



Re-modelling technological innovation
and its impact on economic growth in
South Africa

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DEDICATION

This dissertation is a proud dedication to me. A dedication to all the possibilities I can be. Most importantly, this dissertation is dedicated to my Mother! Every moment that was spent on this paper was dedicated to making you proud. You may have not been able to experience the entire process to its fullest, but you've always been my guiding light, my steadfast shadow anchoring me through it all. Thank you, Mom!

DECLARATION

I, Patrick Radebe declare that

**Re-modelling technological innovation and its impact on economic growth in
South Africa.**

Is my original contribution, and all sources referenced or utilised have been fully cited and acknowledged through complete references. Furthermore, I affirm that this dissertation, in whole or apart, has not been submitted for degree purposes at any other university.

Patrick Radebe

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ABSTRACT

The 4th Industrial Revolution has nudged global economies to shift towards a more digital environment, to which the global economies have to adapt. However, developing nations have experienced a stagnant growth of technological innovation. One significant culprit behind slow technological innovation is that existing measures of technological innovation fail to fully capture the divergent facets of technological innovations in developing countries such as South Africa. Moreover, it is the diffusion rather than the invention of technologies that determines the trajectory in which technological innovation will reflect on economic growth. Therefore, this study aimed to re-model the measure of technological innovation and assess its impact on economic growth in a developing country context like South Africa.

Despite South Africa experiencing a surge in digital penetration, the country still faces the challenge of the digital divide. The digital divide hampers the ability of the larger population to fully participate in and benefit from the opportunities brought forth by the 4th Industrial Revolution, exacerbating inequality, stagnant technological innovations and economic growth. This problem is further compounded by the lack of a comprehensive measure of technological innovation due to measures often focusing on indicators. As a result, the aim of the study was to construct the 4th Industrial Revolution adjusted Technological Innovation Index (IRTII) for measuring technological innovation and to measure its impact on economic growth in South Africa.

To attain the primary results of the study, the Principal Components Analysis (PCA) principle was adopted to construct the index, and the Autoregressive Distributed Lag (ARDL) model was modelled to analyse annual time series data from 1992-2022 to measure the impacts of technological variants on GDP growth. The key findings from this research demonstrate that the IRTII has a positive long-run and short-run significant impact on economic growth. The impulse response further highlights that there is a positive statistically significant shock between the IRTII and economic growth. The study concludes that there is a positive link or impact between the constructed index IRTII and economic growth.

Key Words: Technological innovation, economic growth, digital adoption, South Africa, policy frameworks

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LIST OF ABBREVIATIONS

4IR	Fourth Industrial Revolution
ADF	Augmented Dickey Fuller
AI	Artificial Intelligence
ARDL	Autoregressive Distributive Lag
CAGR	Compound Annual Growth Rate
CSIR	Council for Scientific and Industrial Research
DST	Department of Science and Technology
DTI	Department of Trade and Industry
ECM	Error Correction Model
FDI	Foreign Direct Investment
GDP	Gross Domestic Product
GMM	Generalised Methods of Moments
HCD	Human Capital Development
ICT	Information Communication and Technology
IoT	Internet of Things
IPAP	Industrial Policy Action Plan
IPR	Intellectual Property Rights
IPRS	International Property Rights Index
IRTII	Industrial Revolution Technological Innovation Index

ML	Machine learning
NDP	National Development Plan
OLS	Ordinary Least Squares
PC4IR	Presidential Commission on the 4th Industrial Revolution
PCA	Principal Component Analysis
PRA	Property Rights Alliance
SMMEs	Small Micro Medium Enterprises
SVAR	Structural Vector Autoregression
TFP	Total Factor of Production
TIA	Technology Innovation Agency
USA	United States of America
VAR	Vector Autoregressive
VR	Virtual reality
WIPO	World Intellectual Property Organisation's

CHAPTER ONE: INTRODUCTION

1.1. INTRODUCTION AND BACKGROUND TO THE STUDY

The industrial Revolution, driven by steam power and computers, has led to a surge in technological innovation that has increased production levels, reduced costs, and improved living standards for decades (Schwab, 2016). For example, the use of artificial intelligence has improved communication within factory plants and reduced the costs of production in various industries (Ng *et al.*, 2021). Hence, it has been argued that technological innovation is another significant driver of economic growth (Jones, 2019). Economists define technological innovation as the process of reducing costs and increasing the quality of goods and services produced (Spolaore & Wacziarg, 2013). Bujaria and Martínezb (2016) further accentuate that the process of technological innovation involves a combination of innovation activities such as investment in newer technologies, knowledge generation, investment in research and development, information, finance, business, and human resources.

Maher, Chraiti, Laabi, Oikawa, Oyekan, and Bosson (2021) argue that, historically, developing nations have experienced a stagnant growth of technological innovation. One significant culprit behind slow technological innovation is that existing measures of innovation fail to fully capture the divergent facets of technological innovations in developing countries such as South Africa (Cruz-Cázare *et al.*, 2013; Armbruster *et al.*, 2008; Manzini, 2015). This makes it difficult for developing economies to identify what technological innovation entails in their context, and where they should direct investment if they were to increase technological innovation. For example, Desai, Fukuda-Parr, Johansson and Sagasti (2000) asserted that Intellectual Property Rights (IPR) have been largely attributed to be the highest/primary indicators for measuring technological innovation; however, this measure does not capture the adoption of the use of technological products and services. Additionally, Jiménez-Gómez and Acevedo-Prins (2018) postulate that measures often focus on indicators rather than focusing and relying on direct achievements, and the adoption of technological innovation such as the success

of technologies in the informal sectors. Hence, it is difficult to fully measure the effects of technological innovation in developing countries like South Africa.

Hall and Khan (2003) further argue that in developing countries, it is largely the diffusion rather than the invention of technological innovation that determines the trajectory in which technological innovation will reflect on economic growth and productions levels. Hall and Khan (2003) define technological diffusion as the process by which new technologies spill over into various industries, areas, and sectors, and involves the gradual adoption of technologies in different segments of the economy. In a country like South Africa, elements such as low skills, capital goods sector, the development of market structures, government and regulation, geography, and cultural/ideological shifts, are some of the reasons behind the slow adoption of an industrial revolution (Raj *et al.*, 2020). Roodt and Koen (2020) further emphasise that developing countries have challenges in the adoption of the industrial revolutions because there are high levels of inequality which affects the economic outlook when implementing technological innovation initiatives. For example, there are some communities with access to the internet and smartphones, whilst other communities do not even have access to clean running water, electricity, and the basic infrastructure, which hinders the adoption of the 4th industrial revolution (Kylne, 2019).

Developing countries are further challenged by the lack of digital roadmap strategies, the concern over the potential of social unrest because automation will reduce the chances of offering low-cost labour, and the economic factors related to corruption levels, weak institutions, high levels of debt, and limited access to funding, have all contributed towards the slow adoption of industrial revolutions (Raj *et al.*, 2020). Against this background, the fundamental objective of this study is to construct a multi-dimensional measure of technological innovation in South Africa. However, the point of departure is to measure the impact of multi-dimension technological innovation, such as ours, on economic growth in South Africa. While technological innovation has led to numerous positive changes and advancements, it is crucial to approach this study with a critical and nuanced perspective that considers its multifaceted impacts on society and the economy.

