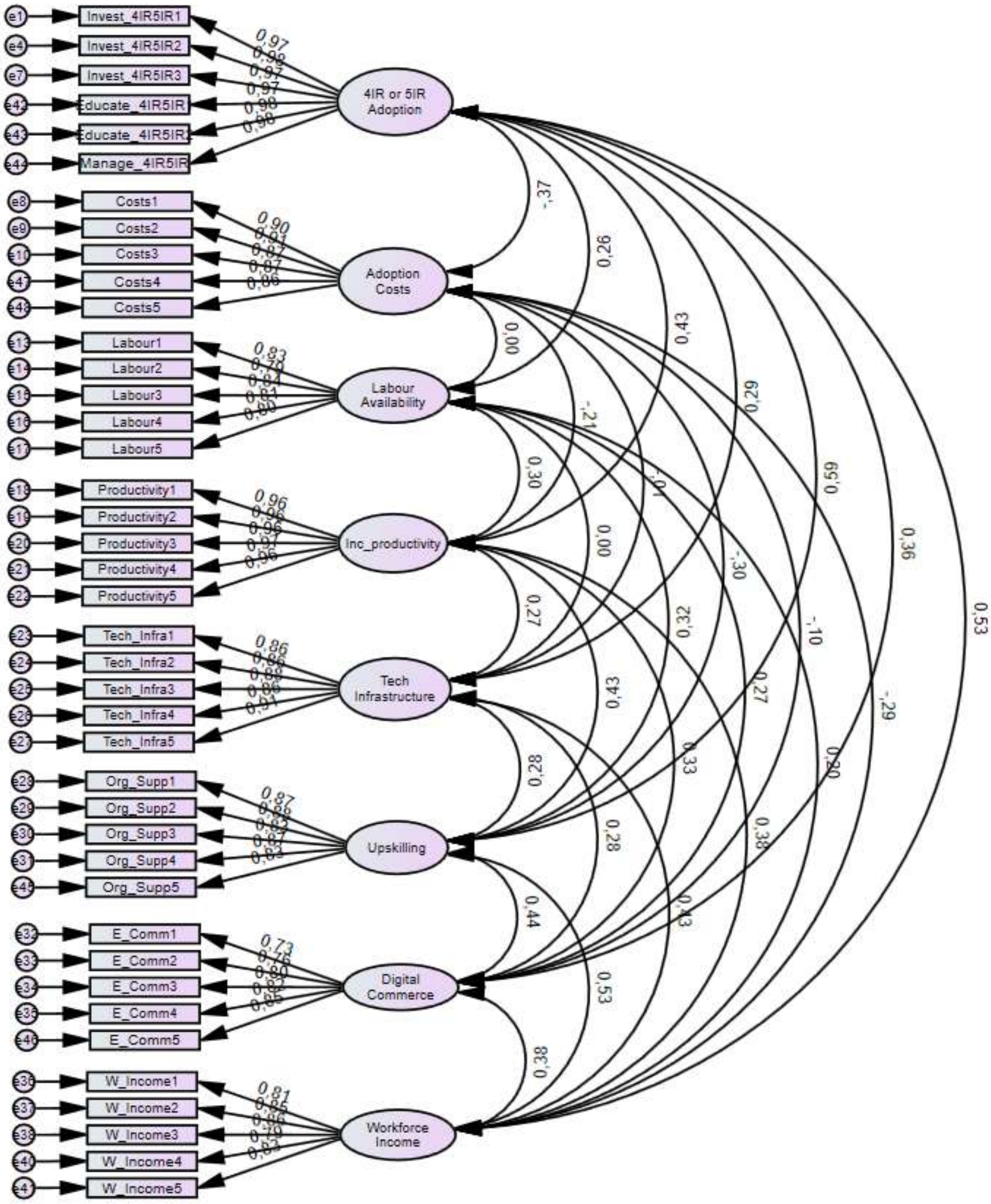

Figure 5.2: Final measurement model

5.3.6 *Hypothesis testing*

The model fitness statistics shown in Table 5.11 below provide strong evidence of goodness of fit of the observed data with the hypothesised structural model.

Table 5.11: Model fit indices for direct relationship structural model

Measure	Estimate	Threshold	Interpretation
χ^2	711.639	--	--
DF	548.000	--	--
$\chi^{2/DF}$	1.299	Between 1 and 3	Excellent
CFI	0.977	> 0.95	Excellent
SRMR	0.073	< 0.08	Excellent
RMSEA	0.037	< 0.06	Excellent
PClose	0.999	> 0.05	Excellent

The ratio of the chi-square index (χ^2 = 711.639) to the degrees of freedom (DF = 548) is 1.299, which is well within the acceptable range of between 1 and 3, showing low discrepancy and hence good fit for the model. The CFI (0.977) is above the minimum threshold for excellent fit (0.95), showing that the model fits the data much better than could be expected of a baseline null model (Hu and Bentler 1999). The SRMR value (0.073) is well below the maximum threshold of 0.08, showing low levels of residual and thus excellent fit. The RMSEA value (0.037) is below the maximum threshold for excellent fit (0.06). According to MacCallum, Browne and Sugawara (1996), an RMSEA value of between 0.05 and 0.08 indicates that a model adequately represents the population covariance matrix. The PClose value (0.999) is greater than 0.05, indicating that the model's fit is not significantly different from a close fit. These indices confirm that the structural model's proposed theoretical relationships are statistically consistent with the observed data.

5.3.6.1 *Direct effects between adoption drivers and modernisation outcomes*

Hypothesis testing was conducted using SEM with unstandardised regression weights, as shown in Table 5.12 below, which detected several statistically significant paths of direct relationships between factors influencing innovation in the AMI and outcomes of modernisation of the AMI.

Table 5.12: Direct effects between adoption drivers and modernisation outcomes

Path			Hypothesis	Path coefficient (β)	t Values	P Values	Validity
Productivity	<---	**Adoption costs**	H1	-0.448	-3.662	***	Yes
Upskilling	<---	**Adoption costs**	H2	-0.303	-4.823	***	Yes
Workforce income	<---	**Adoption costs**	H3	-0.242	-4.576	***	Yes
E-Commerce	<---	**Adoption costs**	H4	-0.072	-1.524	0.127	No
Productivity	<---	**Labour**	H5	0.783	4.520	***	Yes
Upskilling	<---	**Labour**	H6	0.460	5.167	***	Yes
Workforce income	<---	**Labour**	H7	0.250	3.444	***	Yes
E-Commerce	<---	**Labour**	H8	0.273	3.957	***	Yes
Productivity	<---	**Infrastructure**	H9	0.501	4.882	***	Yes
Upskilling	<---	**Infrastructure**	H10	0.246	4.730	***	Yes
Workforce income	<---	**Infrastructure**	H11	0.307	6.693	***	Yes
E-Commerce	<---	**Infrastructure**	H12	0.175	4.246	***	Yes
Path significance: *** p < 0.001							

H1: There is a relationship between the cost of technology adoption and increased productivity.

The cost of technology adoption has a negative and significant relationship with increased productivity ($\beta = -0.448$, $t = -3.662$, $p < 0.001$). This suggests that higher perceived costs of 4IR and 5IR technology adoption significantly reduce productivity outcomes. Therefore, H1 is accepted.

H2: There is a relationship between the cost of technology adoption and organisational support for upskilling.

The cost of technology adoption has a negative relationship with organisational support for upskilling ($\beta = -0.303$, $t = -4.823$, $p < 0.001$). Therefore, H2 is accepted. This suggests that technology adoption costs hinder workforce upskilling and reskilling programmes in the AMI.

H3: There is a relationship between the cost of technology adoption and workforce income growth.

The cost of technology adoption has a negative relationship with workforce income growth ($\beta = -0.242$, $t = -4.576$, $p < 0.001$). Therefore, H3 is accepted. This suggests that technology adoption costs directly reduce workers' income.

H4: There is a relationship between the cost of technology adoption and the promotion of digital commerce.

The cost of technology adoption has no relationship with the promotion of digital commerce ($\beta = -0.072$, $t = -1.524$, $p = 0.127$). Therefore, H4 is rejected. The negative path coefficient demonstrates that technology adoption costs can hinder the adoption and promotion of digital commerce in the AMI, especially for component manufacturers outside urban areas.

H5: There is a relationship between the availability of skilled labour and increased productivity.

The availability of skilled labour has a highly significant ($\beta = 0.783$, $t = 4.520$, $p < 0.001$) and strong positive relationship with increased productivity, which suggests that the availability of skilled labour boosts productivity. Therefore, H5 is accepted.

H6: There is a relationship between the availability of skilled labour and organisational support for upskilling.

The availability of skilled labour has a positive relationship with organisational support for upskilling ($\beta = 0.460$, $t = 5.167$, $p < 0.001$). Therefore, H6 is accepted. This suggests that a skilled workforce is more likely to engage in continuous learning supported by organisations in the AMI.

H7: There is a relationship between the availability of skilled labour and workforce income growth.

The availability of skilled labour has a positive relationship with workforce income growth ($\beta = 0.250$, $t = 3.444$, $p < 0.001$), suggesting that skills have an impact on income growth. Therefore, H7 is accepted.

H8: There is a relationship between the availability of skilled labour and the promotion of digital commerce.

The availability of skilled labour has a significant and positive relationship with the promotion of digital commerce ($\beta = 0.273$, $t = 3.957$, $p < 0.001$), suggesting that skilled labour plays a crucial role in promoting digital commerce. Therefore, H8 is accepted.

H9: There is a relationship between support for technology infrastructure and increased productivity.

Support for technological infrastructure has a positive relationship with increased productivity ($\beta = 0.501$, $t = 4.882$, $p < 0.001$), indicating that infrastructure does drive productivity. Therefore, H9 is accepted.

H10: There is a relationship between support for technology infrastructure and organisational support for upskilling.

Support for technology infrastructure has a positive direct relationship with organisational support for upskilling ($\beta = 0.246$, $t = 4.730$, $p < 0.001$). Therefore, H10 is accepted. This suggests that in the AMI, organisational support for infrastructure drives decisions regarding training and that infrastructure that is not adequately supported remains underutilised.

H11: There is a relationship between support for technology infrastructure and workforce income growth.

Support for technology infrastructure has a positive direct relationship with workforce income growth ($\beta = 0.307$, $t = 6.693$, $p < 0.001$. Therefore, H11 is accepted. This suggests that infrastructure has an impact on the income of workers by translating technology access into income growth.

H12: There is a relationship between support for technology infrastructure and the promotion of digital commerce.

Support for technology infrastructure has a positive direct relationship with promotion of digital commerce ($\beta = 0.175$, $t = 4.246$, $p < 0.001$), although with a lower coefficient. Therefore, H12 is accepted. This suggests that infrastructure plays an essential role in enabling digital transformation and economic advancement.

5.3.6.2 Indirect effects through investment, education, and management

The three mediating variables, namely, investment in 4IR and 5IR technologies, education in 4IR and 5IR technologies, and management of 4IR and 5IR technologies, reflect the factors influencing the adoption of 4IR and 5IR technologies. Investment in 4IR and 5IR technologies is made up of the items *Invest_4IR5IR1*, *Invest_4IR5IR2*, and *Invest_4IR5IR3*; education in 4IR and 5IR technologies is made up of the items *Educa_4IR5IR1* and *Educa_4IR5IR2*; and management of 4IR and 5IR technologies is made up of the item *Manage_4IR5IR*. These items have been categorised in this manner to reflect that the adoption of 4IR and 5IR technologies in the AMI should not be considered as a single phenomenon but as related areas of competence. These include financial commitment to technologies (investment in 4IR and 5IR technologies), human capital development (education in 4IR and 5IR technologies), and the planning and implementation of strategy and change (management of 4IR and 5IR technologies). It is theoretically supported and methodologically beneficial to examine these areas separately, rather than combining them into the same composite measure of adoption, in order to achieve alignment with existing theories with respect to technology adoption, an increase in the credibility of the measure, and the ability to detect previously latent mediating and moderating variables (Kamble, Gunasekaran and Gawankar 2018; Xu, Xu and Li 2018).

According to the RBV and the TOE framework, adopting innovation processes depends on diverse non-transferable sets of capabilities and resources. Financial investment determines the breadth and depth of technologies, such as CPS, IoT, and AI, that a firm can acquire and integrate (Xu, Xu and Li 2018). The implementation and successive augmentation of such resources depend on educational aspects, including skills, training, and digital literacy, as well as on a firm's absorptive capacity to learn and assimilate technology into everyday business operations (Benešová and Tupa 2017; Schwab and Davis 2018). With support from upper and mid-level management, leadership is responsible for enabling digital integration through strategic alignment, process redesign, and change management, ultimately determining whether the adoption of particular technologies leads to disruptive innovation or only to incremental efficiency improvements (Sony and Naik 2020). This study's proposed theoretical framework reveals that the investment, education, and management domains function through different causal pathways, both direct and indirect, thereby substantiating their representation as different latent variables.

Adoption is operationalised in a growing body of empirical studies as a system of constructs rather than a single component. The evidence from case studies is that stronger transitions are achieved in ecologies with institutionalised development of management practices, cooperative relationships with education providers, and access to faculty-led experimentation environments (Hearn *et al.* 2023). Sony and Naik (2020) describe digital leadership and socio-technical integration as separate capabilities that arbitrate the link between technology and performance. By employing a large-scale automotive dataset, Rehman *et al.* (2024) articulate resource-based managerial initiatives alongside IoT and blockchain technology adoption, proposing that risk tolerance acts as a moderator of the resilience-performance relationship, while organisational resilience acts as a mediator of effects impacting innovation performance. By employing a TOE-based framework to distinguish top management support and technological variables, Zhong and Moon (2023) illustrate that adoption has a direct, positive impact on firm performance through product and process innovation, recognising a mediation chain that would collapse if only one adoption score were adopted. To illuminate outcomes of product and service performance, Aitzhanova *et al.* (2024) utilised SEM among SMEs to envision diverse aspects of readiness, strategy and organisation, workforce development, and smart factory implementation; the study recognised organisational structure, strategy, and strategy formulation as critical levers rather than as simple indicators of technological outlay.

This study used bootstrapping with 5 000 resamples in Amos to assess the significance of the indirect effect in support of the mediation hypothesis. Unlike more conventional approaches such as the Sobel test, bootstrapping is highly recommended in the case of SEM because it is not dependent on the assumption of normality of the indirect effects and does not rely on large-sample theory, making it suitable for the non-normal distributions common in psychological and social science data (Cheung and Lau 2008; Sathyanarayana and Mohanasundaram 2025) and providing higher estimation precision. Bias-corrected bootstrapped confidence intervals, which offer superior precision and statistical power under mediation analyses, particularly in non-normality scenarios, have been prominently highlighted in recent methodological meta-analyses (Li *et al.* 2023). Additionally, bootstrap maximum likelihood estimation (MLE) was used to carry out mediation testing. MLE, Amos's default estimation strategy, is commonly used in SEM as it is efficient and unbiased in estimating parameters for large and medium sample sizes. However, MLE does require multivariate normality, an assumption which is not necessarily met by real-world data, especially in the social sciences. Bootstrapping overcomes this limitation by resampling the observed data to provide empirical standard errors and confidence intervals, which are free from distributional assumptions (Ferraz 2020; Mokhtar, Yusof and Sapiri 2023). Together, these approaches ensure valid estimation of mediation effects and provide stronger inferential support for indirect pathways in SEM.

H13-H24: Indirect effects of technology adoption costs on the modernisation of the AMI via 4IR and 5IR investment, education, and management

As shown in Table 5.13 below, the study tested twelve hypotheses (H13 to H24) to examine indirect effects of technology adoption costs on four main modernisation outcomes (increased productivity, organisational support for upskilling, workforce income growth, and promotion of digital commerce) via three mediating channels (investment in 4IR and 5IR technologies, education in 4IR and 5IR technologies, and management of 4IR and 5IR technologies). All indirect routes are statistically significant ($p < 0.001$) according to bootstrapped confidence intervals ($N = 221$, bootstrap sample = 5000).