1.2. TECHNOLOGICAL INNOVATION IN SOUTH AFRICA

The study focuses on South Africa because even though the country has a long and diverse history with technological innovation, its impact is not yet fully understood. South Africa's history of technological innovation dates back to the pre-colonial era, when iron smelting, pottery-making, and painting technologies were developed (Green, 2013). However, modern technological innovation activities surged during the colonial years, which saw the introduction of technologies and industries from European countries, from the 19th century to the 20th century, as highlighted by Scerri (2009). The Africa Mining IQ (2018) indicated that South Africa started experiencing a mining boom during the colonial era through the discovery of diamonds and gold, which resulted in the development of advanced mining technologies and the use of heavy machines for industrialization.

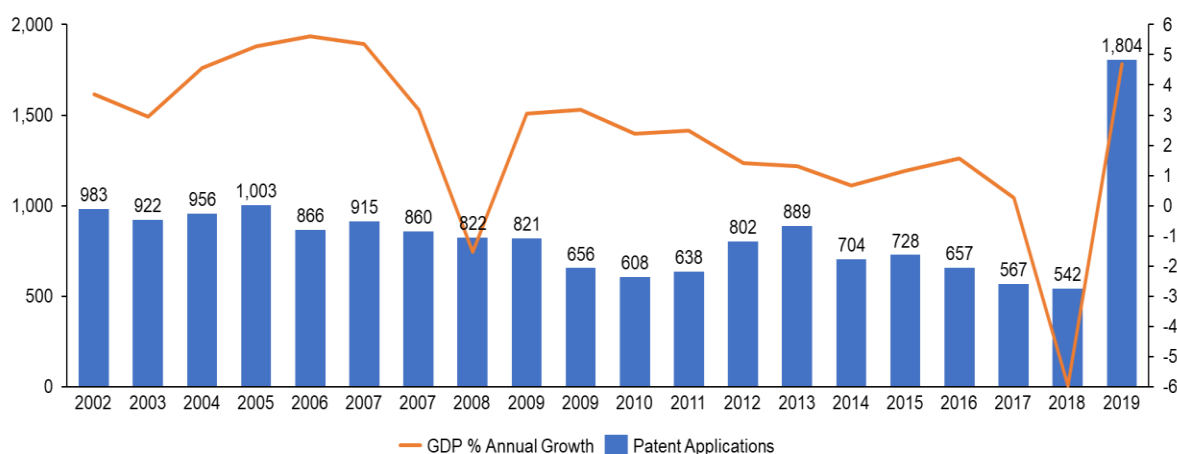
During the mining boom and industrialization phase, South Africa, like the rest of the world, invested heavily in scientific research and development to increase industrialization and improve the standard of living. This resulted in the establishment of the Council of Scientific and Industrial Research (CSIR) in 1945 (Lutjeharms & Thomson, 1930). The CSIR exposed South Africa to foreign technological innovation and increased research investment, leading to the first use of the first computer operating system CTOS in 1952 (My Broadband, 2015). Following the end of apartheid, the South African government implemented more rationalized structures aimed at fostering research and development, which led to increased technological innovation activities and the establishment of tech companies such as Vodacom and Altech (Flowerday, 2015). However, South Africa's technological innovation levels still fall short compared to its peers (Pouris, 2012).

The World Intellectual Property Organization's (WIPO) 2021 Global Innovation Index report assesses the technological innovation performance trends of 123 countries using a wide range of indicators such as technological progress and socio-economic impact. South Africa is ranked 61 out of the 123 countries evaluated. This places South Africa behind developed countries like the United States of America (USA) and Japan. For instance, the USA recorded 729,169 industries in Information Communication and

Technology (ICT), Japan recorded 336,409, and South Africa recorded only 5,948. Additionally, the Department of Science and Innovation (2022) reported that domestic patents granted to South African citizens declined by approximately 50 percent, non-resident patents granted declined by over 42 percent, and South Africa received only 25 patent applications per million population in 2020, while the average patent application in middle-income countries is 641.

Researchers such as Cui *et al.* (2016) have highlighted the ongoing debate surrounding the relationship between technological innovation and economic growth. Specifically, South Africa's lack of or slow implementation of technological policies centred on the 4th industrial revolution has contributed towards only slight growth in the economy. Adams (2020) postulates that although the South African government has esteemed the importance of the 4th industrial revolution by establishing the Presidential Commission on the 4th Industrial Revolution (PC4IR) to aid South Africa optimally position itself in the global stage of the industrial revolution, the policy has fallen short in the urgency of implementing the suggested recommendations. The lack of implementation of the recommendations hinders the support aimed at supporting SMMEs, and optimising the delivery of human capital, health services, and transportation. The challenges in implementing the frameworks such as the PC4IR has resulted in the slow growth of the economy.

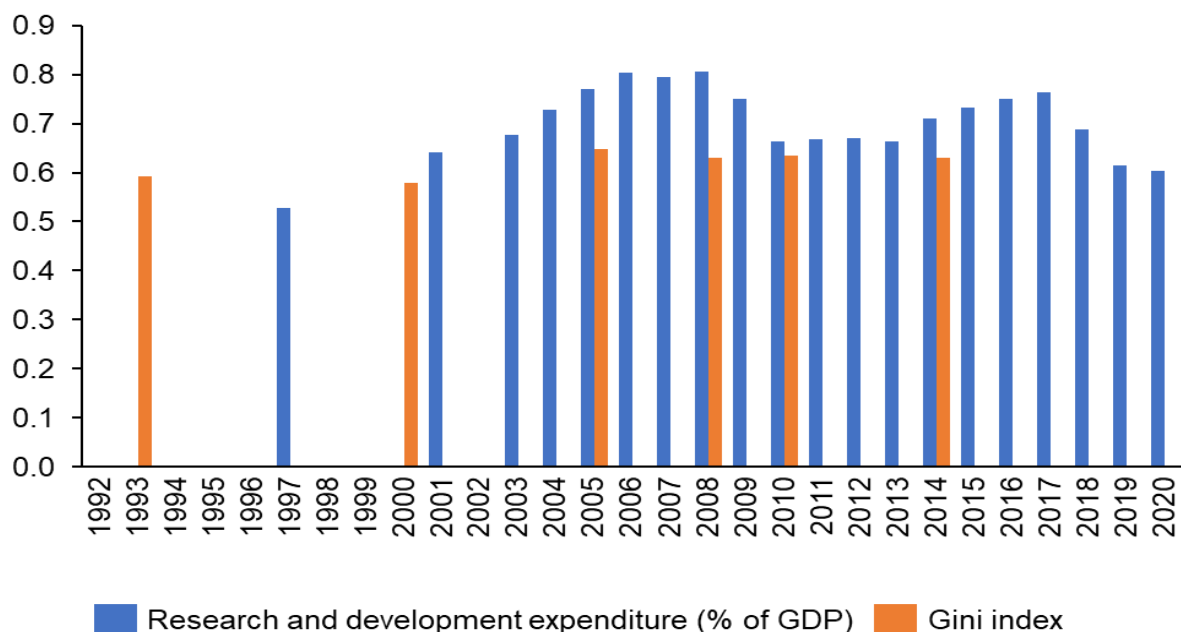
Figure 1: Economic Growth vs Patent Applications South Africa



Source: World Bank (2021)

According to Figure 1, the universal yet traditional indicator of showing the growth in technological innovation, patent applications/IPR, reflects that technological innovation progression was on a downward trend from 2007, and worsening in 2018; similarly, economic growth was on a downward trend from 2007 until 2018. This downward co-movement of technological innovation and economic growth implies that in the case of South Africa, it cannot be ignored that slow technological innovation has contributed to slow economic growth. Figure 1 further shows a spike in patent applications from 2018 to 2019. According to Idea Nav (2022), the surge in patent applications in South Africa has been a result of the continued absorption of digital systems. Gouvea and Gutierrez (2023) emphasise that in the 21st century, technological innovation is an essential element for economic growth, and South Africa's inability to keep up with technological advancements hinders its economic development. Despite some investments in research and development in fields such as renewable energy and biotechnology, South Africa still lags behind many other countries in terms of technological innovation overall (Department of Science and Innovation, 2022). This shortfall puts the country at a disadvantage in attracting foreign investment and achieving growth of GDP per capita.