Table 5.13: Indirect effects of adoption costs through investment, education, and management

Path	Hypothesis	β	SE	95% CI indirect effect		
				LL 95% CI	UL 95% CI	P Value
Adoption costs → Investment → Productivity	H13	-0.304	0.066	-0.452	-0.188	***
Adoption costs → Investment → Upskilling	H14	-0.205	0.042	-0.294	-0.129	***
Adoption costs → Investment → Income	H15	-0.151	0.033	-0.228	-0.095	***
Adoption costs → Investment → E-commerce	H16	-0.101	0.027	-0.164	-0.056	***
Adoption costs → Education → Productivity	H17	-0.298	0.065	-0.447	-0.187	***
Adoption costs → Education → Upskilling	H18	-0.209	0.041	-0.300	-0.136	***
Adoption costs → Education → Income	H19	-0.154	0.032	-0.228	-0.099	***
Adoption costs → Education → E-commerce	H20	-0.099	0.026	-0.160	-0.055	***
Adoption costs → Management → Productivity	H21	-0.292	0.065	-0.437	-0.181	***
Adoption costs → Management → Upskilling	H22	-0.193	0.039	-0.279	-0.123	***
Adoption costs → Management → Income	H23	-0.145	0.032	-0.218	-0.090	***
Adoption costs → Management → E-commerce	H24	-0.094	0.025	-0.152	-0.053	***

Bootstrap sample size = 5000; LL, lower limit; UL, upper limit; CI, confidence interval
*** p<0.001

The investment pathways show significant negative indirect effects of adoption costs on all modernisation outcomes. In particular, the result for H13 demonstrates that costs have a negative impact on productivity via investment (β = -0.304, SE = 0.066, 95% CI [-0.452, -0.188]). The results for H14 to H16 reveal similar effects on upskilling (β = -0.205), income (β = -0.151), and e-commerce (β = -0.101). Adoption costs do not affect e-commerce directly but do negatively affect e-commerce via investment. These results imply that high perceived costs limit the results of modernisation by decreasing the chance of strategic investment in cutting-edge technologies.

The education pathways also show significant negative indirect effects of adoption costs on modernisation outcomes. The results for H17 to H20 indicate that costs have a negative effect on productivity (β = -0.298), upskilling (β = -0.209), income (β = -0.154), and e-commerce (β = -0.099) through reduced education participation. Adoption costs do not affect e-commerce directly but do have a modest negative effect on e-commerce via education. This suggests that when costs are perceived to be high, companies tend to underinvest in education and training interventions that are foundational to workforce readiness and digital transformation.

The management pathways also show significant negative indirect effects of adoption costs on modernisation outcomes. The results for H21 to H24 show that costs have a negative influence on productivity (β = -0.292), upskilling (β = -0.193), income (β =

-0.145), and e-commerce (β = -0.094) through reduced management support for the adoption of 4IR and 5IR technologies. Again, e-commerce is impacted by adoption costs via management of 4IR and 5IR technologies. These findings demonstrate the crucial role of change management and strategic leadership in reducing the negative effects of costs on modernisation.

H25-H36: Indirect effects of labour availability on the modernisation of the AMI via 4IR and 5IR investment, education, and management

As shown in Table 5.14 below, the study tested twelve hypotheses (H25 to H36) to capture the indirect impacts of labour availability on the four main modernisation outcomes (increased productivity, organisational support for upskilling, workforce income growth, and promotion of digital commerce) via three mediating factors (investment in 4IR and 5IR technologies, education in 4IR and 5IR technologies, and management of 4IR and 5IR technologies). All indirect channels are statistically significant ($p < 0.001$), showing the robustness of the mediation impacts.

Table 5.14: Indirect effects of labour availability through investment, education, and management

Path	Hypothesis	β	SE	95% CI indirect effect		
				LL 95% CI	UL 95% CI	P Value
Labour → Investment → Productivity	H25	0.273	0.085	0.124	0.457	***
Labour → Investment → Upskilling	H26	0.190	0.054	0.084	0.297	***
Labour → Investment → Income	H27	0.149	0.044	0.071	0.244	***
Labour → Investment → E-commerce	H28	0.080	0.026	0.039	0.142	***
Labour → Education → Productivity	H29	0.268	0.084	0.120	0.445	***
Labour → Education → Upskilling	H30	0.192	0.056	0.084	0.303	0.001
Labour → Education → Income	H31	0.150	0.045	0.070	0.247	***
Labour → Education → E-commerce	H32	0.078	0.025	0.037	0.139	***
Labour → Management → Productivity	H33	0.250	0.082	0.104	0.426	0.001
Labour → Management → Upskilling	H34	0.170	0.052	0.070	0.275	0.001
Labour → Management → Income	H35	0.135	0.042	0.058	0.228	0.001
Labour → Management → E-commerce	H36	0.070	0.024	0.032	0.128	0.001
Bootstrap sample size = 5000; LL, lower limit; UL, upper limit; CI, confidence interval *** p< 0.001						

The results for H25 to H28 show that labour availability indirectly boosts productivity (β = 0.273), upskilling (β = 0.190), income (β = 0.149), and e-commerce (β = 0.080) through investment. The results for H29 to H32 show that labour availability indirectly boosts productivity (β = 0.268), upskilling (β = 0.192), income (β = 0.150), and e-commerce (β = 0.078) through education, further validating the mediating function of workforce development. This emphasises the crucial role of the knowledge-building and training processes in converting labour capability into modernisation. Similarly, the management pathways show positive mediation impacts. The results for H33 to H36 show that labour availability has indirect positive impacts on productivity (β = 0.250), upskilling (β = 0.170), income (β = 0.135), and e-commerce (β = 0.070) through improved management of 4IR- and 5IR-related changes. These results highlight the importance of strategic leadership in leveraging human capital to drive economic progress.

H37-H48: Indirect effects of infrastructure support on the modernisation of the AMI via 4IR and 5IR investment, education, and management

As shown in Table 5.15 below, twelve hypotheses (H37 to H48) were tested to identify indirect effects of infrastructure support on the main outcomes of modernisation (productivity, upskilling, workforce income, and digital commerce promotion). The strength and validity of these mediators were confirmed by the significance of all indirect effects ($p < 0.001$).

Table 5.15: Indirect effects of technology infrastructure through investment, education, and management

Path	Hypothesis	β	SE	95% CI indirect effect		
				LL 95% CI	UL 95% CI	P Value
Infrastructure → Investment → Productivity	H37	0.185	0.049	0.105	0.304	***
Infrastructure → Investment → Upskilling	H38	0.134	0.033	0.074	0.205	***
Infrastructure → Investment → Income	H39	0.088	0.024	0.049	0.143	***
Infrastructure → Investment → E-commerce	H40	0.053	0.017	0.026	0.096	***
Infrastructure → Education → Productivity	H41	0.178	0.049	0.100	0.292	***
Infrastructure → Education → Upskilling	H42	0.133	0.033	0.074	0.206	***
Infrastructure → Education → Income	H43	0.089	0.024	0.049	0.144	***
Infrastructure → Education → E-commerce	H44	0.051	0.017	0.025	0.093	***
Infrastructure → Management → Productivity	H45	0.178	0.048	0.100	0.289	***
Infrastructure → Management → Upskilling	H46	0.126	0.032	0.069	0.195	***
Infrastructure → Management → Income	H47	0.085	0.023	0.046	0.138	***
Infrastructure → Management → E-commerce	H48	0.049	0.016	0.023	0.090	***
Bootstrap sample size = 5000; LL, lower limit; UL, upper limit; CI, confidence interval *** $p < 0.001$						

An analysis of the investment pathways shows that increasing technical investment considerably improves modernisation outcomes via infrastructure support.

Specifically, the results for H37 to H40 show positive indirect effects on productivity (β = 0.185), upskilling (β = 0.134), income (β = 0.088), and e-commerce (β = 0.053). These results suggest that institutions are more likely to invest in advanced technologies when they have a strong infrastructure, consequently enhancing performance and digital interactions.

The education pathways also show strong mediation impacts. The results for H41 to H44 show that infrastructure support has indirect impacts on productivity (β = 0.178), upskilling (β = 0.133), income (β = 0.089), and e-commerce (β = 0.051) through improved educational initiatives. These results highlight the vital role of infrastructure in improving access to knowledge exchange and training platforms that are crucial for workforce preparation and nurturing innovation.

Similarly, the management pathways show positive mediation impacts. The results for H45 to H48 show that infrastructure support has indirect effects on productivity (β = 0.178), upskilling (β = 0.126), income (β = 0.085), and e-commerce (β = 0.049) through increased managerial involvement in 4IR and 5IR transformation. These results highlight the role of infrastructure as a strategic pillar facilitating organisational transformation and leadership rather than merely a physical enabler.

5.3.7 Structural equation modelling

The postulated structural model is informed by a multi-theoretical framework that documents relationships between support, skills, income, innovation, productivity, costs, and modernisation. The relationship between institutional support and productivity, income, and skills is informed by the RBV and the HCT, both of which propose that availability of resources, including learning opportunities, boosts both organisational and individual performance (Barney 1991; Becker 1962). Additionally, social support theory and economic empowerment theory propose that institutional support structures translate into favourable economic outcomes as well as skills development through the building of capacity and adult learning mechanisms (Sen 1999; Vaux 1988). The postulated relationship between skills and productivity is stressed within the HCT, whereas the relationship between skills and modernisation is informed by the Kolb's Experiential Learning Theory, emphasising that skills, both soft (communication, leadership) and hard (technical competencies), are acquired through cycles of experience, reflection, conceptualisation, and experimentation, and that this process is essential for adapting to modern, dynamic environments (Rogers 2003; Kolb 2014).

The postulation that income is a significant contributor to innovation, modernisation, and costs is informed by Schumpeterian growth theory, which posits that high income contributes to investing in innovative activities (Schumpeter 1934), as well as modernisation theory, which attributes economic progress to both technological and social transformation (Inglehart and Baker 2000). The relationship between income and costs can be further explained using cost-benefit analysis theory and the principle of diseconomies of scale, which posits that growing income can lead to high operational costs due to business growth (Samuelson and Nordhaus 2009).

By incorporating costs as variables that affect skill and innovation, the model aligns with the principles of innovation economics and the investment theory of intelligence, both of which maintain that monetary investment is essential for stimulating skills development and innovation (Horn and Cattell 1966; Vivona, Demircioglu and Audretsch 2022). The link between productivity and income is supported by labour economics theory, which holds that increased productivity leads to higher earnings (Pyo 2018). The link between income and costs is supported by cost theory, which posits that rising income will lead to increased expenditure due to expansion and increased complexity (McCaffrey 2017).

The model's incorporation of innovation as the driver of productivity is supported by Schumpeterian innovation theory, endogenous growth theory, and the DCT, all of which highlight innovation as the driver of efficiency and sustained performance (Hall 2011; Mairesse, Mohnen and Notten 2025; Teece 2007). The development from innovation through to modernisation is supported by various theories including the RBV, TOE and DCT, arguing that innovation is necessary but not sufficient for modernisation; it requires dynamic capabilities, resource orchestration, socio-technical alignment, and supportive infrastructure. Overall, the theoretical underpinnings validate the proposed pathways and undergird the development of a comprehensive SEM model focused on understanding innovation-driven productivity in institutional contexts.

The model fitness statistics shown in Table 5.16 below provide strong evidence of goodness of fit of the observed data with the hypothesised structural model.

Table 5.16: Overall SEM model fit indices

Measure	Estimate	Threshold	Interpretation
χ^2	685.165	--	--
DF	548.000	--	--
$\chi^{2/DF}$	1.250	Between 1 and 3	Excellent
CFI	0.980	> 0.95	Excellent
SRMR	0.073	< 0.08	Excellent
RMSEA	0.034	< 0.06	Excellent
PClose	1.000	> 0.05	Excellent

The ratio of the chi-square index (χ^2 = 685.165) to the degrees of freedom (DF = 548) is 1.250, which is well within the acceptable range of between 1 and 3, showing low discrepancy and hence good fit for the model (Gao *et al.* 2023). The CFI (0.980) is well above the minimum threshold for excellent fit (0.95), showing that the model fits the data much better than could be expected of a baseline null model. The SRMR value (0.073) is below the maximum threshold of 0.08 (Hamidkholgh, Mirzaei and Nemati-Vakilabad 2025), showing low levels of residual and therefore excellent fit. Similarly, the RMSEA (0.034) is below the maximum threshold of 0.06, further showing that the fit of the model is close to actual figures. The PClose value (1.000), testing the null hypothesis of RMSEA ≤ 0.05, is well above the minimum threshold of 0.05 (Butt, Khan and Baig 2025), further showing the fit of the model as excellent. These indices confirm that the structural model's proposed theoretical relationships are statistically consistent with the observed data.

Organisational support is conceptualised as a multidimensional construct encompassing organisational resources, training, mentorship, and policy frameworks. The SEM results shown in Table 5.17 below indicate that organisational support significantly predicts productivity (β = 0.543, $p < 0.001$), workforce income (β = 0.414, $p < 0.001$), skills (β = 0.244, $p < 0.001$), and modernisation (β = 0.242, $p < 0.001$). Skills development, as a function of organisational support, significantly predicts productivity (β = 0.491, p = 0.004) and modernisation (β = 0.145, p = 0.028), thereby justifying human capital as a key output determinant. Workforce income, another capability outcome, significantly predicts innovation ($\beta = 0.618$, $p < 0.001$). Innovation significantly predicts productivity ($\beta = 0.399$, $p < 0.001$) and modernisation ($\beta = 0.125$, $p = 0.005$). These paths suggest that innovation facilitates modernisation and increases productivity.

Table 5.17: Structural relationships in the final SEM model

Paths			Path Coefficient (β)	S.E.	t Value	P Value
Income	<---	Organisational support	0.414	0.058	7.115	***
Income	<---	Adoption costs	-0.117	0.048	-2.444	0.015
Innovation	<---	Workforce income	0.618	0.097	6.389	***
Innovation	<---	Adoption costs	0.122	0.066	1.847	0.065
Skill	<---	Organisational support	0.244	0.055	4.442	***
Product	<---	Skill	0.491	0.171	2.864	0.004
Modernisation	<---	Skill	0.145	0.066	2.192	0.028
Product	<---	Organisational support	0.543	0.133	4.081	***
Modernisation	<---	Organisational support	0.242	0.053	4.529	***
Product	<---	Innovation	0.399	0.113	3.527	***
Modernisation	<---	Innovation	0.125	0.044	2.836	0.005
Product	<---	Adoption costs	-0.259	0.109	-2.389	0.017
Tech_Infra1	<---	Innovation	1.000			
Tech_Infra2	<---	Innovation	1.076	0.064	16.906	***
Tech_Infra3	<---	Innovation	1.067	0.061	17.565	***
Tech_Infra4	<---	Innovation	0.975	0.058	16.770	***
Tech_Infra5	<---	Innovation	1.103	0.059	18.721	***
Labour1	<---	Skill	1.000			
Labour2	<---	Skill	1.037	0.078	13.316	***
Labour3	<---	Skill	0.979	0.067	14.601	***
Labour4	<---	Skill	1.039	0.075	13.887	***
Labour5	<---	Skill	0.976	0.072	13.541	***
Costs1	<---	Adoption costs	1.000			
Costs2	<---	Adoption costs	0.995	0.048	20.946	***
Costs3	<---	Adoption costs	0.936	0.049	19.112	***
Costs4	<---	Adoption costs	0.954	0.050	19.146	***
Costs5	<---	Adoption costs	0.915	0.050	18.455	***
E_Comm1	<---	Modernisation	1.000			
E_Comm2	<---	Modernisation	1.080	0.099	10.908	***
E_Comm3	<---	Modernisation	1.115	0.097	11.510	***
E_Comm4	<---	Modernisation	1.228	0.104	11.782	***
E_Comm5	<---	Modernisation	1.165	0.096	12.074	***
Product1	<---	Productivity	1.000			
Product2	<---	Productivity	0.991	0.030	33.374	***
Product3	<---	Productivity	0.956	0.030	31.421	***
Product4	<---	Productivity	0.981	0.029	33.769	***
Product5	<---	Productivity	0.987	0.031	32.266	***
W_Income1	<---	Workforce income	1.000			
W_Income2	<---	Workforce income	1.029	0.072	14.326	***
W_Income3	<---	Workforce income	1.049	0.073	14.408	***
W_Income4	<---	Workforce income	0.931	0.072	12.880	***
W_Income5	<---	Workforce income	1.019	0.074	13.775	***
Org_Supp1	<---	Organisational support	1.000			
Org_Supp2	<---	Organisational support	1.043	0.058	17.912	***
Org_Supp3	<---	Organisational support	1.019	0.063	16.120	***
Org_Supp4	<---	Organisational support	1.056	0.059	17.908	***
Org_Supp5	<---	Organisational support	0.982	0.060	16.334	***

*** $p < 0.001$

The model reveals a notable negative relationship between adoption costs and workforce income ($\beta = -0.117$, $p = 0.015$) as well as between adoption costs and productivity ($\beta = -0.259$, $p = 0.017$), suggesting that rising costs negatively affect both income and productivity, with productivity experiencing a stronger negative impact. Adoption costs are shown to have a marginally significant positive effect on innovation ($\beta = 0.122$, $p = 0.065$). This suggests that higher costs may encourage firms to pursue innovation as a means of offsetting resource pressures and improving efficiency. For the path showing the impact of organisational support on productivity, indirect effects were observed through income enabling innovation and skills, suggesting that there might be mediation.

5.4 Chapter summary

This chapter has presented, interpreted, and analysed the results of the study. The chapter began by presenting the descriptive statistics of the dataset. The results of the analysis of the data measuring the innovation impact of 4IR and 5IR technology adoption on the modernisation of the AMI were then presented. This included analysis of the demographic data, EFA, reliability analysis, correlation analysis, CFA, hypothesis testing, and SEM.

The next chapter discusses these results, compares them with existing literature and examines the implications of the results for the AMI.

CHAPTER SIX

DISCUSSION OF RESULTS

6.1 Introduction

This chapter contextualises the empirical findings by comparing them with established literature and highlighting their theoretical and practical implications. This is followed by a discussion of the results in relation to the AMI, particularly in the South African context, and an examination of the study's novel contributions to literature. Thereafter, the chapter examines the implications of the results for the AMI. The chapter concludes with a summary.

6.2 Interpretation of the results and comparison with existing literature

The AMI is undergoing a seismic shift through the convergence of digital technology, automation, and human-centric innovation encapsulated in the 4IR and 5IR paradigms. The empirical evidence in this study provides contextualised insight into the experience and application of these technological shifts within the context of the South African AMI. The respondents comprise senior managers with direct responsibilities for strategic technology decisions, making their insights highly relevant to the study. This is reflected in the literature that identifies leadership and managerial competence as drivers of digital manufacturing transformation (Malik *et al.* 2024).

6.2.1 Factor analysis results

Factor analysis in this study provides a firm foundation for the establishment of the latent constructs influencing innovation and outcomes of modernisation in the South African AMI. The analysis not only validates the measurement model but also presents evidence complementary to and consistent with previous literature on industrial transformation, particularly in emerging economies.

6.2.1.1 Suitability for factor analysis and dimension reduction

The KMO value (0.922) and the significant result of Bartlett's sphericity test (χ^2 = 10222.702, $p < 0.001$) confirm the suitability of the sample for factor analysis. These results meet the factorability conditions as stated by Williams, Onsman and Brown (2021), indicating that the correlation in the data matrix is sufficient to justify the use of PCA. Extraction of eight components with eigenvalues greater than one and a cumulative variance explanation of approximately 82% suggests high information retention and efficient dimension reduction. This is particularly important in social science studies, where constructs are complex and multifaceted (Holm, Jann and Karlson 2025).

6.2.1.2 Exploratory factor structure and construct validity

The rotated component matrix presents an understandable and interpretable factor structure, with each of the eight components measuring a distinct conceptual domain. The first component, representing 4IR and 5IR technology adoption, consists of seven items with relatively high loadings (ranging from 0.878 to 0.890). These items reflect the application of global 4IR technologies, as well as human-centred and sustainability-oriented innovations, in manufacturing (Alves, Lima and Gaspar 2023; Fanoro, Božanić and Sinha 2021). This construct forms the core of the automotive industry's technology trajectory, particularly in South Africa, where there is a desire to harmonise global competitiveness with local socioeconomic imperatives (South Africa, Department of Trade, Industry and Competition 2019).

The remaining factors, namely, skilled labour availability, increased productivity, promotion of digital commerce, organisational support for upskilling, workforce income growth, support for technology infrastructure, and cost of technology adoption, also possess high internal consistency and conceptual distinctness.

6.2.1.3 Confirmatory factor analysis and measurement model fit

The measurement model is further validated by the CFA, in which all constructs show CR values above the minimum threshold of 0.70 and AVE values above the minimum threshold of 0.50 (Baharum *et al.* 2023). All of the constructs demonstrate excellent psychometric properties, with CR values ranging from 0.894 to 0.991, AVE values ranging from 0.629 to 0.946, and MaxR(H) values ranging from 0.899 to 0.991.

The model fitness statistics provide strong evidence of the goodness of fit of the structural model. The ratio of the chi-square index to the degrees of freedom ($\chi^{2/DF}$ = 1.142), the CFI (0.989), the SRMR value (0.035), and the RMSEA value (0.025) were all in the acceptable or excellent range (Gao *et al.* 2023; Hamidkholgh, Mirzaei and Nemati-Vakilabad 2025). The PClose value (1.000) also indicates a close fit of the model. These results indicate the proposed measurement model to be theoretically meaningful as well as statistically valid.

6.2.1.4 Discriminant validity and construct independence

Discriminant validity is confirmed by the Fornell-Larcker criterion, where the square root of every construct's AVE is greater than its correlation with other constructs. All the constructs in the model meet the Fornell-Larcker test. For example, the square root of the AVE of *4IR/5IR Technology Adoption* is 0.973, which is greater than its correlations with other constructs, such as *Organisational Support for Upskilling* (r = 0.594), *Workforce Income Growth* (r = 0.527), and *Increased Productivity* (r = 0.428). Similarly, the square root of the AVE of *Organisational Support for Upskilling* is 0.858, which is greater than its correlations with other constructs, such as *Workforce Income Growth* (r = 0.526) and *Technology Infrastructure Support* (r = 0.283). The matrix establishes that each of the constructs represents a distinctive aspect of the overall landscape of digital transformation and labour dynamics in the South African AMI.

6.2.2 Reliability analysis results

Reliability analysis is a core step in ensuring the internal consistency of measurement tools in empirical studies. In this study, which examines the innovation impact of recent industrial revolution technology adoption on the modernisation of the AMI, construct reliability is pivotal in ensuring the strength of follow-up statistical tests. The results show excellent levels of reliability for the majority of constructs, with Cronbach's alpha levels being well above the generally recommended threshold of 0.70 (Karakaya and Alparslan 2022), indicating that the measurement tools used in the study are consistent and reliable in measuring the desired latent variables.

The Cronbach's alpha scores for almost all of the constructs exceed 0.90, indicating high internal consistency (Taber 2018). This is very important in the context of the South African AMI, where technological change is a strategic imperative and a complex process. The fact that these constructs show such high consistency suggests that the study views the multidimensionality of innovation and its socioeconomic modernisation consequences as critical to the success of the SAAM 2035 (South Africa, Department of Trade, Industry and Competition 2019).

Cost of technology adoption remains one of the major inhibitors of technology advancement in the South African AMI, particularly in the context of SMEs in the automotive value chain (Inyang, Kanakana and Laseinde 2023). The reliability of the construct *Cost of Technology Adoption* ($\alpha = 0.946$) ensures the accurate capture of this crucial factor in analysis and hence the validity of prescriptions around reducing cost-related financial inhibitions via government or public-private arrangements. The constructs *Technology Infrastructure Support* ($\alpha = 0.942$) and *Availability of Skilled Labour* ($\alpha = 0.906$), which also show excellent reliability scores, play a central role in revealing the drivers of 4IR and 5IR technology adoption.

The second-highest internal consistency is shown by the construct *Increased Productivity* ($\alpha = 0.984$), which is notable considering that productivity is one of the major performance indicators in manufacturing (Sokolov *et al.* 2023). Improving productivity is crucial in the South African AMI, considering the country's status as a regional manufacturing hub for international OEMs and the need to remain globally competitive (Wuttke 2022). The high internal consistency of this construct supports the validity of findings from the analysis of the structural model relating 4IR and 5IR technology adoption to productivity improvement (Saah and Mbohwa 2025).

Similarly, the excellent reliability scores for the constructs *Organisational Support for Upskilling* and *Workforce Income Growth* (α = 0.933 and α = 0.916) highlight the importance of human capital formation in the context of technology change. The development of skills has been highlighted by the South African government as well as industry actors in an attempt to nurture the transition to high-end production (South Africa, Department of Trade, Industry and Competition 2019). The reliability of these constructs ensures the effectiveness of the study in measuring how technology adoption correlates with workforce development and income boosts, which are the defining features of inclusive industrialisation (Ajmi *et al.* 2025).

The reliability score for the construct *Promotion of Digital Commerce* (α = 0.894) is less than 0.90. This suggests that while digital commerce is recognised as an emerging dimension of competitiveness, its operationalisation varies across firms, likely due to differences in digital maturity and market orientation. The evolution of digital commerce in the AMI, particularly in South Africa, is relatively new (Sichoongwe 2023).

Reliability testing thus confirms the strength and sufficiency of the measurement tools used in this study to explore the innovation impact of recent industrial revolution technology adoption on the modernisation of the AMI and its implications within the South African AMI. High internal consistency in most constructs adds to the validity of this study's findings and enhances their credibility in accordance with modern literature and policy documents.

6.2.3 Relationships between innovation drivers and modernisation outcomes

The correlation analysis provides useful evidence of the interrelationship between factors influencing innovation and outcomes of modernisation in the South African AMI. The positive and statistically significant correlations between *4IR/5IR Technology Adoption* and *Workforce Upskilling* (r = 0.572), *Workforce Income* (r = 0.506), and *Increased Productivity* (r = 0.429) indicate that firms that rapidly adopt advanced manufacturing technologies, such as robotics, AI, and the IoT, also report stronger human capital development, higher wage trajectories, and better performance. This pattern is consistent with South African evidence that digital technologies in manufacturing raise quality, throughput, and supply chain performance while catalysing workforce transformation mechanisms through which productivity gains and wage premia materialise for higher-skill roles. Studies report precisely these outcomes for the adoption of AI and other 4IR technologies, linking technology to quality, productivity, and workforce upgrading in manufacturing contexts, including automotive value chains (Nzama *et al.* 2024; Zulu, Pretorius and van der Lingen 2022). In parallel, macro-micro South African scholarship documents skills-biased technological change, where new technologies increase demand for skilled labour and are associated with rising returns to skill and wage dispersion, an established pathway that helps explain the positive associations of *4IR/5IR Adoption* with *Workforce Upskilling* and *Workforce Income* in the correlation matrix shown in Table 5.7 (Rattsø and Stokke 2013).

The positive links between *Infrastructure Support* and *4IR/5IR Adoption* (r = 0.277), and between *Labour Availability* and *4IR/5IR Adoption* (r = 0.246), align with South African research showing that foundational infrastructure, including broadband, reliable power, and plant-level automation platforms, and depth of human capital are decisive for technology diffusion and productivity. Long-term South African research shows infrastructure capital as a significant driver of aggregate and manufacturing productivity, an enabling base without which digital systems and cyber-physical integration cannot scale (Fedderke and Bogetić 2009). Complementary South African scholarship on broadband infrastructure gaps emphasises that closing last-mile connectivity deficits raises firms' ability to adopt data-intensive applications, further supporting the adoption-infrastructure correlation observed in this study (Roux 2015).

The negative correlations of *Adoption Costs* with *Increased Productivity* (r = -0.206), *Workforce Upskilling* (r = -0.289) and *Workforce Income* (r = -0.269) are in line with peer-reviewed South African analyses showing that high operating and capital costs, including those stemming from power unreliability and the need to self-provision energy, erode firms' financial headroom for new technology and skills investment and depress performance. Studies have found that load shedding materially reduces operating hours, increases input costs, and weakens firm performance, crowding out modernisation capital expenditure and training budgets and, ultimately, wage growth (Musabayana 2024; Zulu and Maama 2025). South African industrial engineering research similarly flags the financial and strategic barriers to the deployment of 4IR technologies, including capital expenditure, integration risk, and capabilities, reinforcing the negative associations between cost and modernisation outcomes observed in this study (Zulu, Pretorius and van der Lingen 2022).

The positive intercorrelations of *Workforce Upskilling* with *Workforce Income* (r = 0.489) and *Increased Productivity* (r = 0.409) mirror a well-documented South African dynamic: workers with advanced skills that complement new technologies see greater productivity contributions and stronger wage trajectories. Evidence anchored in South African labour market research shows that the diffusion of skill-complementary technologies reinforces returns to education and on-the-job learning, consistent with the medium-to-strong correlations observed in this study (Rattsø and Stokke 2013). In the manufacturing context, peer-reviewed South African research on AI and automation reports that firms realising value from digital investments do so alongside structured capability building, including operator upskilling, cross-functional analytics, and digital maintenance, which feeds directly into productivity outcomes (Nzama *et al.* 2024).

While this study foregrounds digital commerce as a socioeconomic variable, the broader South African literature suggests that improvements in logistics, connectivity and plant-to-market integration are associated with digital sales enablement and operational efficiency, especially for components and aftermarket channels in the AMI. Studies in the sub-Saharan African context identify logistics digitalisation, including track-and-trace, warehouse automation, and data platforms, and infrastructure upgrades as levers for competitiveness and growth, complementing firm-level technology adoption patterns and helping to interpret positive associations between infrastructure, e-commerce operations and productivity (Kuteyi and Winkler 2022). This infrastructure-productivity nexus, established for the South African manufacturing sector at large, confirms why better backbone services co-move with firm performance measures captured in the correlation matrix (Fedderke and Bogetić 2009).

As a whole, the correlation structure coheres with South African industrial policy priorities that target simultaneous progress in digital adoption, capability development, and enabling infrastructure to enhance competitiveness and inclusion in globally integrated value chains such as the AMI. The literature underscores the need for strategic alignment and organisational readiness as preconditions for realising the productivity and wage benefits observed in the correlations, while macro-level research highlights infrastructure as a prerequisite for firm-level technology absorption (Fedderke and Bogetić 2009; Zulu, Pretorius and van der Lingen 2022).

6.2.4 Structural path relationships (Direct and mediated effects)

The SEM results show an acceptable model fit, with $\chi^{2/DF}$ (2.682), CFI (0.966), SRMR (0.044), and RMSEA (0.087) values all within acceptable limits. These values indicate that the hypothesised relationships between factors influencing innovation and outcomes of modernisation have substantial statistical validity. In South Africa, where the AMI is a key driver of industrial output and export earnings, such a validated model provides an essential blueprint for understanding the practical expressions of digital transformation. The SAAM 2035 currently promotes the adoption of advanced manufacturing technologies to improve competitiveness and support local production.

6.2.4.1 Relationship between drivers of innovation and outcomes of modernisation

Adoption costs and productivity

The negative correlation between technology adoption costs and productivity ($\beta = -0.448$, $p < 0.001$) indicates that high operating and capital costs hinder efficiency in the AMI. This is in line with findings by SARChI Industrial Development that identify high outlay costs and financial constraints as key impediments to 4IR adoption in South African manufacturing firms, particularly Tier-2 and Tier-3 firms with low profit margins (Alexander 2021). Similarly, research into technology adoption in SMEs in South Africa has shown that cost pressures hinder modernisation and competitiveness because firms struggle to prove the return on investment in cutting-edge technology during economic volatility (Avenyo, Bell and Nyamwena 2024; Saah, Mbohwa and Madonsela 2023). These findings underscore the need for targeted incentives and financing mechanisms, as envisaged in the SAAM 2035, to reduce adoption costs and unlock productivity gains.

Adoption costs and workforce upskilling

The negative correlation between technology adoption costs and organisational support for upskilling ($\beta = -0.303$, $p < 0.001$) suggests that when firms allocate significant resources to technology acquisition, they may reduce investment in workforce development. This is consistent with South African evidence that budgetary trade-offs often deprioritise training when capital expenditure rises, despite the critical role of skills in realising the benefits of 4IR technologies (Olaitan, Vijayalekshmi and Kumar 2024; Samuels and Singh 2025). Maisiri, Darwish and Van Dyk (2019) assert that while skills development is widely acknowledged as a principal enabler of Industry 4.0, companies often encounter financial and structural difficulties in conducting broad-based training initiatives. This insight highlights a legislative need for public-private partnerships and SETA-driven programmes to co-fund upskilling within the AMI.