Figure 2: Research and Development Expenditure (%GDP) and Gini Index: South Africa



Source: World Bank (2021)

Figure 2 depicts the comparison of R&D expenditure and the Gini coefficient in South Africa. The increase in R&D from 1997 did not have a strong impact on nor cause a shift in the income inequality gap. The disparity may be attributed to the understanding that as new technologies are developed, those demographic segments with higher skills, education, or access to the new technologies tend to benefit more, widening the inequality gap (Chan *et al.*, 2022). According to Mzekandaba (2024), South Africa's R&D expenditure has been affected by a number of factors such as budgetary constraints, policy shifts such as tax incentives for R&D, and economic instabilities, which have reduced public and private investment in R&D. As a results R&D expenditure, as a percentage of GDP, has been stagnant. Without a deliberate effort to continuously bridge the technological innovation gap, South Africa's economy will continue to struggle and fall behind.

Broughel and Thierer (2019) highlight that policymakers' attitudes toward technological innovation in the 4th Industrial Revolution have negatively affected policies aimed at fostering technological innovation. This is because the rapid growth of technological innovation poses challenges for policymakers, governments, and societies to adapt to its changes, and presents threats related to job creation, inequality, production levels, and sustainability. Wyckoff (2015) suggests that technological innovation was initially perceived as a means of increasing productivity and improving lives. However, as it has become more complex and integrated, scrutiny of its impact on society has increased, leading to different perspectives on its use. This outcome has influenced the development of principles of technophobia and technophilia. Richards (1993) explains that technophobes perceived innovations, such as the new manufacturing machines, steam engines, power looms, and steel and iron production techniques during the first industrial revolution, as a threat to conservative ways of living, such as farming. Conversely, during the Age of Science and Engineering, Information Age, and Digital Age, technophiles saw technological advancement as the advancement of humanity, economies, and the improvement of standards of living, despite concerns raised by technophobes. According to Wyckoff (2015), technophiles view technological innovation as the foundation of our economies, driving industrial revolutions through transportation, medicine, and the internet, enabling us to solve complex problems and connect people, goods, and services

across the world. However, the impact of technological innovation has yielded varied and sometimes conflicting results, highlighting the complexities and nuances involved in its analysis. While Kritowski (2012) argues that technological innovation is critical for economic progress and societal well-being, other studies have shown that it has contributed to increasing income inequality.

For example, Aghion, Akcigit and Howitt (2019) found that the increase in technological innovation in the United States increased income inequality, with the top one percent quartile and other income quartiles benefiting more. Similarly, Kanbur *et al.* (2014) found that technological innovation in Asian countries widened the income gap, by increasing the demand for skilled labour while reducing the demand for semi-skilled and non-skilled labourers. Additional studies that have reported similar results include Qureshi (2021), Adriano (2020), Rotman (2014) and Acemoglu (2003) that have highlighted the potential negative effects, such as job displacement and a lack of sustainable development in middle- to low-income countries. On the other hand, Hodula (2023), Jaumotte *et al.* (2013), and Vona and Patriarca (2011) have demonstrated that technological innovation is associated with a reduction in inequality. Kahn *et al.* (2020) stressed that technological redundancies may result in an unemployment crisis due to the efficiencies that are created in specific sectors in the economy. Additionally, Kahn *et al.* (2020) has shown that technological innovation ultimately creates more jobs than it eliminates, fosters economic growth, and supports long-term sustainable development in high-income countries. A one-size-fits-all conclusion cannot be drawn, and further research is necessary to comprehensively understand the multifaceted effects of technological innovation and devise effective policies that maximise its benefits while mitigating negative consequences.

According to Kelly *et al.* (2021), the traditional approach to measuring technological innovation overlooks other important forms of digital technological innovation, such as social innovation, business model innovation, open innovation, and financial development. Iqbal and Piwowar-Sulej (2022) allude that social innovation involves developing and implementing new solutions to social problems, while business model innovation creates new ways of doing business that can disrupt traditional markets. Open

innovation, on the other hand, refers to the collaboration and sharing of ideas and resources across organizational boundaries (Hameed *et al.*, 2021). Excluding these essential forms of technological innovation, the traditional approach to measuring technological innovation fails to provide a comprehensive picture of technological innovation in the modern economy, where technological innovation is a continuous process (Kelly *et al.*, 2021). Moreover, this narrow approach may discourage investment in non-technological forms of innovation, leading to a lack of diversity in the technological innovation ecosystem. The concept of technological innovation has evolved, and with the advent of the 4th Industrial Revolution, there has been a critical evaluation of technological innovation due to its multifaceted and complex nature.

1.3. PROBLEM STATEMENT

Lower growth rates of technological innovation in South Africa have been considered to be another significant culprit behind stagnant economic growth in South Africa (Kahn, Sithole & Buchana, 2022). This problem is further compounded by the lack of a suitable measure of technological innovation for South Africa. This makes it challenging to appropriately measure the impact of technological innovation on economic growth, thereby impeding the ability of policymakers to adequately design policies geared towards stimulating technological innovation and economic growth. Other facets of the challenge include the challenge of integrating old and new technologies, data security, skills, and talent gaps, and sustainable IT systems when measuring technological innovation. These challenges have negatively impacted the country's economic growth (My Broadband, 2020).

To address this problem, a more inclusive approach to measuring technological innovation is needed (Petersen & Kruss, 2019). This approach should not only include technological advancements but also consider social innovation, business model innovation, and financial development (Oeij *et al.*, 2019; Hsu *et al.*, 2004). This would provide a comprehensive picture of technological innovation in the modern economy and could lead to more effective investment strategies and policies to support innovation (Bujaria & Martínezb, 2016). The study by Kahn *et al.* (2022) attempted this approach in South Africa; however, the study's measure did not factor in external factors such as

market conditions and societal adoptions of technologies. Secondly, the technological measure through the use of National Systems of Innovation Surveys did not cover all sectors of the economy, providing a one-directional view on technological progress in South Africa. South Africa's technological adoption of technological products and services across the world requires a comprehensive view of the impact technological innovation has on the economy outside of the narrow view of the manufacturing and ecological footprint.

The Industrial Revolution Technological Innovation Index (IRTII) introduced in this study aims to offer a broader and more nuanced perspective on the multifaceted contributions of the 4th Industrial Revolution (4IR) developments to economic growth. Unlike traditional measures of technological innovation, which often overlook critical aspects of digital adoption, the IRTII has been specifically designed to incorporate variables that capture the complexities of technological integration. The index captures digital divide variables such as digital adoption rates, access and usage. By accounting for previously excluded factors, this index seeks to provide a more holistic understanding of how technological innovation interacts, and impacts economic growth. The enhanced framework offers valuable insights into the dynamics of 4IR-driven economic transformation in South Africa, serving as a foundational tool how to better understand methods for fostering sustainable and inclusive growth.