Adoption costs and workforce income

The negative correlation between technology adoption costs and workforce income growth ($\beta= -0.242$, $p < 0.001$) indicates that pay increases could be muted because of financial stresses emanating from technology spending. Evidence from South African labour studies indicates that skill-biased technological change increases wage disparities by favouring highly skilled workers (Bhorat *et al.* 2020). However, due to limited profitability, even experienced employees may experience delayed wage progression when firms confront significant adoption costs. This dynamic highlights the importance of cost-sharing mechanisms and productivity-linked wage models to ensure inclusive income growth during digital transitions.

Adoption costs and promotion of digital commerce

While adoption of technology is inhibited due to costs, this does not significantly impact promotion of digital commerce in the AMI, as shown by the non-significant link between promotion of digital commerce and cost of technology adoption ($\beta = -0.072$, $p = 0.127$). According to existing studies, electronic commerce in automotive supply chains has become increasingly dependent on consumer interaction strategies, platform interoperability, and logistical integration rather than solely on the cost of technology (Priyadarshini 2025). Logistics preparedness and omni-channel integration remain central in ensuring successful digital commerce (Risberg 2022).

Labour availability and modernisation outcomes

The high positive correlation between availability of skilled labour and increased productivity ($\beta = 0.783$, $p < 0.001$) confirms the relevance of human capital to performance. South African studies have consistently shown that a shortage of skilled workers constrains the competitiveness of manufacturers, while firms strong in technology and digital competencies are productive and achieve better performance (Maisiri, Darwish and Van Dyk 2019). The emphasis on skills development as a global competitiveness pillar in the SAAM 2035 concords with these findings. A reinforcing loop is observable in the positive correlations between availability of skilled labour and organisational support for upskilling ($\beta = 0.460$), workforce income growth ($\beta = 0.250$), and promotion of digital commerce ($\beta = 0.273$). Individuals with advanced skills tend to engage more frequently in continuous education, secure higher wages, and promote digital business frameworks. Research conducted in South Africa regarding skill-biased technological change indicates that digital transformation amplifies the demand for sophisticated skills, which subsequently fosters the adoption of innovation and leads to increased salary premiums (Samuel and Moagi 2022; Katunga, Keating and Mange 2024).

Infrastructure support and modernisation outcomes

Support for technology infrastructure has positive and statistically significant relationships with increased productivity (β = 0.501), organisational support for upskilling (β = 0.246), workforce income growth (β = 0.307), and promotion of digital commerce (β = 0.175), emphasising that infrastructure is a foundational enabling factor. Investment in South African infrastructure creates substantial direct and indirect productive benefits and stimulates growth in private investment and innovation initiatives (Fedderke and Bogetić 2009). Broadband expansion research has shown that increased connectivity accelerates e-commerce and digital inclusion and sustains these gains (Munyoka 2022).

Overall, the SEM results are consistent with South African research that highlights three interrelated modernisation levers: infrastructure investment, talent development, and cost reduction. While skilled labour and infrastructure emerge as crucial facilitators of productivity, income development, and digital transformation, high adoption costs continue to be a structural barrier. These results support the SAAM 2035's strategic priorities, which include integrated interventions in infrastructure, skills, and technology to position the South African AMI for global competitiveness.

6.2.4.2 Mediated effects through investment, education, and management

The results of the SEM structural model analysis provide further insight into the factors influencing innovation and the outcomes of modernisation in the South African AMI. The model tested 36 hypotheses related to indirect effects via investment in 4IR and 5IR technologies, education in 4IR and 5IR technologies, and management of 4IR and 5IR technologies (H13 to H48). The use of unstandardised path coefficients provides a more realistic description of the direction and magnitude of these relations in real terms.

Indirect effects of adoption costs through investment

The results for H13 to H16 show that costs have significant negative indirect effects on productivity (H13: β = -0.304), organisational support for upskilling (H14: β = -0.205), workforce income growth (H15: β = -0.151), and promotion of digital commerce (H16: β = -0.101) through investment. These results further clarify the direct negative impact of costs on productivity, upskilling, and income (H1 to H4), suggesting that high operational costs, such as electricity tariff rates, logistics costs, and input costs, also hinder firms' ability to invest in enhancement and innovation. Studies have shown that cost pressures on the South African AMI reduce the profit margins of automotive parts manufacturers and hence inhibit investment in innovative technologies and workforce training (Barnes and Black 2013; Gonyora *et al.* 2021). In addition, high logistics costs and unstable supply of energy retard industrial competitiveness and postpone investment in industrial modernisation (Aberdeen 2022). The significant negative indirect effect on e-commerce (H16) is especially crucial since it implies that high overhead costs prevent businesses from investing in the appropriate systems and technologies to support digital platforms, even when such technologies are affordable (Anzolin 2024).

Indirect effects of adoption costs through education

The results for H17 to H20 show that costs indirectly hinder modernisation through education. The strongest negative effect is on productivity (H17: β = -0.298), followed by organisational support for upskilling (H18: β = -0.209), workforce income growth (H19: β = -0.154), and promotion of digital commerce (H20: β = -0.099). From a theoretical viewpoint, these interventions are reasonable; financial constraints on employers inhibit their capacity to pay for apprenticeships, fund training programmes, and interact with educational institutions. The systematic reduction of training budgets by firms because of fiscal pressures has caused constant underinvestment in skills improvement within automotive suppliers in South Africa (Horn 2007). An analysis of the SAAM 2035 suggests that a lack of funds to invest in education and training systems constrains the ability of component manufacturers to adopt new technologies (Alexander 2021). The mediated effect on income (H19) confirms the assumption that without proper education and training, workers remain stuck in low-value jobs with few chances of upward mobility (Sibiya 2024).

Indirect effects of adoption costs through management

The results for H21 to H24 show that costs hinder modernisation through management structures and practices. Again, productivity is most affected (H21: $\beta = -0.292$), followed by organisational support for upskilling (H22: $\beta = -0.193$), workforce income growth (H23: $\beta = -0.145$), and promotion of digital commerce (H24: $\beta = -0.094$). These results are in line with the RBV, which contends that for businesses to convert resources into a competitive advantage, they need managerial skills in addition to tangible assets (Barney 1991). Businesses that face ongoing financial pressure frequently shift managerial focus from long-term modernisation to short-term survival tactics, which undermines efforts for innovation and process enhancements (Mdau and Grobbelaar 2024). Weak margins among South African component suppliers have been linked to a managerial capability trap, where investments in digital platforms and lean production methods are subordinated to cost containment (Rathilall and Singh 2018). The significant negative effect on e-commerce adoption (H24) further illustrates how strategic management choices around digitalisation are constrained under financial pressure.

Together, the results for H13 to H24 confirm that cost pressures are a fundamental barrier to modernisation in the South African AMI. While the direct relationships show costs of technology adoption lowering productivity, organisational support for upskilling, and workforce income, the indirect relationships reveal the mechanisms by which this happens: firms under cost strain cannot invest adequately, cannot sustain training partnerships, and cannot develop strong managerial systems. These results are aligned with industry studies that suggest that the rising costs of electricity, logistics, and raw materials are major hindrances to the competitiveness of South African component suppliers and their ability to move forward in the value chain (Komarasamy and Hoque 2015; Naudé and Badenhorst-Weiss 2011). Therefore, by showing that cost increases not only have immediate negative effects but also erode the institutional mechanisms of investment, education, and management, which are crucial to sustaining modernisation, the results of the mediation analysis complement those of the direct relationships analysis.

Indirect effects of labour availability through investment

The results for H25 to H28 show that the availability of skilled labour indirectly facilitates modernisation through investment, with significant effects on productivity (H25: β = 0.273), organisational support for upskilling (H26: β = 0.190), workforce income growth (H27: β = 0.149), and promotion of digital commerce (H28: β = 0.080). In addition to confirming the findings of the direct relationships analysis for H5 to H8, which identify skilled labour as a robust determinant of outcomes of modernisation, these results imply that firms are more likely to invest in production upgrades and new technologies if they have access to a large and skilled workforce. Firms with robust human resource skills are better positioned to make investment plans that exploit the strengths of the AMI in South Africa, where there is an abundance of labour but a persistent skills shortage (Macpherson, Werner and Mey 2023). This is in line with global evidence showing that a skilled workforce attracts investment in automation and digital technologies, while labour scarcity deters such investment (Danzer, Feuerbaum and Gaessler 2024).

Indirect effects of labour availability through education

The results for H29 to H32 show that availability of skilled labour indirectly facilitates modernisation through education in 4IR and 5IR technologies, with the strongest effect on productivity (H29: β = 0.268), followed by organisational support for upskilling (H30: β = 0.192), workforce income growth (H31: β = 0.150), and promotion of digital commerce (H32: β = 0.078). This indicates that when firms leverage their labour base by aligning it with education and training systems, the benefits of modernisation multiply. South African studies have found that the AMI relies significantly on work-centred training, apprenticeships, and collaboration with technical and vocational education and training (TVET) colleges and higher education institutions to enhance worker versatility (Allais *et al.* 2021; Sibiya 2024). These results imply that labour is both a direct and indirect catalyst for education-led upgrading; when companies have a steady workforce, they invest in training and upgrading projects and reap productivity and wage benefits. Notably, the mediating effect of education on e-commerce adoption (H32) suggests that e-adoption is reliant on a digitally literate workforce that is maintained via education (Li, Yang and Yin 2024).

Indirect effects of labour availability through management

The results for H33 to H36 show that the availability of skilled labour indirectly enhances modernisation through management practices. Productivity benefits the most (H33: $\beta = 0.250$), followed by organisational support for upskilling (H34: $\beta = 0.170$), workforce income growth (H35: $\beta = 0.135$), and promotion of digital commerce (H36: $\beta = 0.070$). These results highlight the complementarity between human resources and managerial systems. A well-trained and available workforce allows managers to implement structured routines such as lean manufacturing, Kaizen, and quality circles. Case studies of South African automotive component firms show that where management and labour collaborate effectively, production stability improves and modernisation initiatives take root (Mashilo 2019; Zondo 2020). Conversely, weak management-labour relations have been linked to reduced efficiency and limited innovation diffusion (Barnes and Black 2013). The indirect effect on e-commerce adoption suggests that labour and management together influence the digital readiness of firms, particularly when managers use labour resources strategically to align operations with digital platforms (Holopainen, Ukko and Saunila 2022).

When viewed alongside the direct relationships (H5 to H8), the indirect relationships (H25 to H36) provide a deeper understanding of how labour functions as both a resource and an enabler in modernisation. Labour availability directly boosts productivity, skills, income, and digital adoption. Indirectly, these effects are amplified when labour interacts with investment, education, and management systems. The investment pathways show that firms are more willing to allocate capital when they have a reliable workforce to operate and absorb new technologies. The education pathways highlight that labour becomes more effective when reinforced by structured training and education programmes, improving both productivity and wage outcomes. The management pathways demonstrate that labour resources reach their full potential when guided by strong managerial practices that channel workforce skills toward modernisation goals. These results resonate with South African evidence showing that human resources remain central to the competitiveness of the component manufacturing base. Despite technological advances, firms in South Africa cannot bypass the labour dimension; modernisation is viable only when labour, education, and management are jointly mobilised (Macpherson, Werner and Mey 2023; Maisiri and Van Dyk 2021).

The results shown in Table 5.15 demonstrate the critical role that infrastructure plays in facilitating modernisation through the mediating impacts of management, education, and investment. The results for the hypotheses regarding the indirect effects of infrastructure support (H37 to H48) indicate that infrastructure has a strong indirect impact on e-commerce, income, productivity, and upskilling. In addition, Table 5.12 shows that infrastructure has a direct and beneficial impact on modernisation outcomes, especially productivity ($\beta = 0.501$, $p < 0.001$); this highlights the role of infrastructure as a foundational enabler, as discussed in Section 6.2.4.1 above. The results collectively imply that infrastructure both directly propels modernisation and facilitates it through organisational and institutional factors.

Indirect effects of infrastructure support through investment

The results for H37 to H40 show that infrastructure support indirectly facilitates modernisation through investment in 4IR and 5IR technologies. This most strongly benefits productivity ($\beta = 0.185$, CI [0.105, 0.304], $p < 0.001$), followed by upskilling ($\beta = 0.134$, CI [0.074, 0.205], $p < 0.001$). These results support the idea that dependable infrastructure, including electricity, transportation, and digital connectivity, reduces operational hurdles, which in turn motivates businesses to increase investment in personnel development and technology adoption (Anzolin 2024; Sichoongwe 2023). The benefits of infrastructure are increased when businesses proactively reinvest in procedures that improve productivity and human capital, as shown by the positive mediation through investment. Notably, the result for H40 shows that infrastructure support indirectly boosts the promotion of digital commerce through investment ($\beta = 0.053$, CI [0.026, 0.096]). This illustrates the digital-ready aspect of modernisation, where digitalisation is limited to the use of online platforms until sufficient infrastructure permits broader digital transitions.

Indirect effects of infrastructure support through education

The results for H41 to H44 show that infrastructure support indirectly facilitates modernisation through education in 4IR and 5IR technologies, with productivity (β =

0.178, CI [0.100, 0.292]) again benefitting the most. This is consistent with the direct effect of infrastructure support on organisational support for upskilling (Table 5.12, H10: β = 0.246), but here it becomes clear that education in 4IR and 5IR technologies acts as a crucial mechanism. These indirect effects indicate that better infrastructure facilitates training programmes, knowledge dissemination, and partnerships with higher education institutions, which in turn improve workforce adaptability (Maisiri and Van Dyk 2021; Sutherland 2020). Organisational support for upskilling (β = 0.133, CI [0.074, 0.206]) and workforce income growth (β = 0.089, CI [0.049, 0.144]) also benefit, highlighting the role of education in raising the productivity-wage nexus. In addition, the significant effect on promotion of digital commerce (H44: β = 0.051, CI [0.025, 0.093]) suggests that an educated workforce is more likely to engage with digital tools, even when costs remain high.

Indirect effects of infrastructure support through management

The results for H45 to H48 show that infrastructure support indirectly facilitates modernisation through management of 4IR and 5IR technologies. Productivity again shows the strongest benefit (β = 0.178, CI [0.100, 0.289]), suggesting that effective managerial capabilities are necessary to translate infrastructural availability into operational efficiency. This echoes the RBV, which emphasises that physical infrastructure alone is insufficient unless complemented by managerial competencies that direct its use (Barney 1991). Organisational support for upskilling (β = 0.126, CI [0.069, 0.195]) and workforce income growth (β = 0.085, CI [0.046, 0.138]) also benefit, indicating that management influences training priorities and wage structures. The significant but weaker effect on promotion of digital commerce (β = 0.049, CI [0.023, 0.090]) suggests that digital modernisation requires not only infrastructure but also strategic managerial commitment.

When Tables 5.12 and 5.15 are examined together, a distinct pattern becomes apparent: infrastructure serves as a foundational facilitator of investment, education, and management in addition to being a direct enabler of modernisation. While the direct effects of infrastructure support are substantial, the mediation analysis demonstrates that when institutions and businesses mobilise complementary resources, the impact of infrastructure is amplified. While the direct effects show infrastructure improving organisational support for upskilling and workforce income growth, the mediated effects reveal how this occurs through structured investments in training, stronger education systems, and effective managerial allocation of resources.

The combination of strong direct and mediated pathways reduces suspicion of inflated results because it presents a theoretically consistent chain of causality. Considering that bottlenecks in infrastructure, including electricity, logistics, and ICT, are well-documented constraints facing component manufacturers in the South African AMI (Gonyora *et al.* 2021; Pillay and Dall-Orsoletta 2024), these findings demonstrate that addressing infrastructure deficits is not just a direct productivity issue but also a lever for broader modernisation through organisational systems.

6.2.5 Structural equation modelling

The SEM results show that organisational support is a strategic antecedent of innovative behaviour and capability advancement, resulting in higher productivity. In addition, the direct impact of support on productivity (β = 0.501), transcending mere human resource or cultural considerations, makes it a major productivity lever. Here again, as in the perceived organisational support (POS) theory, caring conditions contribute to proactivity and innovative behaviour.