According to DataReportal (2023), South Africa stands at a 72.3 percent internet penetration rate, with 43.4 million users, which account for 42.9 percent of the country's total population. Gillwald, Mothobi and Rademan (2018) argue that technological exclusion is a significant reality in a number of areas in South Africa, with digital exclusion exacerbating the already-existing social inequalities. The data from DataReportal (2023) supports this point by indicating that over 55 percent of South Africa's population does not use or have access to internet, which adds to the challenge of the full adoption of the 4th Industrial Revolution, due to the unequal access to digital infrastructure. This digital divide hampers the ability of marginalised communities to participate fully in the opportunities created by 4IR, exacerbating inequality rather than reducing it.

Following the challenge of the digital divide, South Africa faces the challenge of relevant skills in the adoption of technological innovation inventions especially in the 4th Industrial Revolution (Layton-Matthews & Landsberg, 2022). Lubinga, Maramura and Lubinga (2023) postulate that South Africa's higher education institutions are producing inconsistent capabilities in adopting digital technologies, resulting in the mismatch between market demands and the available pool of labour. This further poses challenges in employment, particularly in those traditional industries who may be displaced by the automation and technological shocks. Given the witnessed surge in digital adoption in South African areas, the pertinent challenges associated with technological innovation within the 4th Industrial Revolution, the measure of technological innovation needs to be adjusted to factor in changes that come with 4IR (McKinsey Insights, 2022; Layton-Matthews *et al.*, 2022).

Technological innovation proxies commonly used in studies to measure innovation and its impact on economic growth often include patent applications, research and development expenditure, and total factor productivity. However, these proxies do not always produce consistent results. For example, some studies find that patent applications are positively correlated with economic growth, while others find no significant relationship (Nguyen & Doytch, 2020; Sinha, 2008; Crosby, 2007). Similarly, research and development expenditure is positively correlated with economic growth in some studies but not in others (Jones, 1995; Guloglu & Tekin, 2012). These differences in results may be due to variations in the methodology used to measure technological innovation, and the specific context of each study. Therefore, it is important to carefully consider the choice of proxy and methodology when studying the impact of technological innovation on economic growth.

This study introduces the index as a refined framework to address existing research gaps related to traditional measurements of technological innovation that do not account for digital adoption. Traditional measures often overlook critical variables associated with digital adoption and the multifaceted nature of 4IR advancements, resulting in a limited understanding of their broader impact. By incorporating factors such as internet usage, mobile cellular, and telephone usage, the IRTII offers a more comprehensive and

dynamic approach. This expanded measure aims to provide insights into the evolving role of technological innovation in driving economic growth while addressing gaps in current methodologies. Furthermore, the study investigates the relationship between the IRTII and economic growth in South Africa, offering a nuanced perspective on how inclusive and continuous technological progress can support sustainable economic development.

1.4. RESEARCH OBJECTIVES

1.4.1. Primary objectives

The primary objective of this study is to construct the 4th Industrial Revolution adjusted Technological Innovation Index (IRTII) for measuring technological innovation, and to measure its impact on economic growth in South Africa. This study will answer the research question: What is the link between technological innovation and economic growth during the digital age in South Africa?

1.4.2. Theoretical objectives

To facilitate the achievement of the primary objective, the following theoretical objectives have been formulated:

- To identify technological innovation conditions in South Africa.
- To identify technological innovation trends in South Africa.
- Review and synthesise theories surrounding economic growth and technological innovation.

1.4.3. Empirical objectives

To facilitate the achievement of the primary objective, the empirical portion of the study consists of the following objectives:

- To construct the 4th Industrial Revolution Adjusted Technological Innovation Index (IRTII).
- To evaluate and examine the relationship between IRTII and economic growth in South Africa.

1.5. CONTRIBUTION OF THE STUDY

Sheefeni (2022) has highlighted that South Africa's economy has been facing significant challenges in meeting its key macroeconomic targets of increasing economic growth, maintaining low inflation levels, and reducing unemployment. In addition, Chukwuemeka (2020) pointed out that poverty and poor healthcare systems have also contributed to South Africa's stagnant economic growth, and the Covid-19 pandemic has further exposed the country's weak economic structures. Like many other countries, South Africa faces the challenge of formulating policy frameworks that can address economic challenges and promote the growth and development of the country. Several post-apartheid policies, such as the Reconstruction and Development Programme (RDP), Growth, Employment and Redistribution (GEAR), Accelerated and Shared Growth Initiative for South Africa (ASGISA), New Growth Path (GNP), and the National Development Plan (NDP)-2030, have been implemented (SAHO, 2019). However, the effectiveness and usefulness of these policies have been questioned, and while some compatriots have applauded the government's efforts, it is clear that more needs to be done for South Africa to achieve its macro- and microeconomic objectives.

Taking into consideration the aforementioned challenges, the primary objective of this study is to provide empirical evidence to policymakers on the role of technological innovation in the growth and development of a country within the 4th Industrial Revolution. In doing so, the study will employ the principles of the PCA to the construction of the IRTII, which will serve as the proxy for technological innovation. Thereafter, the ARDL model precepts will be utilised to assess whether the relationship between technological innovation and economic growth exists. The comprehensive model is inclusive of key variants such as technology transfers and human capital development to encapsulate different forms of technological innovation. Although existing literature suggests a positive relationship between technological innovation and economic growth, there is, however, a lack of comprehensive and inclusive empirical evidence to support this claim.

Furthermore, the study aims to assess the technological conditions and factors that influence technological innovation in the country. The assessment will be conducted through assessing South Africa's policy frameworks and institutions that aid the creation

of a conducive technological environment, as well as assessing the current technological trends. This analysis will aid policymakers in comprehending the current conceptualisation of technological innovation, and the current state of technological innovation in South Africa. Additionally, the study aims to inform policy decisions by providing theoretical and empirical evidence on the significance of technological innovation for economic growth, development, human capital enhancement and technology transfers which will have a positive impact on achieving macro- and micro economic policies.

1.6. CHAPTER CLASSIFICATION

In Chapter one of this study, an introduction, background, and problem statement are presented. Chapter one further provides a broad overview of the study objectives and the factors that have led to the current state of research surrounding the research topic. Following this, Chapter two will provide an in-depth review of the existing literature on the subject, identifying gaps in current knowledge in the field. Chapter three of the study will encapsulate the theoretical objectives by profiling the trends and conditions of technological innovation in South Africa. In Chapter four, the research design and methodology will be detailed, including the selection and approach of relevant data, and the analytical techniques used to evaluate the research question. Chapter five and six will present the results and findings of the research, outlining the main outcomes of the inquiry, including any pertinent trends or significant patterns identified in the data as well as a discussion of the main findings. Finally, Chapter 7 will provide an overall summary, recommendations, limitations and conclusion, reflecting on the research questions, and highlighting any limitations or avenues for further investigation.

CHAPTER TWO: LITERATURE REVIEW

2.1. INTRODUCTION

According to Chiffi *et al.* (2021), investigating the theoretical intricacies of technological innovation is essential for comprehending the current dynamics of technology and their impact on economic growth. Chiffi *et al.* (2021) further highlight that different technological theories play a role in understanding different inventions. Bujari and Martinez (2016) stress that knowledge and information are key drivers in addressing technological innovation process ideas, which are characterised by understanding agents such as research institutions, universities, regulators, and competitors. Therefore, understanding the theories that frame technological innovation provides a comprehensive understanding on the nature of current technological patterns (Ben-Hassen, 2021).