The reinvestment procedure described in endogenous growth theory, where monetary slack facilitates investment in innovative activity resulting in efficiency growth, is validated through the chain of support that enhances income, enabling innovation, which drives productivity. Similarly, support enables skills, which in turn enhances the productivity chain; this confirms the validity of the DCT and the HCT, both of which focus on the importance of skills development in the process of implementing modernisation and innovative strategies.

Modernisation theory assumes that modernisation progresses as a structural capability formed through both innovation and complementary mechanisms. Such key associations with innovation and capabilities demonstrate that modernisation acts as a channel linking higher productivity with the evolution of capabilities.

While the slightly positive effect of adoption costs on innovation implies that strategically invested expenditure can fuel innovation, the negative effects of adoption costs on income and productivity highlight the necessity for cost discipline. This is in line with the principles of the RBV and literature related to industrial policy.

Overall, the results highlight the strategic role of organisational support in enabling structural transformation through innovation and modernisation, income generation, and crystallisation into skills to achieve increased productivity output.

6.3 Integrated discussion of innovation drivers, mediators, and modernisation outcomes

The AMI is an anchor of the South African economy, contributing significantly to the country's GDP and generating billions of rands in export revenues annually (Kunychka 2022). As the industrial powerhouse of the African continent, South Africa faces both opportunities and challenges with regard to embracing 4IR and 5IR technologies. These challenges include high operational costs, unreliable power supply, competition from low-cost imports, and the need for improved supply chain integration and productivity to remain globally competitive (Ikome, Laseinde and Katumba 2023).

This study aims to explore the effect of various factors influencing innovation, such as labour, infrastructure, and cost, on modernisation outcomes in the South African AMI. Four major outcomes of modernisation have been identified: workforce income growth, organisational support for upskilling, increased productivity, and promotion of digital commerce. Investment in 4IR and 5IR technologies, education in 4IR and 5IR technologies, and management of 4IR and 5IR technologies have been identified as mediating factors that explain how structural inputs lead to modernisation. The study's findings offer a nuanced understanding of modernisation in the South African AMI, which is particularly vulnerable to cost-related pressures, infrastructure constraints, and international competition.

The findings for the hypotheses relating to both direct (H1 to H12) and indirect (H13 to H48) relationships indicate a distinctly interconnected model in which labour, infrastructure, cost dynamics, and intermediaries such as innovation, investment, management, and education all influence modernisation outcomes in the South African AMI. While the prevalence of significant relationships, apart from the relationship between the cost of technology adoption and the promotion of digital commerce (H4), indicates that the suggested model has significant explanatory power, the consistency of significance raises questions of possible sensitivity of the model. In any case, subtle differences between mediated and direct paths permit distinction between relationships that act as theory reinforcement from those that yield new contributions to the established literature base.

6.3.1 Direct effects of innovation drivers on modernisation outcomes (H1-H12)

6.3.1.1 Costs and modernisation outcomes (H1-H4)

The results show that technology adoption costs have statistically significant negative effects on workforce income growth (H3: $\beta = -0.242$, $p < 0.001$), organisational support for upskilling (H2: $\beta = -0.303$, $p < 0.001$), and productivity (H1: $\beta = -0.448$, $p < 0.001$). These results validate other research that describes how increases in energy tariffs, transportation costs, and input costs negatively impact the competitive advantage of South African manufacturing (Msimango, Orffer and Inglesi-Lotz 2023). However, technology adoption costs do not significantly affect the promotion of digital commerce (H4: $\beta = -0.072$, $p = 0.127$), which suggests that variables such as digital literacy, consumer readiness, and trust in digital platforms may play a greater role in digital adoption than cost (Avenyo, Bell and Nyamwena 2024).

These findings endorse modernisation theory, which posits that the capacity of enterprises to allocate resources for enhancement is limited by structural determinants (Zhang, Xu and Ma 2022). In this context, the structural burden of elevated operating costs diverts financial resources from investments and skills development initiatives that could potentially enhance productivity.

6.3.1.2 Labour and modernisation outcomes (H5-H8)

The availability of skilled labour has by far the strongest positive impact on modernisation, with positive effects on productivity (H5: $\beta = 0.783$, $p < 0.001$), organisational support for upskilling (H6: $\beta = 0.460$, $p < 0.001$), workforce income growth (H7: $\beta = 0.250$, $p < 0.001$), and promotion of digital commerce (H8: $\beta = 0.273$, $p < 0.001$). These results affirm the centrality of human capital to modernisation, in alignment with the RBV (Barney 1991), which regards skills and capabilities as valuable, rare, and inimitable resources.

According to Pillay and Dall-Orsoletta (2024), the South African AMI has traditionally relied on its labour-intensive supplier base, especially component manufacturers, to absorb trained and semi-skilled workers. Strong relationships between workforce skills, productivity rates, and the use of digital commerce reflect that competitiveness is increasingly determined by considerations such as employee readiness, adaptability, and ICT skills. South African industrial policy instruments prioritise socioeconomic transformation, with the positive impact of employment on income rates strongly supporting this focus.

6.3.1.3 Infrastructure and modernisation outcomes (H9-H12)

Infrastructure support is a major contributor to modernisation, with significant positive impacts on the promotion of digital commerce (H12: $\beta = 0.175$), workforce income growth (H11: $\beta = 0.307$), organisational support for upskilling (H10: $\beta = 0.246$), and productivity (H9: $\beta = 0.501$). These findings align with research highlighting the transformative impact of ICT infrastructure, logistics arrangements, and electricity provision on industrial capabilities (Obokoh *et al.* 2024).

Poor infrastructure in South Africa, including power instability, dilapidated transportation links, and limited Internet access, has been a significant barrier to modernisation. However, the robust and positive links between infrastructure and modernisation observed in this study show that firms that can utilise accessible infrastructure efficiently, particularly in provinces such as Gauteng and KwaZulu-Natal, reap the benefits of modernisation. Due to superior infrastructure and resource availability, firms in well-developed regions are generally better positioned for modernisation than those in less developed regions. Therefore, the ability to modernise is not uniform and depends heavily on a firm's geographic and industrial context.

6.3.2 Mediated effects: Costs and modernisation (H13-H24)

6.3.2.1 Costs and investment mediation (H13-H16)

Technology adoption costs hinder the process of modernisation indirectly by impacting investment in 4IR and 5IR technologies, with significant effects on promotion of digital commerce (H16: $\beta = -0.101$), productivity (H13: $\beta = -0.304$), organisational support for upskilling (H14: $\beta = -0.205$), and workforce income growth (H15: $\beta = -0.151$). These findings indicate that when operational costs are high, firms often cannot afford modernisation-related spending. Studies have noted that South African component suppliers are typically constrained by thin profit margins, causing them to defer or forego plans for modernisation due to rising energy and logistics costs (Katumba and Timothy 2016).

Of particular significance is the negative indirect effect of technology adoption costs on the promotion of digital commerce through investment (H16). As reported in the literature, the inclination of enterprises to allocate resources toward digital platforms is constrained by the financial encumbrance resulting from overhead costs, even when digital alternatives are affordably priced (Anzolin 2024; Rakgoale, Bag and Pretorius 2024). This exemplifies how structural cost pressures detrimentally affect the outcomes of modernisation by permeating through investment pathways.

6.3.2.2 Costs and education mediation (H17-H20)

Technology adoption costs hinder the process of modernisation indirectly by impacting education in 4IR and 5IR technologies, with significant effects on workforce income

(H19: β = -0.151), organisational support for upskilling (H18: β = -0.209), productivity (H17: β = -0.298), and promotion of digital commerce (H20: β = -0.099). These findings align with a common pattern in which enterprises encountering financial challenges tend to deprioritise apprenticeships, training, and partnerships with educational institutions (Ngcobo and Khumalo 2022; Sibisi and Makka 2021). Notably, the mediated impact on workforce income growth (H19) shows that workers remain in low-value occupations with little opportunity for wage mobility when education and training initiatives are inadequately financed (Mazorodze 2024). These findings show how financial constraints in firms lead to limited socioeconomic advancement for employees in a nation with endemic inequality.

6.3.2.3 Costs and management mediation (H21-H24)

The influence of management models on costs of technology adoption hinders modernisation, with negative effects on productivity (H21: β = -0.292), organisational support for upskilling (H22: β = -0.193), workforce income growth (H23: β = -0.145), and promotion of digital commerce (H24: β = -0.094). These findings align with the RBV, which emphasises managerial capabilities as a crucial internal resource for developing competitive advantages (Barney 1991). When managers prioritise survival measures in reaction to cost pressures, long-term modernisation efforts suffer (Rico, Pandit and Puig 2020).

The findings support Rahmandad and Repenning (2016)'s concept of a managerial capability trap, where component suppliers are unable to invest in long-term modernisation because their management capabilities and financial resources are tied up in constant short-term problem solving. This traps them in a state of operational inefficiency, inhibiting their ability to adopt modern digital platforms and lean manufacturing practices.

6.3.3 Mediated effects: Labour and modernisation (H25-H36)

6.3.3.1 Labour and investment mediation (H25-H28)

The availability of skilled labour positively impacts modernisation through investment in 4IR and 5IR technologies, with significant effects on productivity (H25: $\beta = 0.273$), organisational support for upskilling (H26: $\beta = 0.190$), workforce income growth (H27: $\beta = 0.149$), and promotion of digital commerce (H28: $\beta = 0.080$). These findings suggest that a skilled and adaptable workforce attracts and justifies further investments in modernisation. Firms with competent labour forces are more likely to channel capital toward new technologies, training, and digital adoption, confident that human capital can absorb such investments effectively.

6.3.3.2 Labour and education mediation (H29-H32)

The availability of skilled labour positively impacts modernisation through education in 4IR and 5IR technologies, with significant effects on productivity (H29: $\beta = 0.268$), organisational support for upskilling (H30: $\beta = 0.192$), workforce income growth (H31: $\beta = 0.150$), and promotion of digital commerce (H32: $\beta = 0.078$). This shows that labour not only has a direct impact on modernisation but also has implications for the effectiveness of educational programmes. Highly skilled workers and labour unions often trigger demands for further training and certification, thus creating a positive loop between labour skills and educational progress (Kostøl 2024; Singh, Yadav and Pradhan 2023).

A key component of the SAAM 2035 is the promotion of initiatives focused on collaborative training between educational institutions and businesses. Where a strong labour force with sufficient skills is in place, such collaborative models of training have been shown to produce ascertainable modernisation outcomes. However, research suggests that while formal technical schools, higher education institutions, and business programmes contribute to growth, they are not the sole drivers of industrial transformation; factors such as technology, market exposure, and policy also play substantial roles (Sibiya 2024).

6.3.3.3 Labour and management mediation (H33-H36)

The availability of skilled labour positively impacts modernisation through management practices, with significant effects on productivity (H33: $\beta = 0.250$), organisational support for upskilling (H34: $\beta = 0.170$), workforce income growth (H35: $\beta = 0.135$), and promotion of digital commerce (H36: $\beta = 0.070$). These findings support related literature that highlights the importance of labour quality and flexibility in determining managerial effectiveness. A skilled labour force is crucial for successfully executing managerial strategies such as lean production, digital transformation, and continuous improvement initiatives (Zondo 2020).

6.3.4 Mediated effects: Infrastructure and modernisation (H37-H48)

6.3.4.1 Infrastructure and investment mediation (H37-H40)

Support for technology infrastructure positively impacts modernisation through investment in 4IR and 5IR technologies, with significant effects on productivity (H37: $\beta = 0.185$), organisational support for upskilling (H38: $\beta = 0.134$), workforce income growth (H39: $\beta = 0.088$), and promotion of digital commerce (H40: $\beta = 0.053$). These findings are supported by studies demonstrating that better infrastructure reduces business costs, which induces firms to reinvest the cost savings in upgrades (Msimango, Orffer and Van Reenen 2023).

6.3.4.2 Infrastructure and education mediation (H41-H44)

Support for technology infrastructure positively impacts modernisation through education in 4IR and 5IR technologies, with significant effects on productivity (H41: $\beta = 0.178$), upskilling (H42: $\beta = 0.133$), income (H43: $\beta = 0.089$), and e-commerce (H44: $\beta = 0.051$). This indicates that modernisation has a complementary relationship with human and physical capital: robust infrastructure facilitates access to education and training, which is a key driver of modernisation.

6.3.4.3 Infrastructure and management mediation (H45-H48)

Support for technology infrastructure positively impacts modernisation through management of 4IR and 5IR technologies, with significant effects on productivity (H45: $\beta = 0.178$), organisational support for upskilling (H46: $\beta = 0.126$), workforce income growth (H47: $\beta = 0.085$), and promotion of digital commerce (H48: $\beta = 0.049$). This shows that the successful achievement of modernisation outcomes is dependent on leveraging infrastructure through efficient managerial practices rather than on infrastructure alone.

6.3.5 Integrated discussion

The inclusion of mediators provides deeper insights beyond the direct effects of factors influencing innovation on modernisation outcomes. For instance, while costs have a detrimental direct impact on modernisation, the mediating channels of investment, education, and management reveal the nuanced pathways through which that influence is transmitted.

This study contributes to the current body of knowledge by clarifying how cost constraints restrain opportunities for modernisation in the South African AMI. It also shows that positive influences of skilled labour on modernisation are supported by intermediary processes, creating a continuous improvement loop in which skilled labour supports education, attracts investment, and facilitates sound management, all of which enhance modernisation. The RBV’s argument that a set of interrelated resources creates competitive advantage is reinforced by the indirect effects of infrastructure support on modernisation through investment, education, and management, which once again underline complementarities between managerial, financial, and physical resources.

6.4 Novel contributions to literature

6.4.1 Hypothesis testing

Several findings of this study extend existing literature. Firstly, the negative indirect effects of technology adoption costs on the promotion of digital commerce (H16, H20, H24) show that digital modernisation in South Africa is driven by access to technology and financial flexibility. This finding adds to current debates on digital adoption in emerging markets, showing that structural cost can indirectly deter digital transformation.

Secondly, the negative indirect effect of technology adoption costs on workforce income growth via education in 4IR and 5IR technologies (H19) reveals the socioeconomic implications of modernisation at the firm level. This finding shows how economic pressures faced by firms are translated into inhibited upward mobility for workers, resulting in the perpetuation of inequality. This insight integrates modernisation theory with structuralist perspectives on development.

Thirdly, the positive indirect effects of the availability of skilled labour on modernisation (H25 to H36) yield new findings for the South African AMI, indicating that skilled labour plays a role not only as a resource input but also as a motivating force for investment, education, and managerial efficiency. This finding highlights employees' abilities as a modernisation-facilitating factor, which is sometimes overlooked in firm-level modernisation assessments.

Overall, the results of the hypothesis testing show that complex interactions between the availability of skilled labour, support for technology infrastructure, costs of technology adoption, and mediators such as management, education, and investment in 4IR and 5IR technologies all impact the modernisation of the South African AMI. Costs of technology adoption act as a structural constraint impeding modernisation both directly and indirectly. While support for technology infrastructure provides vital fundamental support, the availability of skilled labour is the most important facilitator, operating through both direct impacts and mediated routes. The use of mediators clarifies the fundamental processes at play, offering fresh theoretical viewpoints and useful insights. The findings have implications for industry and policy: firms must build managerial capacity and invest in human assets, while policymakers must tackle structural cost pressures and infrastructural vulnerabilities. Collectively, these initiatives can help the South African AMI shake off modernisation bottlenecks and attain sustainable competitiveness in the age of global digital transformation.

6.4.2 Emerging theory: Support-driven capability and innovation theory

This study proposes the support-driven capability and innovation theory (SCIT), a novel framework explaining the contribution of institutional support towards generating both organisational and individual capabilities, thereby facilitating innovation, modernisation, and increased productivity. The theory is grounded in multiple established theoretical frameworks, including the RBV, the HCT, modernisation theory, and innovation economics, and is further validated by the results obtained using SEM.

6.4.2.1 Overview and core insight

The structural findings consistently place organisational support as the chief driver of the system, leading to productivity. Support exhibits significant direct correlations with income ($\beta = 0.414$, $p < 0.001$), skills ($\beta = 0.244$, $p < 0.001$), modernisation ($\beta = 0.242$, $p < 0.001$), and, notably, productivity ($\beta = 0.543$, $p < 0.001$). These findings mirror the POS theory, which posits that workers respond to supportive environments with exertion, tenacity, and innovation; organisations can quantify the value of these measurable outcomes and convert them into performance gains (Baccarella *et al.* 2022; Eisenberger *et al.* 1986). These findings also complement the assertion of the RBV and the DCT that supportive, facilitative environments are resources in their own right because they legitimise improvement, encourage cross-functional cooperation, and provide a stable foundation for investment in improvement (Baccarella *et al.* 2022; Teece, Pisano and Shuen 1997).