This chapter encapsules the theories associated with technological innovation and further aims to achieve the third theoretical objective stated in section 1.4.2. First, it provides an overall understanding of different industrial revolutions that will aid in understanding what influenced the current industrial revolution. Second, the chapter will discuss the theoretical assumptions on the impact of technological innovation and economic growth. The third subsection of the chapter elucidates the economic theories associated with technological innovation. Finally, this chapter will highlight empirical studies from both developed and developing countries that have assessed the impact of technological innovation on economic growth. Its aim is to establish whether a definitive link exists between the two phenomena.

2.2. INDUSTRIAL REVOLUTIONS OVERVIEW

Industrial revolutions have resulted in a significant turning point in history that marks the transition from manually operated production equipment to automated machinery systems (Vyas, 2018). The first industrial revolution, which began in the late 18th century, was characterised by the invention of steam power and mechanised factories (History, 2009). According to Dubai Sensor (2021), the emergence of the first industrial revolution played a pivotal role in the emergence of capitalism, European imperialism, and the boom

of the agricultural sector. Dubai Sensor (2021) further denotes that as a result, the industrial revolution marshalled improvements in trade and commercialisation, such as the development of communication methods, new energy sources, and the advancement of the iron and textile industries.

Despite the positive impact driven by the first industrial revolution, the revolution also augmented negative impacts such as child labour, pollution, and transmission of diseases, as well as an increased population, which meant increased urbanisation and encouragement of unhealthy practices due to the construction of low budget houses and fetching of water from pipes at the end of the street in some areas (Dubai Sensor, 2022). The second industrial revolution, which began in the late 19th century and continued into the early 20th century, was marked by further advances in manufacturing, including the widespread use of assembly lines and mass production techniques (Rotatori *et al.*, 2019). Dubai Sensor (2021) further echoes that the second industrial revolution streamlined communication and transportation efficiencies such as railways, motor vehicles, telephones and telegraphy, which enabled better facilitation of goods, services, people and trade globally.

The second industrial revolution impelled the development of advanced medicine and many substances in fields such as chemistry, physics, and biology. However, Richmond Vale Academy (2022) argues that the industrial revolution perpetuated social inequality, as the benefits trickled down unevenly, and new technologies displaced the technologies of the first industrial revolution. The second industrial revolution faced limitations related to an increase in globalisation, an increase in consumer demand, customs innovation, and technology saturation, as old technologies reached their limits, creating a gap for the third industrial revolution. According to the Institute of Entrepreneurship Development (2019), the third industrial revolution, also known as the digital revolution, began in the 1980s with the introduction of computers and automation technology into manufacturing processes, and has continued to evolve with the development of new technologies.

The integration of new technologies includes inventions such as machine learning, telecommunications, electronics, and the internet of things, leading us into the fourth industrial revolution, also known as Industry 4.0 (Dubai Sensor, 2021). The fourth

industrial revolution is characterised by the integration of cyber-physical systems and advanced automation technologies into the manufacturing process, enabling a new era of smart factories and intelligent manufacturing systems (Institute of Entrepreneurship Development, 2019). All four industrial revolutions have been marked by major advancements in technology and automation, leading to increased efficiency and productivity in manufacturing processes. These advancements have also had significant impacts on society and the economy, including changes in employment patterns, business acumen, transportation and communication (Britannica, 2024).

With the introduction of the 4th industrial revolution, which is more focused on artificial intelligence and clean energy, developing countries like South Africa are expected to experience a surge in technological innovation (Asghar *et al.*, 2020). This will further necessitate new and improved measures of technological innovation. However, given the complexities and the ongoing debate between technophiles and technophobes, the relationship between the current contextualisation of technological innovation and economic growth is yet to be fully understood (Flichy, 2008). This is the literature gap that this study attempts to fulfil. This study addresses the literature gap by developing an industrial revolution-adjusted technological innovation index to better understand the nexus between technological innovation and economic growth within the South African context.

2.3. THE ROLE OF TECHNOLOGICAL INNOVATION IN ECONOMIC GROWTH

The roots of economic growth have been advocated to be stringently reinforced in factors such as technological changes, digital trade, and technology transfers which play a significant role in advancing economies (Basha *et al.*, 2023). Such factors have played a significant role in navigating the growth of numerous sectors, promoting the transformation of societies, and shaping industrious futures (Broughel & Thierer, 2019). According to Mohamed *et al.* (2022), there is a significant amount of literature that has consistently highlighted technological innovation as a catalyst that drives economic growth, as well as accenting the innovation-based growth theory which is positively linked with economic growth and development. Mohamed *et al.* (2022) further highlight that technological innovation advancement extends further than production improvements but

also fundamentally alters the landscape of consumption and distribution of goods and services.

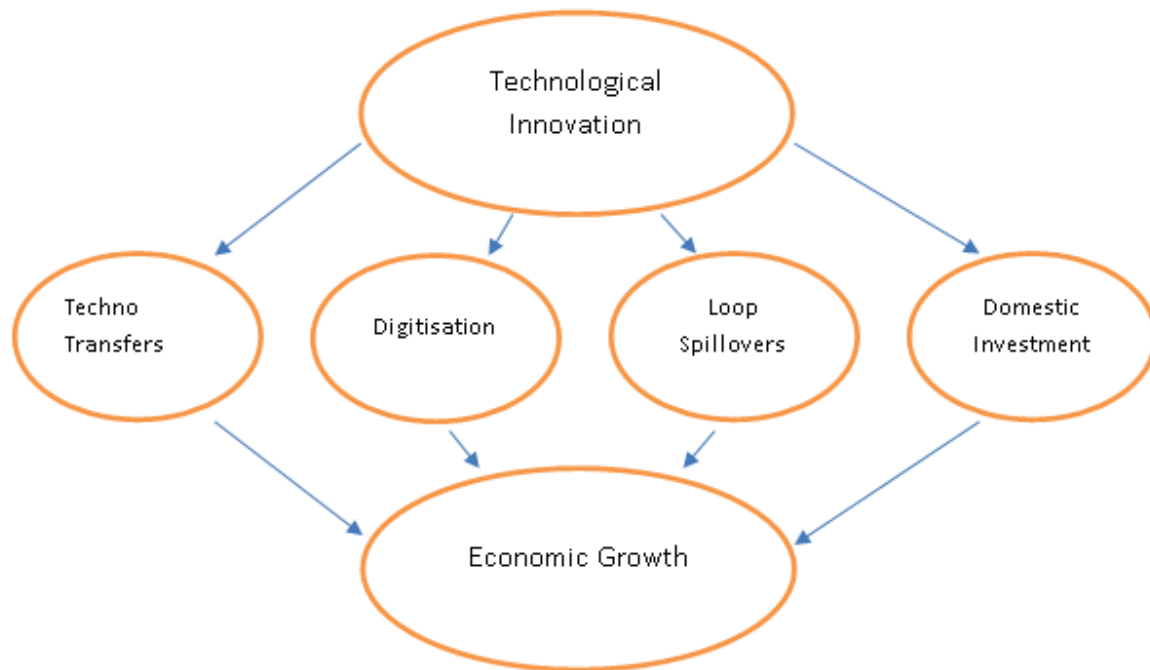
Mohnen and Hall (2013) assert that technological innovation such as novel technologies related to the 4th industrial revolution, and integration of advanced integration of systems such as IoT, machine learning, and data analytics, serve as catalysts for enhancing productivity through the adoption of such systems to streamline outcomes and enable cost reduction processes, and enhance production time as well as resources, without reducing the quality of the product or service. Studies by Horvat *et al.* (2019) and Autor and Salomons (2018) demonstrated that technological innovation advancements such as automation have revolutionised many sectors and industries by affixing precision and efficiency within the production process to enable firms to produce more, and reduce costs and resources, ultimately increasing profit margins and competitiveness. These studies further highlight that the increase in production resulted in increased cost reduction and resourcing, enabling the allocation of resources to be directed towards diversification avenues and be invested in other innovation cycles.

Technological innovation creates new industries and introduces new markets that create an opportunity for employment creation, and foster entrepreneurship avenues (Maclaurin, 1950). The introduction of new markets supports the creation of new channels of demand, consumption and distribution of goods and services. Start-up enterprises that are driven by technological innovation processes and ideas that provide alternatives to current systems can drive up competition and potentially disrupt large sector corporations (Coccia, 2021). Geldes *et al.* (2017) postulate that as new markets and industries are created, new business ecosystems are introduced, job creation is encouraged, so boosting consumption, uplifting local economies, and stimulating macro-economies. Eswaran (2020) makes an example of the rise of the internet that created the e-commerce market, resulting in the creation of online businesses and employment in streams like digital marketing, web development and logistics.

In addition to the creation of new markets, Archibugi and Iammarino (2002) assert that technology facilitates the global integration of economies by connecting markets, expanding knowledge processes and fostering economic collaborations. Dnishev and

Alzhanova (2016) and Rigdon (2023) further highlight that digital communication and internet tools have evidently transformed how businesses operate and perform through the transition to frictionless collaboration amongst employees, and the ability to instantaneously connect with customers nationally and globally has made it easy for firms to access global markets and previously unreachable markets and collaborate with other firms for either vertical or horizontal integration. According to Graw (2023), the interconnectedness of economies and businesses expands the flow of information, processes, ideas, storing and retaining information, and resources, which overall ensures smoother systems, operations and efficient allocation of resources driving global growth.

Figure 3: Technological Innovation and Economic Growth Relationship



Source: Mohamed *et al.* (2021)

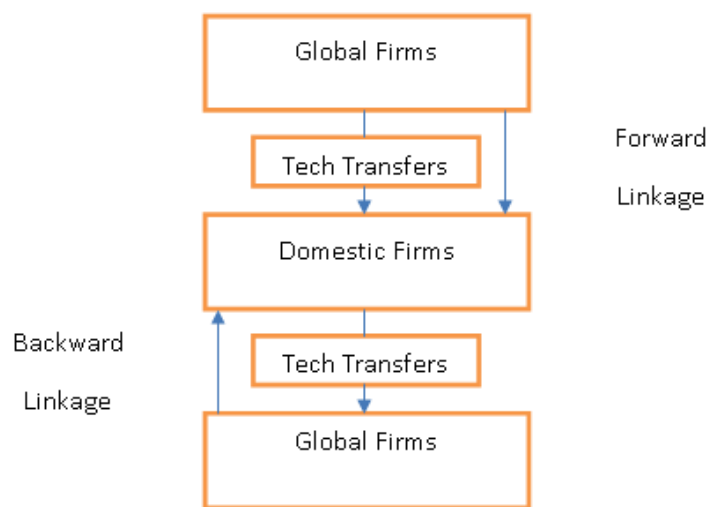
According to Mohamed *et al.* (2021), technological innovation catalyses economic growth through a web of interconnected metabolisms as depicted in Figure 3. Figure 3 elucidates that technological innovation cultivates an environment of competition between Multi-National Corporations (MNC) with local branches in foreign countries, expanding the spread of technological transfers through skills; and the increased levels of productivity of local branches increases economic growth in the host country (local branch) (Mohamed *et al.*, 2021). Khumalo and Mongale (2015) postulate that technological transfers through

its numerous channels such as foreign direct investment, collaborations, and trade; and the establishment of MNC allow economies to access high-end expertise, knowledge, and skills from other countries that propel domestic competencies.

The introduction of new technologies often results in digitisation, transforming traditional processes in different sectors, enhancing productivity, efficiency, and accessibility, for example, in sectors such as finance, with the increase in digital payment, digital currencies, and neo-banking (Khumalo, 2024). Additionally, as technological innovation spreads to digitisation, spillover loops emerge, where the benefits of innovation spread beyond the initial industry; for example, technological innovation in telecommunications spilling over to e-commerce and logistics sectors (KLA, 2024). Mohamed *et al.* (2021) further postulate that the surge in technological innovation spurs domestic investments by directing capital into new and emerging markets, and infrastructure projects. The interest derived for the new markets results in the development of new products, services and jobs, and with the capital injected in new markets, the public and private sector will invest in research support and education, with the intended goal of long-term economic growth.

All the technological innovation elements contribute towards continued economic growth by enhancing productivity, fostering competitiveness, supporting the creation of new markets, and driving an innovation-led economic development approach, positioning developed and developing countries for continued growth. Newman *et al.* (2015) postulate that technological transfers create economic spillovers that boost and encourage domestic investment as integrated organisations inject their technologies into the economy, leading to increased competitiveness and efficiencies, as depicted in Figure 4.

Figure 4: Technological Transfer Feedback Loop Spillovers



Source: Newman *et al.* (2015)

According to Newman *et al.* (2015), technological transfers may occur through horizontal spillovers across different sectors, which may be Backward Linkage or Forward Linkage, which all facilitates the transfer of the technologies across different countries. Backward linkages are facilitated when domestic countries that supply inputs to global firms or MNC experience a surge in the quality of the supply, in which global firms heavily incentive domestic firms to further improve the quality or improve the efficiency, and the improved technological efficiencies boost competition in the domestic economy and economies of scale in global firms. Similarly, forward linkages are facilitated when technological transfer supplies downstream from global firms to domestic firms in which global firms have branches, and the skills are transferred from global firm employees to domestic firms (Newman *et al.*, 2015). Technological transfer spillovers both foster the enhancement of technological innovation in global and domestic firms, and economic growth due to shared efficiencies.

Newman *et al.* (2015) further stress that technological advancements from transfers spillover to other industries, as new additional knowledge disseminates across the fostering feedback loop. Lee (2020) and Mohamed *et al.* (2021) theorised that the technological innovation activities from transfer spillovers expand and manifest in various