While SCIT draws conceptually from RBV and DCT, it differs in both scope and explanatory orientation. RBV remains firm-centric, focusing on unique internal resources such as skills, managerial capability, and technological assets. DCT extends RBV by explaining how firms reconfigure these resources in dynamic environments through sensing, seizing, and transforming mechanisms. SCIT goes further by integrating both internal and external domains: it emphasises that modernisation outcomes arise only when firm-based capabilities are complemented by broader support structures such as technological infrastructure, skills ecosystems, and institutional enablers. This positions SCIT as a hybrid capability–support theory that bridges the gap between internal resource explanations (RBV) and adaptive transformation mechanisms (DCT), offering a more comprehensive account of innovation-driven modernisation in the AMI.

6.4.2.2 Support as a facilitator of capability development and the creation of monetary slack

Two channels for capability development are evident. Firstly, support affects skills ($\beta = 0.244$, $p < 0.001$), suggesting that supportive environments nurture capability development through training accessibility, coaching, and sheltered learning time, aligning with the HCT (Becker 1962) and the capability development theory (Shawcross and Ridgman 2019). Secondly, support impacts on income ($\beta = 0.414$, $p < 0.001$), suggesting that support is converted into monetary slack by enhancing revenue stability and facilitating cost avoidance; this provides a relocatable source of funds for investing in innovation (Mairesse, Mohnen and Notten 2025; Romer 1990). In combination with the support to modernisation path, the results suggest that support is not only effective but also infrastructural, facilitating the accumulation of capabilities such as skills and digital/e-commerce systems as well as providing fiscal headroom for transformation.

6.4.2.3 Innovation and modernisation as drivers of transformation

The effect of income on innovation ($\beta = 0.618$, $p < 0.001$) reveals an evident reinvestment mechanism which aligns with endogenous growth theory. In this mechanism, internal slack funds experimentation and technology adoption, which is described in recent reviews of the innovation-productivity literature as a consistent empirical pattern (Mairesse, Mohnen and Notten 2025; Romer 1990). The operation of this mechanism is revealed by the positive effects of skills on productivity ($\beta = 0.491$, $p = 0.004$) and modernisation ($\beta = 0.145$, $p = 0.028$), suggesting that trained personnel convert opportunities into efficiency by adopting new tools and processes, which is reminiscent of the DCT. In addition, the positive effects of innovation on productivity ($\beta = 0.399$, $p < 0.001$) and modernisation ($\beta = 0.125$, $p = 0.005$) are consistent with meta-analytic and encyclopaedia evidence that innovation improves operations and reorganises socio-technical systems, which are proximate drivers of productivity (Damanpour 2017; Katebi *et al.* 2024).

6.4.2.4 Costs: Constraint versus strategic investment

The impacts of costs are asymmetric. Costs negatively affect income ($\beta = -0.117$, $p = 0.015$) and productivity ($\beta = -0.259$, $p = 0.017$), suggesting that structural operating costs drain the resources and efficiencies upon which modernisation depends. However, costs have a marginally significant positive impact on innovation ($\beta = 0.122$, $p \approx 0.065$), suggesting that investment costs, such as technology capex spend, can promote innovation despite the dampening effect of operating expenses on short-term results. This assertion is consistent with the cost-benefit rationale of industrial innovation policy and managerial innovation execution mentalities that combine rapid cost ramp-down with performance improvements (Garcia-Macia and Sollaci 2024; McKinsey 2025).

6.4.2.5 Definition of the proposed theory

The SCIT is a middle-range theory positing the following:

(a) Organisational support is a strategic antecedent that:
   (i) monetises into income (financial slack);
   (ii) builds capabilities in the form of human capital (skills) and structural/technological upgrading (modernisation); and

(iii) directly improves productivity.

(b) Income and skills unlock innovation.

(c) Innovation further modernises operations and raises productivity.

(d) Cost discipline conditions the magnitude and sometimes the sign of these effects.

6.4.2.6 Mechanisms

The mechanisms of the theory are as follows:

(a) Reciprocity (support enhances income and skills): supportive environments elicit discretionary effort and learning adoption (POS, HCT) (Baccarella *et al.* 2022; Shawcross and Ridgman 2019).

(b) Reinvestment (income leads to innovation): slack funds R&D, adoption, and experimentation (endogenous growth) (Mairesse, Mohnen and Notten 2025).

(c) Execution (skills lead to productivity and modernisation): skills enable process discipline and technology assimilation (DCT) (Shawcross and Ridgman 2019).

(d) Transformation (innovation drives productivity and modernisation): new methods and technologies reorganise work and increase efficiency (innovation-performance literature) (Damanpour 2017; Katebi *et al.* 2024).

(e) Constraint/investment (costs affect income and productivity; weak positive path to innovation): operating costs suppress outcomes; targeted costs can be innovation-conducive (policy and practice) (Garcia-Macia and Sollaci 2024; McKinsey 2025).

6.4.2.7 Formal propositions derived from the estimates

The formal propositions of the theory are as follows:

P1 (Support monetisation): Organisational support directly affects income positively, creating a financial surplus which can be invested back into innovative projects. The reinvestment process results in such support also having an indirect positive effect on productivity through a sequential process in which income leads to the facilitation of innovation, thus improving productivity. In other words, when organisations provide significant support, they not only boost short-term financial outcomes but also encourage efficiency enhancements through the stimulus of innovations (Mairesse, Mohnen and Notten 2025).

P2 (Support-to-capabilities): Organisational support enhances the abilities of the workforce, particularly through skills development. Upgraded skills further enhance productivity through improved operational efficiency and accelerate modernisation through the infusion of the latest technological and process advancements. Thus, organisational support indirectly propels the upgrading of structures and technology through the development of human capital (Shawcross and Ridgman 2019).

P3 (Innovation engine): Innovation functions as a core transformation mechanism in the system. It raises productivity by introducing new methods, technologies, and processes that improve efficiency, and it drives modernisation by enabling digitalisation and structural upgrades. This underscores innovation's dual role as both a performance enhancer and a modernisation catalyst (Damanpour 2017; Katebi *et al.* 2024).

P4 (Cost discipline): Cost structures shape the effectiveness of the entire system. Higher operating costs reduce income and productivity, constraining the resources available for reinvestment and efficiency improvements. However, targeted investment costs, such as those directed toward technology or infrastructure, can weakly stimulate innovation, suggesting that cost management should distinguish between structural overhead and strategic spending (Garcia-Macia and Sollaci 2024).

P5 (Dual path of support): Organisational support impacts outcomes through two related mechanisms. Firstly, it has direct effects on productivity and modernisation, underscoring its role as a strategic asset. Secondly, it affects outcomes indirectly through the acquisition of skills and earnings that enable innovation and related performance improvements. The dual-path framework is compatible with organisational theories that perceive support as both cultural and structural facilitators of innovations (Baccarella *et al.* 2022).

6.4.2.8 Theoretical contributions

The SCIT contributes theoretically in three ways. Firstly, it repositions organisational support as a strategic resource that is monetised as income, crystallises into capabilities, and directly lifts productivity, bridging POS with productivity-centred strategy work (Baccarella *et al.* 2022; Mokhber, Khairuzzaman and Vakilbashi 2018). Secondly, it integrates capability formation and reinvestment into a single architecture in which support creates skills and slack, skills and slack fuel innovation, and innovation transforms operations; this single architecture connects the HCT, the DCT, and endogenous growth theory in a testable chain (Becker 1962; Mairesse, Mohnen and Notten 2025; Teece, Pisano and Shuen 1997). Thirdly, the SCIT clarifies the role of modernisation as a distinct capability domain that, similar to digital commerce, is both enabled by support and innovation and implicated in the path to productivity, consistent with organisational innovation perspectives (Garcia-Macia and Sollaci 2024; McKinsey 2025).

6.4.2.9 Boundary conditions and moderators

The SCIT expects market volatility to boost returns for innovation and downstream productivity. Previous studies have established that creativity-fostering contexts deliver greater rewards in turbulent markets (Baccarella *et al.* 2022). Cost discipline is a moderating condition: uncontrolled structural costs can suppress the realisation of productivity innovations, and strategic and programmatic capital spending can underpin innovation channels (Garcia-Macia and Sollaci 2024; McKinsey 2025). The maturity of skills and technological capabilities is probably a key conditioning factor; companies that own an advanced skill base and superior infrastructure can more readily combine support and revenue into their innovations (Shawcross and Ridgman 2019; Garcia-Macia and Sollaci 2024).

6.5 Implications of the hypothesis results for the South African automotive manufacturing industry

The results of this study, which tested 48 hypotheses covering both direct and mediated paths, provide comprehensive and in-depth insights into the innovation impact of recent industrial revolution technologies on the modernisation of the South African AMI. In addition to validating numerous direct effects of factors influencing innovation, the mediating variables illuminate the systemic dynamics linked to modernisation. The implications of these results are manifold and point to opportunities and challenges in several key areas, including workforce development, competitiveness, digital transformation, and industrial policy. This section outlines the implications of these results for the South African AMI, linking them to relevant theoretical concepts and current debates in the literature on manufacturing.

6.5.1 Human capital and workforce development

The results indicate that the availability of labour exerts strongly significant positive influences on both upskilling ($\beta = 0.460$) and productivity ($\beta = 0.783$). This highlights the essential role that human capital plays in shaping competitiveness in the AMI. In South Africa, the pool of qualified personnel is considerably constrained by historical educational inequities, insufficient investment in technical skills development, and a disconnect between university programmes and industry requirements (Maisiri and Van Dyk 2021). Consequently, unless the South African AMI invests regularly in technical and vocational education, it risks falling into a capability trap (Repenning and Sterman 2001) in which short-term gains in productivity are prioritised over long-term skills development.

Consistent with the profile of respondents, the sector's gender imbalance narrows the pool of digitally skilled talent available for 4IR and 5IR roles. A less diverse workforce dampens capability formation in analytics, automation, and human–machine collaboration competencies this study identifies as pivotal mediators of modernisation outcomes. The imbalance also limits the reach of firm-led upskilling initiatives and slows diffusion of new work practices, thereby weakening the pathways from adoption drivers to outcomes. Addressing gender participation is therefore a practical lever for expanding skills supply and raising the absorptive capacity required by the AMI's digital transition.

In addition, the statistically strong association between 4IR/5IR technology adoption and workforce income growth ($\beta = 0.506$) suggests that increased adoption of advanced technologies goes hand in hand with increased skills development, higher incomes, and improved organisational performance; however, not all productivity gains are directly converted into collective economic gains for employees. This is in line with international discussions around "jobless growth" in the manufacturing sector, where technology implementation increases output without an explicit increase in wages (Gil 2020).

The results indicate that although the South African AMI is advancing technologically, the absence of a deliberate integration of skills and economic mobility into technology adoption efforts may exacerbate existing inequalities. This finding reinforces the necessity for workforce-oriented innovation strategies that merge digital investments with comprehensive apprenticeship schemes, retraining programmes, and partnerships between industry and universities.

6.5.2 Infrastructure as an enabler of modernisation

The results show that support for technological infrastructure notably affects upskilling ($\beta = 0.246$) and productivity ($\beta = 0.501$), both directly and through the indirect mediating mechanisms of investment, education, and management. This indicates that infrastructure support not only provides the foundation for the production process but also plays a crucial, complementary role in maximising the impacts of modernisation.

These results have significant implications for South Africa, a nation where competitiveness is impeded by persistent energy shortages and load shedding, inadequate transportation networks, and deficiencies in digital connectivity (Ballim 2025). Consequently, without reliable infrastructure, even well-conceived investments in 4IR and 5IR technologies are likely to yield only limited returns. Firms often allocate management resources to mitigate infrastructure limitations, thereby diminishing the available capacity for training and innovation.

Infrastructure interventions underscore the reliance of modernisation on ecosystem dynamics. For instance, the incorporation of digital commerce has been identified as being minimally responsive to both direct influences and mediated variables. This observation highlights challenges related to cybersecurity, consumer confidence in e-commerce platforms, and broadband penetration in South Africa (Malapane and Ndlovu 2024; Netshirando, Kadyamatimba and Munyoka 2024). This underscores the importance of aligning ICT strategies with industrial policy to ensure that infrastructure advancements are congruent with the aims of industrial enhancement.

6.5.3 The cost constraint and its systemic effects

Cost pressures, identified as the primary constraint in this study, exert a significant adverse effect on productivity ($\beta = -0.448$), thus hindering modernisation. In addition, the findings of the study indicate that financial limitations hinder modernisation by constraining managerial capabilities, undermining educational initiatives, and diminishing investment inflows.

For component suppliers in South Africa, which operate within very tight margins due to the complexities of global value chains, this situation has considerable implications. Pressures from multinational OEMs for cost efficiency and just-in-time delivery restrict the financial resources available to suppliers for investment in 4IR and 5IR technologies (Higuchi *et al.* 2023). Consequently, the AMI risks becoming ensnared in a cycle characterised by limited capabilities, a focus on cost reduction, and price-based competition rather than focusing on innovation, quality, and digital integration as competitive strategies.

This situation has significant implications for industrial policy, which must change its focus from short-term competitiveness incentives to long-term capability investment and the avoidance of embedded cost-driven constraints. Cost barriers can potentially be reduced through selective subsidies, tax advantages, and concessional lending for digitisation initiatives. Public assistance must also benefit smaller suppliers less adept at absorbing costs than larger OEMs.

6.5.4 Managerial capabilities and organisational learning

The results showing the mediating effects of management reveal a multifaceted dynamic: less robust enterprises encounter challenges in transforming labour availability and infrastructure into advancements in modernisation and productivity, whereas more resilient firms succeed in this endeavour. This observation aligns with the theory of the "capability trap" posited by Repenning and Sterman (2001), which asserts that managers tend to favour immediate problem solving over the implementation of lean methodologies and organisational growth.

This finding reflects a significant disparity within the South African AMI, where managerial skills are often strong within OEMs but may be lacking within smaller component manufacturers. Access to world-class global best practice in lean and digital technologies, as well as leadership-building and managerial skills, is a critical complement to investments in technology. Without this, businesses will be unable to successfully deploy the most recent technologies in manufacturing processes even if they acquire such technologies.

6.5.5 E-commerce and digital enterprise lag

Surprisingly, the integration of digital commerce is the outcome that is least impacted by factors influencing innovation, both directly and indirectly. This suggests that, despite world trends toward platform-based business models, formidable barriers to the digitalisation of supply chains and consumer interfaces still exist.

Beyond firm-level readiness, the findings point to several ecosystem-level barriers that constrain the growth of digital commerce in the AMI. These include fragmented digital platforms across OEMs and suppliers, limited standardisation of data-exchange protocols, and weak interoperability between legacy manufacturing systems and emerging digital platforms. In addition, uneven broadband penetration in peri-urban industrial zones, cybersecurity vulnerabilities, and regulatory uncertainties relating to digital contracting and cross-border data flows impede the ability of firms to scale digital commerce initiatives. These ecosystem constraints offer a broader explanation for why digital commerce consistently emerged as the least responsive outcome in the SEM results despite firms investing in internal technological and human-capital capabilities.

This finding points to a gap in the value chain positioning of the South African AMI. Enterprises that fail to leverage the potential of digital platforms risk not participating in consolidated logistic networks and global procurement systems, which are increasingly reliant on real-time digital data (Loonam and O'Regan 2022). In addition, this finding highlights a competitiveness gap between nascent digital enterprises and physical manufacturing, which has steadily progressed in modernisation.

These observations accentuate a need for ecosystem-level interventions, including the strengthening of cybersecurity regulations, the establishment of trust frameworks for e-commerce, and the provision of incentives for businesses to interact with e-commerce platforms (Abisoye and Akerele 2022). Small businesses could see fewer barriers to entry through collaborative platforms, possibly brokered by trade associations like the NAACAM.

6.5.6 Theoretical implications: Resource-based view and beyond

The study's findings substantiate the RBV, stressing the importance of both physical infrastructure and human capital as key resources for enabling digital transformation. However, the findings go beyond the traditional RBV by also showing that resources alone are insufficient when cost barriers and a lack of managerial abilities prevent their optimal functioning.