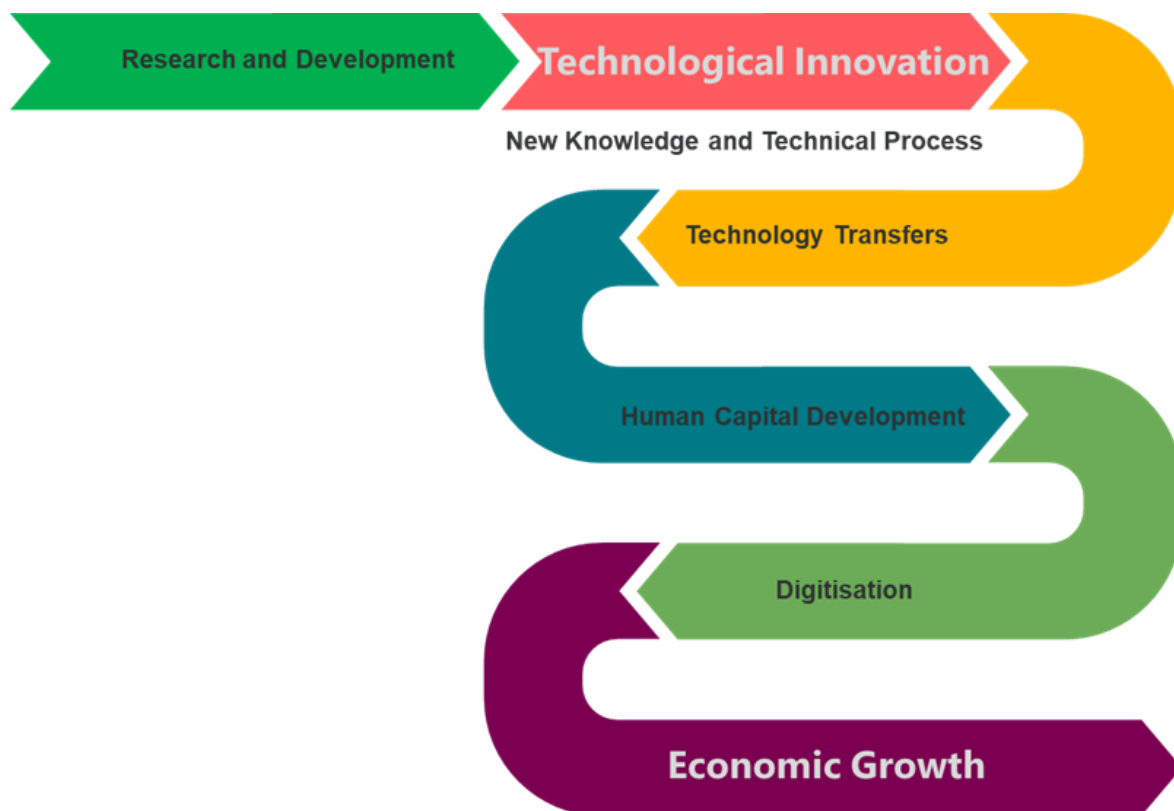
forms such as digitisation, product, and service development, amplifying production activities, and enhancing skills within the workforce. Ultimately, the cycle of technological innovation that cycles from technological transfers, domestic investments, digitisation; and feedback loop spillovers fuels sustainable economic growth by continuously enhancing technological frontiers, which boost an economy's overall economic capacity.

Armour and Teece's (1980) study indicated a vertical integration between research and development (R&D) and technological innovation, suggesting that technological innovation fosters R&D, leading to more breakthroughs. Mahardhani (2023) supported the findings by Armour and Teece (1980) by indicating that policies that encourage technological innovation and R&D play a pivotal role in creating an environment that pivots economic growth. The policies ensure that R&D investments are prioritised and expanded to ensure sufficient scientific breakthroughs that contribute to knowledge expansion and the development of new technologies. Miguel-Benavente's (2006) study proposed that the development of new knowledge does not solely result in economic growth, but also fuels the economy to be a knowledge-based economy.

Converging operational technologies and digital technologies through the vertical integration process has contributed towards the improvement of key sectors in health, education, and infrastructure which catalyse growth and development (Slade, 2021). UN (2016), OECD (2019) and Ivaldi and Ciacchi (2021) reported that the continuous developments in technological innovation act as a catalyst for the creation of smart cities with efficient and sustainable transport services, reliable energy systems, and enhanced public sector services. Healthcare and technological innovation have resulted in innovations such as telehealth or telemedicine, biotechnology, and medical robotics, which have improved the accessibility and distribution of quality healthcare (Amjad, Kordel & Fernandes, 2023; Kim *et al.*, 2021). In education, technological innovation facilitates the transition to a more digital environment of learning through e-learning, making quality education more accessible in the ever-changing work environment, and remodelling as well as reshaping what education means, as the world moves further into remote learning space (Govender, 2022).

Mohamed *et al.* (2021) explain that the role of technological innovation comes through different synergic forms that are interconnected, resulting in economic growth. Lee (2020) states that efforts directed at research and development (R&D) foster the creation of new technologies that drive innovation. Additionally, the R&D activities spill over, as the interest in technology transfers through plausible collaborations. According to Scarrà and Piccaluga (2022), technological transfers through R&D activities mechanism spillover and are disseminated to different key industries and sectors within the economy. In positive contrast, Scarrà and Piccaluga (2022) further add that the integration of technological innovations in different industries and sectors requires a skilled labour environment, echoing the role and importance of the development of human capital in the process of absorbing technological innovations. Following the synergic process of the role of technological innovation on economic growth, Lui *et al.* (2021) denote that extensive technological innovation activities, such as digitisation, become a crucial enabler of production efficiencies and global and domestic connectivity.

Figure 5: Technological Innovation Synergic Process



Source: Mohamed *et al.* (2021)

Mohamed *et al.* (2021) highlight that the different interconnectedness of the technological innovation activities is an accumulation of factors that result in sustained economic growth by fostering competitiveness, improving production efficiencies and driving economic development. Figure 5 illustrates the synergic cohesive chain on how the role of technological innovation in impacting growth may arise from R&D activities and technology transfers to human capital development and digitisation, to underscore the transformative impact of technological innovation.

Overall, technological innovation plays a pivotal role in driving economic growth, as it influences the increase in production and its processes, fosters the creation of employment, pioneers the creation of new markets, facilitates global economic integration, and enhances research and development in key sectors of the economy. Studies by Lui *et al.* (2021) and Scarrà and Piccaluga (2022) have argued that economies that prioritise investment in technological innovations position themselves to be players in the forefront in terms of economic growth and development. Moreover, such economies gear up and set a more dynamic environment for global competitiveness that is essential in adapting to the technological integrations that shape a direction that fosters a more inclusive, sustainable, and equitable economy (Scarrà & Piccaluga, 2022).

2.4. THEORETICAL FRAMEWORK

Theoretical frameworks play a crucial role in explaining the significance of the study, by incorporating existing literature to build up contextualisation (Naik, 2018). The study's theoretical frameworks are based on established theories and assumptions that further provide a basis of understanding. To establish a foundational understanding for this study, four key theories were selected to contextualise the research paper, namely, the Schumpeterian theory, Solow growth theory, endogenous growth theory, and the unified growth theory.

2.4.1. Schumpeterian Theory

According to Schumpeter, innovation occurs when entrepreneurs introduce new products or services that displace existing ones (Aghion *et al.*, 2015). Aghion *et al.* (2015) further

stress that the Schumpeter theory denotes three main ideas: - i) innovations drive growth; ii) innovations are results from entrepreneurial investments that are motivated by prospects of profit; iii) innovations displace old technologies leading to its theory of creative destruction. This process of “creative destruction” creates new growth opportunities, as businesses adapt and invent new methods of production and distribution (Ziemnowicz, 1942). Over time, these changes can lead to the emergence of entirely new industries, driving sustained economic growth.

Schumpeter's theory emphasises the importance of entrepreneurship and risk-taking in driving innovation and growth and suggests that economies with high levels of competition and entrepreneurial activity are more likely to experience sustained development. Aghion (2018) postulates that the Schumpeterian theory explains the importance policies and intuitionism play in shaping and incentivising innovation which leads to economic growth. Incentivised innovations posit the creation of new products, efficient processes, and new markets. On a similar note, Aghion *et al.* (2015) argue that the Schumpeterian model emphasizes innovation-led growth, resulting in high turnover. Increased technology and competition lead to positive growth outcomes. The Schumpeterian model is based on three assumptions: innovation leads to long-term growth, modern technologies replace old ones, and entrepreneurial investment drives innovation.