The DCT similarly highlights the importance of not only possessing resources but also being able to restructure them in response to technological advances (Teece 2007). The connection between workforce income growth and technology adoption demonstrates that resources do not always yield balanced outcomes. This highlights the significance of implementing institutional and ecosystemic perspectives that integrate industrial, social, and policy factors in the study of modernisation.

6.5.7 Policy implications

Several policy-level implications arising from the findings of this study are discussed below.

6.5.7.1 Workforce development

The South African AMI needs to designate the development of the workforce as its primary strategic priority instead of deferring it as a secondary issue. This can be achieved by expanding vocational training, sanctioning dual education models as seen in Germany and Spain (Bentolila, Cabrales and Jansen 2023; Ertl 2020), and incorporating information technologies into technical education.

6.5.7.2 The role of infrastructure investment in shaping industrial policy

Digital infrastructure, enhanced logistics, and reliable energy supply should be regarded as facilitators of industrial competitiveness rather than as mere public services. The mediations related to infrastructure in this study clearly demonstrate that these foundational elements are crucial for modernisation and productivity enhancement.

6.5.7.3 Cost reduction techniques

The consistently adverse impacts of costs highlight the need for targeted financing frameworks, subsidies for R&D, and economic incentives aimed at alleviating challenges faced by SME suppliers.

6.5.7.4 Developing managerial competence

In addition to investing in technologies, resources should be designated for change management initiatives, the implementation of lean methodologies, and managerial training programmes. Coordination among various stakeholders, such as the government, business communities, and financial institutions, is essential for fostering a secure, affordable, and efficient e-commerce ecosystem.

6.5.8 Socioeconomic implications

The results highlight a significant gap between the welfare of workers and improvements in productivity. In light of the weak relationship between workforce income growth and technology adoption, the rollout of 4IR and 5IR technologies risks worsening inequality unless explicit redistribution policies are adopted. In the South African context, where the manufacturing sector is considered crucial for the achievement of inclusive prosperity, this situation has substantial socioeconomic repercussions. The findings of this study can be used to inform policies for inclusive industrialisation and technology adoption in which the mobility and welfare of workers are mainstreamed.

Additionally, the results highlight the risk of polarisation: large enterprises with advanced management techniques and sophisticated infrastructure are likely to perform better than smaller firms, which risk marginalisation. This results in a dual-tiered industry, with advanced businesses incorporated in value supply chains and less advanced firms confined to low-value markets. Addressing this gap needs to remain a primary issue for policymakers and business executives.

6.6 Chapter summary

This chapter has discussed the results of the study. The chapter began by interpreting the results and comparing them with existing literature. This was followed by a discussion of the results in relation to the AMI, particularly in the South African context, and an examination of the study's novel contributions to literature. Thereafter, the implications of the results for the AMI were examined.

The next chapter summarises the findings, discusses the implications and limitations of the study, and provides recommendations for future research.

CHAPTER SEVEN

CONCLUSION AND FUTURE WORK

7.1 Introduction

The findings of this study were discussed in the previous chapter. This chapter summarises the findings, draws conclusions, and provides recommendations for further research. The chapter begins with a summary of the findings of the study. Thereafter, the implications and limitations of the study are discussed, followed by suggestions for future research. The chapter concludes with a summary.

7.2 Summary of findings

This study set out to examine the interplay between key factors influencing innovation, namely, costs of technology adoption, availability of skilled labour and support for technological infrastructure, and key modernisation outcomes, namely, increased productivity, organisational support for upskilling, workforce income growth, and promotion of digital commerce, within the South African AMI. The study also examined the mediating effects of investment in 4IR and 5IR technologies, education in 4IR and 5IR technologies, and management of 4IR and 5IR technologies on this interplay. The findings, which were obtained by using SEM and bootstrapped mediation analysis to test 48 hypotheses, provided strong empirical evidence for both direct and indirect pathways influencing modernisation. Importantly, with all but one hypothesis supported, the results show a consistent pattern that integrates theoretical expectations with contextual realities in the South African manufacturing environment.

The findings reinforce the study's operational definition of modernisation by showing that productivity, workforce upskilling, income growth, and digital commerce respond differently to the drivers and mediating pathways examined. Productivity and organisational support for upskilling emerge as the most responsive indicators of modernisation, aligning with technological readiness and workforce capability effects identified in the SEM. Workforce income growth shows more modest shifts, reflecting broader labour-market constraints, while digital commerce remains the least responsive outcome due to ecosystem-level barriers. Together, these findings validate the multidimensional framing of modernisation adopted in this study and illustrate how 4IR and 5IR adoption generates uneven but measurable modernisation impacts within the South African AMI.

The short-term impacts highlight the crucial role played by investment and infrastructure in enabling modernisation. On the one hand, strong support for technology infrastructure, such as reliable logistics networks, power supply, and ICT infrastructure, directly increases productivity, empowers organisational support for upskilling, increases income rates, and strengthens electronic commerce. These findings are similar to those of existing studies globally that highlight the role of infrastructure as an integral part of modernisation in the AMI (Kalkha *et al.* 2023; Zhou and Jiang 2024). On the other hand, costs exert an unequivocal negative impact on three of the indicators of modernisation. High power costs, logistical challenges, and increasing input costs hinder the competitiveness of firms, reduce the resources available for innovation, and reduce their ability to pay competitive wages. This finding reflects the well-documented issue of cost pressures being caused by structural inefficiencies in South Africa (Komarasamy and Hoque 2015; NAACAM 2025).

The impacts of education and management are also highly evident. Firms that invest in workforce education and organised management practices fare better in the areas of innovation and productivity. This aligns with the theory of skill-biased technological change, which highlights the value of human capital and managerial skills for the harnessing of new technologies (Goldin and Katz 2018).

The mediation results expanded the analysis by revealing the mechanisms through which infrastructure and costs shape outcomes. Three mediators emerged as critical channels: investment, education, and management. Infrastructure support indirectly improves productivity, organisational support for upskilling, workforce income growth, and promotion of digital commerce through all three mediators. For example, infrastructure support fosters investment in advanced machinery and digital platforms, strengthens partnerships with educational institutions, and supports managerial efficiency. These findings reinforce the enabling role of infrastructure not only as a direct determinant of modernisation outcomes but also as a catalyst for resource mobilisation and organisational capabilities.

Costs exert negative indirect effects through investment, education, and management. High operating expenses constrain capital expenditure, reduce budgets for training, and divert managerial attention to short-term survival strategies. These mechanisms explain why firms under sustained financial strain struggle to modernise, even when digital opportunities exist. This is particularly pronounced in the South African AMI, where thin profit margins leave little scope for reinvestment (Gonyora *et al.* 2021; Komarasamy and Hoque 2015).

The mediated relationships also offer new insights to enhance existing academic research in this area. For instance, while the adverse impact of costs on income and productivity is well established, this study examines how costs are transmitted through numerous mediating channels, amplifying their suppressive impact. Similarly, the findings show that the impact of infrastructure goes beyond direct provision of services to include facilitation of investment, training, and improvements in strategic management.

Taken together, the findings provide a holistic view of modernisation dynamics in the South African AMI. The direct effects of factors that influence innovation, such as infrastructure support, show the foundational importance of these factors in modernisation, while the indirect effects of these factors reveal the systemic ways in which the effects of costs and infrastructural conditions permeate through investment, education, and organisational practices. The mediation results enhance theory by demonstrating that modernisation is not a linear outcome but is contingent on interconnected channels of resource allocation, human capital, and managerial choices.

The findings also provide new insights in the context of the South African AMI. While prior studies have emphasised cost pressures and infrastructure deficits as independent barriers to modernisation, this study shows how these factors cascade through investment, education, and management to shape modernisation outcomes. Similarly, the enabling role of support for technology infrastructure in facilitating promotion of digital commerce and organisational support for upskilling provides empirical support for the SAAM 2035, which stresses interventions integrating skills, technology, and infrastructure (Anzolin 2024; Costa *et al.* 2024).

7.3 Implications of the study

The findings of this study have significant implications for theory, practice, and policy in the context of the South African AMI. By examining the direct effects of factors that influence innovation on modernisation outcomes, as well as the indirect effects of these factors mediated through 4IR- and 5IR-related investment, education, and management, the study contributes new insights that extend existing literature while offering actionable recommendations for firms and policymakers.

7.3.1 Theoretical implications

Theoretically, the results both confirm and extend resource-based and capability-focused views concerning firm performance. The significant direct and mediated effects of infrastructure support emphasise that physical and digital infrastructures serve a dual role, acting both as external facilitators and as internal resources that impact a firm’s ability to invest, manage, and develop skills. This finding aligns with the RBV (Barney 1991) and also extends it by showing how infrastructure indirectly influences firm performance through organisational processes.

The mediated effects of costs also yield new theoretical insights. While previous studies have viewed costs as exogenous constraints, this study finds that costs hinder modernisation by limiting investment, restricting education opportunities, and negatively impacting managerial skills. This multifaceted mediation suggests that modernisation needs to be perceived as an intrinsic process instead of an input-output mechanism. In addition, the study confirms that human capital and skill-biased technological change are central to modernisation (Goldin and Katz 2018;

Sivropoulos-Valero 2021), observing that education and managerial skills act as both direct drivers of modernisation and key mediating channels through which structural variables exert effects.

The SCIT contributes in three ways. Firstly, it repositions organisational support as a strategic resource that monetises into income, crystallises into capabilities, and directly lifts productivity, bridging POS with productivity-centred strategy work (Baccarella *et al.* 2022; Mokhber, Khairuzzaman and Vakilbashi 2018). Secondly, it integrates capability formation and reinvestment into a single architecture in which support creates skills and slack, skills and slack fuel innovation, and innovation transforms operations; this single architecture connects the HCT, the DCT, and endogenous growth theory in a testable chain (Becker 1962; Mairesse, Mohnen and Notten 2025; Teece, Pisano and Shuen 1997). Thirdly, the SCIT clarifies the role of modernisation as a distinct capability domain, that, similar to digital commerce, is both enabled by support and innovation and implicated in the path to productivity, consistent with organisational innovation perspectives (Garcia-Macia and Sollaci 2024; McKinsey 2025).

7.3.2 Managerial and practical implications

For professionals in the AMI, the results highlight the critical nature of an integrated strategy towards modernisation. Firms in the AMI, especially component suppliers, encounter significant cost challenges that restrict their capacity for reinvestment. This study demonstrates that these financial limitations not only adversely affect productivity directly but also hinder mediating paths, such as 4IR- and 5IR-related investment, education, and management, that are essential for sustained competitiveness. This suggests that organisations need to emphasise strategic cost control, including investments in energy efficiency, optimisation of logistics, and implementation of lean methodologies, in order to be able to allocate resources for modernisation efforts.

The critical relevance of education and skills development highlights the need for organisations not to rely solely on capital investments in breakthrough technologies.

Workforce development must be embedded in modernisation strategies to ensure that the workforce has the appropriate capabilities for adaptation and innovation. The results also suggest that high-performing management practices enhance the conversion of resources into performance outcomes. In light of this, businesses need to invest in managerial education, leadership development, and process improvements to maximise the payback on their investments in infrastructure and technology.

The results also indicate that digitalisation and online commerce require more than cost-effective technological platforms. For successful implementation, an enabling environment provided by management and infrastructure needs to be combined with the availability of human resources. Managers should consider digitalisation an integral part of a modernisation strategy rather than a separate investment.
The SCIT emphasises support as a vital strategy for executive management. Support, including funding, acknowledgement, and autonomy, must be institutionalised in order to unleash revenue and skills, systematically channel reinvestment from revenue into innovation, upskill the workforce to achieve modernisation goals, and proactively manage costs by lowering structural overhead while strategically investing in targeted innovation efforts (Baccarella *et al.* 2022; Garcia-Macia and Sollaci 2024).

7.3.3 Policy implications

The study's findings have particular relevance for the development of South African industrial policy, specifically the SAAM 2035. The results confirm the importance of removing cost barriers, such as electricity levies, port inefficiencies, and logistics delays, in improving competitiveness. Without policies for removing these cost barriers, firms will continue to have few investment opportunities and few opportunities for modernisation.

The significant impact of infrastructure in both direct and indirect paths highlights the crucial role of government spending on energy security, transport networks, and ICT networks in enabling industrial progress. Policymakers need to prioritise inclusive infrastructure construction to ensure that businesses can harness the potential of technology.

The significant impact of education as a mediator stresses the importance of close industry-education collaboration. Policies rewarding businesses for participating in skills development initiatives, apprenticeships, and cooperation with technical universities would help remedy the long-standing skills mismatch problem in the AMI.

The significant impact of management as a mediator highlights the need for policy architectures to prioritise organisational and managerial development in businesses, in addition to technology diffusion, through measures such as selective support for SME suppliers.

7.4 Limitations of the study

Although the study adds importantly to existing knowledge on the effect of innovation factors on the modernisation of the South African AMI and the mediating roles of 4IR- and 5IR-related investment, education, and management, various limitations are evident. Firstly, the cross-sectional nature of the data used in the structural model limits the ability to draw causal inferences and to reflect the dynamics over time. Secondly, the focus of the sample on firms that are solely active in the automotive component industry may restrict the generalisability of the findings to other manufacturing fields. Thirdly, while the analysis incorporates key aspects such as expenditure incurred in adopting technology, support of technological infrastructure, and supply of skilled labour, other relevant factors, such as the regulatory environment, firm size, and leadership style, are not included. Finally, the study’s reliance on self-reported data may induce response biases when gauging the perceived impacts of adopting technology. Future studies should utilise longitudinal approaches, allow for wider comparison among various industry fields, and utilise a mixed-method approach to gain a more comprehensive understanding and triangulate the findings.

7.5 Recommendations for future research

Based on the major insights into direct and indirect facilitators and hindrances to modernisation in the South African AMI revealed by this study, several potential future research directions are evident. Firstly, because this study was based on cross-sectional survey data, limiting causal inference, future studies could employ longitudinal approaches to analyse interactions between innovation factors, factors driving adoption of 4IR and 5IR technologies, and modernisation outcomes over the long term. This would allow for stronger causal assertions and richer insights into the dynamic change processes.

Secondly, while the mediating roles of 4IR- and 5IR-related investment, education, and management were a key focus of this study, other mediating variables, such as innovation culture, organisational learning, and collaborative networks, were not examined. These mediators could significantly affect modernisation outcomes and should be explored in future models.

Thirdly, the results indicate that the growth of digital commerce is highly influenced by factors revolving around cost and managerial limitations. Subsequent studies could explore the phenomenon of digital transformation in more depth by examining the mechanisms by which business enterprises incorporate Industry 4.0 technologies, including automation, AI, and data analytics, into mainstream manufacturing techniques. Comparisons between South African firms and their counterparts in other emerging markets could yield deeper insights into contextual enablers and challenges.

Fourthly, this study's focus on component manufacturers reflects the predominance of such firms in the South African AMI. Although this focus yields relevant industry-specific information, expanding the scope of subsequent studies to OEMs and downstream value chain players could enable a more comprehensive understanding of the modernisation process.

Fifthly, the use of qualitative approaches, including interviews and case studies, could complement quantitative results by providing rich, contextual understanding of the experiences of employees and managers facing challenges with modernisation. Such approaches are particularly effective in gaining insight into complex phenomena, such as leadership styles, organisational culture, and points of view among employees, which often cannot be measured quantitatively. The use of such approaches in future studies could provide deeper insight into the dynamics of modernisation and assist in the development of competitiveness strategies for the South African AMI that benefit from the local context.

Finally, the marginally significant impact of costs on innovation ($p = 0.065$) observed in the SEM results calls for studies that disaggregate costs into operational and capital components and probe non-linear, U-shaped relationships. In line with contemporary innovation-productivity research, longitudinal or quasi-experimental studies could strengthen causal claims and test moderated mediation (Baccarella *et al.* 2022; Mairesse, Mohnen and Notten 2025). While this study models modernisation as an outcome of support and innovation, future studies could examine the conditions under which modernisation directly increases productivity, potentially contingent on technology, process fit and absorptive capacity.

7.6 Chapter summary

This concluding chapter has summarised the findings of the study, discussed the implications of the study, and provided recommendations for future research. The chapter began with a summary of the findings of the study. Thereafter, the implications and limitations of the study were discussed, followed by suggestions for future research.

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ANNEXURE A: ETHICAL CLEARANCE

Institutional Research Ethics Committee
Research and Postgraduate Support Directorate
2nd Floor, Berwyn Court
Gate 1, Steve Biko Campus
Durban University of Technology

P O Box 1334, Durban, South Africa, 4001

Tel: 031 373 2375
Email: lavishad@dut.ac.za
http://www.dut.ac.za/research/institutional_research_ethics

www.dut.ac.za

16 June 2025

Mr M L Nzama
39 Dilkoosh Road
Queensburgh
4093

Dear Mr Nzama

Economic impact of 4IR/5IR technologies on the automotive manufacturers
Ethics Clearance Number: IREC 255/24

The DUT-Institutional Research Ethics Committee acknowledges receipt of your final data collection tool for review.

We are pleased to inform you that the data collection tool has been approved. Kindly ensure that participants used for the pilot study are not part of the main study.

In addition, the DUT-IREC acknowledges receipt of your gatekeeper permission letters.

Please note that FULL APPROVAL is granted to your research proposal. You may proceed with data collection.

Any adverse events [serious or minor] which occur in connection with this study and/or which may alter its ethical consideration must be reported to the DUT-IREC according to the DUT-IREC SOP's.

Please note that any deviations from the approved proposal require the approval of the DUT-IREC as outlined in the DUT-IREC SOP's.

It is compulsory for a student or researcher to apply for recertification on an annual basis. The failure to do so will result in withdrawal of ethics clearance. It is the responsibility of the researcher and the supervisor to apply for recertification.

Please note that you are required to submit a Notification of Completion of Study form together with an abstract to the DUT-IREC office on completion of your study.

Yours Sincerely

Professor P Mashau
Chairperson: DUT-IREC

ANNEXURE B: GATEKEEPERS' LETTERS

NAACAM
National Association of Automotive Component and Allied Manufacturers

Allhart Office Park, Building 5, 1st Floor,
152 Western Service Road, Woodmead, 2191

Postnet Suite# 597, Private Bag 29
Gallo Manor, Gauteng, 2052

+27 (0)11 392-4060
www.naacam.org.za
info@naacam.co.za

29 May 2025

To Whom It May Concern,

RE: PERMISSION GRANTED TO CONDUCT STUDY ON ECONOMIC IMPACT OF 4IR/5IR TECHNOLOGIES

This letter serves to formally confirm that Mr. Manqoba Nzama, a researcher at Durban University of Technology, has been granted permission to conduct a research study titled **"Economic Impact of 4IR/5IR Technologies on the Automotive Manufacturers".**

While NAACAM is unable to distribute the survey directly, we have provided Mr. Nzama with access to our approved, public and POPIA compliant mailing list for the purpose of contacting relevant companies independently.

We trust this letter satisfies the requirements of the Institutional Research Ethics Committee (IREC). Should you require any further information or clarification, please do not hesitate to contact us.

Best regards,

Beth Dealtry

Head: Policy & Regulatory Affairs

NAACAM

beth@naacam.co.za

naamsa THE AUTOMOTIVE BUSINESS COUNCIL
naamsa NINETY
Block F Alenti Office Park
457 Witherite St | The Willows X82
PRETORIA | 0184
info@naamsa.co.za
www.naamsa.net
+27 12 807 0152

Wednesday,

May 28, 2025

To Whom It May Concern,

Subject: Permission Granted to Conduct Study

This letter serves to formally confirm that Mr. Manqoba Nzama, a researcher at Durban University of Technology, has been granted permission to conduct a research study titled **"Economic Impact of 4IR/5IR Technologies on the Automotive Manufacturers".**

While it is not naamsa | The Automotive Business Council's policy to distribute the survey directly to its members, Mr. Nzama is welcome to contact naamsa member companies directly to complete the survey. The naamsa office would be happy to facilitate, to encourage member companies to participate in the post graduate study survey in the interest of the domestic automotive industry as well as to participate in an interview.

We trust this letter satisfies the requirements of the Institutional Research Ethics Committee (IREC). Should you require any further information or clarification, please do not hesitate to contact us.

Best regards

Dr Norman LAMPRECHT

Chief Trade and Research Officer

Mobile: 082 829 1692

ANNEXURE C: CONSENT LETTER

LETTER OF INFORMATION

Title of the Research Study: Economic impact of 4IR/5IR technologies on the automotive manufacturers

Principal Investigator/s/researcher: Manqoba Nzama, MMSc

Co-Investigator/s/supervisor/s: Prof. Oludayo Olugbara, PhD (Com Sie); Dr. Smangele Moyane, PhD (LIS)

Brief Introduction and Purpose of the Study:

Hello,

I hope this message finds you well. My name is Manqoba Lwazi Nzama, and I am a PhD student at DUT pursuing a Doctor of Philosophy in Business and Information Management degree. As part of my degree requirements, I am conducting research on the Economic impact of 4IR/5IR technologies on the automotive manufacturers.

I would like to invite you to participate in this research study. Your participation is entirely voluntary, and your insights will be invaluable in helping us better understand the impact that 4IR and 5IR technologies have on the automotive industry in South Africa which is crucial for ensuring economic competitiveness, fostering innovation, supporting workforce development, promoting sustainability, and guiding informed policymaking.

What is Research
Research is a systematic search or inquiry aimed at generating new, generalized knowledge that can benefit society. Through this study, I aim to explore in detail the significant and far-reaching effects that 4IR and 5IR technologies are having on automotive manufacturers.

You are being invited to participate because your expertise and experience as a Head of Manufacturing or Operations, Plant Manager, Chief Technology Officer, or in a related role within the automotive industry, make you uniquely qualified to provide valuable insights into the adoption and implementation of 4IR/5IR technologies in manufacturing processes. Please feel free to ask any questions you may have about the study. It's important to me that you fully understand what participation involves before making any decision. You are welcome to discuss the study with your family and friends, and you are under no obligation to decide immediately. I will provide you with a copy of this document to take home for further consideration.

Outline of the Procedures: The aim of this study is to examine the influence of technology adoption costs, analyze the effect of skilled worker availability, assess the role of technology infrastructure support, and evaluate the economic implications—including productivity enhancement, organizational support for upskilling, worker income growth, and digital commerce expansion—on automotive manufacturers' decisions regarding the adoption of 4IR/5IR technologies. To achieve this, I will be, I will be conducting surveys with key stakeholders within the automotive industry to gather their insights and experiences related to the adoption and implementation of these technologies.

As a participant, you will be asked to complete a survey. This will take approximately 15-30 minutes. The survey will be conducted online to provide more convenience for you.

Risks or Discomforts to the Participant: There are no foreseeable risks or discomforts associated with this study. However, if you feel uncomfortable at any point, you are free to stop or withdraw from the study without any consequences. Your participation is completely voluntary.

Explain to the participant the reasons he/she may be withdraw from the Study: You may withdraw from the study at any time, for any reason, without any penalty or loss of benefits to which you are otherwise entitled. If you decide to withdraw, you will continue to receive any standard care or benefits you would have received regardless of the study. The researcher may also withdraw you from the study if necessary, for reasons such as non-compliance, illness, or any adverse reactions.

Benefits: While there may not be any direct benefits to you personally from participating in this study, your participation will contribute to a broader understanding of how 4IR/5IR technologies are being adopted and implemented within the automotive industry. This research may benefit others by providing valuable insights that could guide more effective technology integration strategies, enhance workforce development programs, and inform policy decisions that support the sustainable growth of the industry.

Remuneration: You will not receive any monetary or other types of remuneration for your participation in this study.

Costs of the Study: There are no costs to you for participating in this study.

Confidentiality: Your privacy and the confidentiality of your information are of utmost importance. All information collected in this study will be kept strictly confidential. Data will be anonymized, and your identity will not be disclosed in any reports or publications. Only the research team will have access to the data, and it will be stored securely in a password-protected file.

Results: The results of this study will be shared through a publication of the thesis which will be available freely at the DUT open scholar.

Research-related Injury: This online questionnaire is designed to pose minimal risk to participants. However, if you experience any discomfort, stress, or other negative effects that you believe are directly related to participating in this research, please take the following steps:

Immediately discontinue the questionnaire. If you are experiencing any medical emergency, please seek immediate medical attention or call your local emergency services. For non-emergency concerns related to this research, please contact the research team.

Please note that this study does not provide compensation for research-related injury. Any costs incurred due to research-related injury would be your responsibility or that of your insurance provider. Your well-being is our priority. If you have any questions or concerns at any point during or after the questionnaire, please don't hesitate to reach out to the research team.

Storage of all electronic and hard copies including tape recordings All electronic and hard copies of the data, including any recordings, will be stored securely for five years after the completion of the study. After this period, the data will be securely destroyed. Only the research team will have access to the data during this time.

Persons to contact in the Event of Any Problems or Queries: Please contact the researcher on 081 714 4303, my supervisor Prof. Moyane on 083 660 8045 or the Institutional Research Ethics Administrator on 031 373 2375. Complaints can be reported to the Acting Director: Research and Postgraduate Support Prof K Motaung on TtiDirector@dut.ac.za

CONSENT

Full Title of the Study: Economic impact of 4IR/5IR technologies on the automotive manufacturers

Names of Researcher/s: Manqoba Nzama

Statement of Agreement to Participate in the Research Study:

- I hereby confirm that I have been informed by the researcher, Manqoba Nzama, about the nature, conduct, benefits and risks of this study - Research Ethics Clearance Number: IREC 255/24,
- I have also received, read and understood the above written information (Participant Letter of Information) regarding the study.
- I am aware that the results of the study, including personal details regarding my sex, age, date of birth, initials and diagnosis will be anonymously processed into a study report.
- In view of the requirements of research, I agree that the data collected during this study can be processed in a computerised system by the researcher.
- I may, at any stage, without prejudice, withdraw my consent and participation in the study.
- I have had sufficient opportunity to ask questions and (of my own free will) declare myself prepared to participate in the study.
- I understand that significant new findings developed during the course of this research which may relate to my participation will be made available to me.

______________________	__________	__________	____________________________
Full Name of Participant	**Date**	**Time**	**Signature / Right Thumbprint**

I, ________________________ (name of researcher) herewith confirm that the above participant has been fully informed about the nature, conduct and risks of the above study.

___________________________________	_________	______________________
Full Name of Researcher	**Date**	**Signature**
___________________________________	_________	______________________
Full Name of Witness (If applicable)	**Date**	**Signature**
___________________________________	_________	______________________
Full Name of Legal Guardian (If applicable)	**Date**	**Signature**

ANNEXURE D: QUESTIONNAIRE

Dear Participant,

Thank you for participating in this survey. Your input is crucial for our research on the Economic impact of 4IR/5IR Technologies on the Automotive manufacturers. Please answer the following questions to the best of your ability. Your responses will be kept confidential and used for research purposes only.

1. Demographic information

1.1 Which age range do you belong to: [ ] (18-25;26-30;31-35;36-40;41-45;46-50;51+)

1.2 Which gender do you identify with: [ ] (Male / Female)

1.3 What is the highest Education Level you have attained: [ ] (High School /Higher certificate/Diploma/ Bachelor's Degree / Honours Degree/Master's Degree / PhD or equivalent)

1.4 What position do you currently occupy? : [ ] (Chief Technology Officer (CTO); Head of Digital Transformation; Chief Information Officer (CIO); Head of Research and Development (R&D); Operations/Plant/General Manager; Technology Officer/Related Position; R&D.

1.5 How long have you worked in the automotive manufacturing sector?: [ ]

1.6 Please select the type of automotive sector you are currently working on: [ ] (Passenger Vehicle Manufacturers; Light Commercial Vehicle (LCV) Manufacturers; Medium and Heavy Commercial Vehicle (MCV and HCV) Manufacturers; Automotive Component Manufacturers)

2. Factors of 4IR or 5IR technology adoption

On a scale of 1 to 5, please indicate your level of agreement with the following statements, where 1 indicates "Strongly Disagree" and 5 indicates "Strongly Agree."

Adoption of 4IR/5IR technologies	Strongly disagree	Disagree	neutral	Agree	Strongly agree
1. The financial investment in 4IR/5IR technologies has led to an increase in our productivity.					
2. The availability of skilled labour for 4IR/5IR technologies has enhanced overall productivity in our organization.					
3. Continuous professional development programs for 4IR/5IR skills have supported the upskilling of our employees.					
4. The cost of adopting 4IR/5IR technologies is a barrier to our organization.					
5. The adoption of 4IR/5IR technologies has resulted in notable productivity gains.					
6. Organizational support for upskilling has increased due to 4IR/5IR technology adoption.					
7. Our organization has seen a substantial promotion of digital commerce following the adoption of 4IR/5IR technologies.					

3. Factors influencing innovation of AMI

On a scale of 1 to 5, please indicate your level of agreement with the following statements, where 1 indicates "Strongly Disagree" and 5 indicates "Strongly Agree."

Cost of Technology Adoption	Strongly disagree	Disagree	neutral	Agree	Strongly agree
1. The cost of adopting 4IR/5IR technologies is a significant barrier.					
2. The financial investment required for 4IR/5IR technologies is manageable.					
3. Our organization has allocated sufficient budget for 4IR/5IR adoption.					
4. Cost-benefit analyses are conducted to justify 4IR/5IR technology investments.					
5. We have access to financial incentives or subsidies for 4IR/5IR adoption.					
Availability of Skilled Labour	**Strongly disagree**	**Disagree**	**neutral**	**Agree**	**Strongly agree**
1. We have access to the skilled labour needed to implement 4IR/5IR technologies.					
2. There are adequate training programs for 4IR/5IR skills in our organization.					
3. The current workforce is prepared for the transition to 4IR/5IR technologies.					
4. We actively recruit new talent with expertise in 4IR/5IR technologies.					
5. Continuous professional development is encouraged and supported.					
Support for Technology Infrastructure	**Strongly disagree**	**Disagree**	**neutral**	**Agree**	**Strongly agree**
1. Our organization has the necessary technological infrastructure for 4IR/5IR adoption.					
2. There is strong support for technological advancements within the company.					
3. We have partnerships with technology providers to support 4IR/5IR implementation.					
4. Our IT systems are regularly updated to support new technologies.					
5. We have a dedicated team to manage and support 4IR/5IR technology integration.					

4. Factors of modernisation of AMI

On a scale of 1 to 5, please indicate your level of agreement with the following statements, where 1 indicates "Strongly Disagree" and 5 indicates "Strongly Agree."

Increased Productivity	**Strongly disagree**	**Disagree**	**neutral**	**Agree**	**Strongly agree**
1. The adoption of 4IR/5IR technologies has increased productivity.					
2. Our organization has experienced faster turnaround times for projects.					
3. 4IR/5IR technologies have effectively streamlined processes and workflows.					
4. We have observed a notable reduction in manual labour and repetitive tasks.					
5. Labour productivity levels have improved with the use of 4IR/5IR tools.					
Organizational Support for Upskilling/Technological advancement	**Strongly disagree**	**Disagree**	**neutral**	**Agree**	**Strongly agree**
1. Our organization provides ample opportunities for upskilling in 4IR/5IR technologies.					
2. Employees receive adequate training for new technological advancements.					
3. There is strong support for continuous learning and development.					
4. Training programs are tailored to address specific 4IR/5IR skills.					
5. Upskilling initiatives are aligned with our strategic goals.					
Workforce Income Growth	**Strongly disagree**	**Disagree**	**neutral**	**Agree**	**Strongly agree**
1. The adoption of 4IR/5IR technologies has led to higher income for the workforce.					
2. Employees have experienced financial growth due to upskilling opportunities.					
3. There are noticeable improvements in employee compensation post-4IR/5IR adoption.					
4. The organization offers performance-based incentives related to 4IR/5IR skills.					
5. Salary scales have been adjusted to reflect new technology competencies.					
Promotion of Digital Commerce	**Strongly disagree**	**Disagree**	**neutral**	**Agree**	**Strongly agree**
1. 4IR/5IR technologies have significantly promoted digital commerce in our company.					
2. There is a noticeable increase in online transactions and digital sales channels.					
3. Our digital commerce strategies have been enhanced by adopting 4IR/5IR technologies.					
4. We have developed new digital products/services due to 4IR/5IR adoption.					
5. Customer engagement through digital platforms has increased.					