Innovation-originated market power can be more effective than pure price competition, as technological innovation often creates temporary monopolies that yield excessive profits (Ziemnowicz, 1942). According to Ziemnowicz (1942) and Aghion *et al.* (2015), the Schumpeterian theory narrates the prominent relationship between market structure, competitiveness, business dynamics, and the metabolism of economic growth and development. However, as more alternatives and supplies emerge in the market, the original innovator's profit advantage is eliminated as prices decrease.

The Schumpeterian growth model echoes the role entrepreneurship and technological innovation play in terms of driving economic growth and has been substantial in understanding modern economic dynamics. However, the model succumbs to a number of limitations (Aghion, 2018). Aghion *et al.* (2015) highlight that the Schumpeterian growth

model emphasises technological innovation as a key driver of economic growth; however, the model does not fully account for nor acknowledge the role capital accumulation plays in technological innovation, opening a gap to introduce physical and human capital into the model. Aghion (2016) further argues that the theory assumes that increased competition slows economic growth and monopolises necessitate technological innovation. According to Romero (2020), the Schumpeterian growth model's argument of new technologies replacing old technologies is a short-sighted argument, because new technologies can complement old technologies, for instance, the integration of internet-based streaming services with traditional televisions, which previously required broadcasting infrastructure and networks, but now has evolved to digital streaming augmenting the viewership of TV shows.

Mehmood, Alzoubi and Ahmed (2019) postulate that the Schumpeterian growth model does not account for sectoral uniqueness in exploring technological innovation. This is important, considering that different sectors have different technological cycles. According to Medearis (2001), applying the policy recommendation of the Schumpeterian growth model may pose a challenge, as the theory advocates for the adoption of monopolies to drive technological innovation, but monopolies harness an anti-competitive environment reducing consumer welfare, and if government policies heavily protect large institutions, this may distort market segmentation, hinder entry of new firms with innovative products or services, stifle competition and reduce the overall growth in economy. Medearis (2001) further critiques the argument of the theory, that technological innovation growth is excessive under laissez-faire, but on the contrary, empirical evidence suggests that innovation grows on competition.

2.4.2. Solow Growth Model

Pawel, Tomasz and Rafal (2023) emphasise that Solow proposed the growth model as a neoclassical alternative to the Keynesian models. Other studies argue that the model is important to help understand the disparity in long-run growth (Gundlach, 2007; Koutun & Karabona, 2013). Vaidya (2015) explains that the Solow growth model is an exogenous neoclassical model that explains and measures economic growth by considering increased levels of capital accumulation, labour, and technological innovation. The Solow

growth model suggests that technological innovation allows firms to produce more output than before, translating into higher economic growth and income per capita, as firms become more efficient and generate new investment opportunities (Anushree, 2020). Solow's model also suggests that the benefits of technological progress are most apparent over the long-term and that government policies can play an important role in supporting research and development and fostering innovation (Zhang, 2018). The Solow model asserts that some countries are more productive than others due to the continuous integration of technology in production systems. Through technology, constant growth in productivity is created (Feldstein & Horioka, 1992).

According to Feldstein *et al.* (1992), the Solow growth model is founded on a number of assumptions that (i) technological progress is an external/exogenous factor, (ii) it assumes diminishing returns to capital, (iii) savings rate is determined outside of the model also making it an exogenous factor, (iv) the theory assumes a steady state of equilibrium and (v) capital accumulation is an integral key for economic growth. Feldstein *et al.* (1992) and Harrod and Domar (2008) argue that, according to Solow, understanding growth requires understating the accumulation of capital, physical capital, and human capital, and also understanding technological progress and institutions.

Gundlach (2005) dissected the assumptions about the Solow model by explaining that a country experiences greater technological advancement if the country has better access to global technological spillovers; the country with extended exogenous access has a competitive advantage compared to a country with the same savings and population but which does not have access to global technologies. Holtz-Eakin (1993) challenges the assumption of capital accumulation by arguing that infrastructure development is equally important as physical capital to achieve sustained growth.

Although the Solow growth model provides a sound explanation of economic growth, it has notable limitations. The model fails to explain long-term economic growth, because it treats technology as an exogenous factor, leaving the key driver of growth unexplained and outside the model (Das, 2015). This limitation gives way to the endogenous growth model, which explains technological progress as an endogenous factor derived from economic activities and policies. Das (2015) further alludes that the model explains that

capital accumulation occurs due to the savings rate of households. However, the model does not elucidate where the fixed savings saved by households comes from, making it unclear whether households will continue generating income to direct towards savings.

Chand (2018) alludes that the Solow model's accumulation of human capital does not directly include crucial factors in human capital such as education, health, and skills that contribute to the efficiencies of production. Additionally, the Solow model does not account for the role played by institutions, governance structures, and policy adoptions, that play a fundamental role in creating an environment that induces growth, and the omission limits the model's capabilities as institutions, governance structures, and policy adoption are enablers of economic growth, and any other assumption of the Solow model (Bosworth & Collins, 2008).

The Corporate Finance Institute (2015) stresses that the simplification of the Solow model towards population growth as an exogenous factor ignores the impact of demographic change on the population, like health, economic conditions, income, climate, and environment. The model's simplification approach in explaining long-term growth has promoted the adoption of comprehensive models that aim to elucidate, explain, and fill the gaps of the model, such as accounting for endogenous factors, human capital, and institutional factors.

2.4.3. Endogenous Growth Theory

The endogenous growth theory challenges the exogenous assumptions made by the Solow growth model, and posits that internal factors play a critical role in driving economic growth (Akcigit & Howitt, 2019). The Corporate Finance Institute (2022) notes that the Romer model, which is an endogenous model, considers technological change as an endogenous factor and the primary driver of economic growth. The Romer model also assumes that the integration of human capital development and existing proficiencies can lead to innovative ideas that enhance production, well-being, and economic growth (Gordon, 2023). The theory emphasizes that investment in research and development, education, and human capital development, are essential for driving technological progress.

Faster Capital (2023) notes that the endogenous growth theory introduces the notion of ideas being one of the key drivers towards technological progress, and that ideas have no rivalry. Howitt (2010) further highlights that government policies can influence these factors by providing incentives for research and development, and by promoting the diffusion of knowledge across firms. Romer (1990) and Howitt (2010) denote that the endogenous theory provides an understanding that technological innovation progress influences long-run economic growth.

According to Chirwa and Odhiambo (2018), capital investments towards technological advancements exhibit increased economies of scale and thus account for the efficient allocation of resources in key sectors and areas such as infrastructure, education, healthcare, medicine, and telecommunications. In addition, Chirwa and Odhiambo (2018) further echo that the theory elucidates that with extended investments in key economic areas, the economies of scale and returns are amplified, propelling the long-run growth in the economy. When the endogenous model is incorporated by both public and private sector support, the policy support emerges as a critical proponent for technological advancement, which as a result yields a long-run positive impact on economic growth (Nair, 2018).

The theory emphasises the role of research and development as a driver of technological advancements which catalyses economic growth; as firms and institutions heavily invest in R&D, the outcomes are directed towards the discovery of new technologies, improving pre-existing systems, and increasing the smoothness of the production process (Diao, Roe, & Yeldan, 1999; Kruse-Andersen, 2023). Kruse-Andersen (2023) adds that the continued focus and priority towards innovation represents a move towards endogenous growth that heightens levels of production, enabling the expansion of economies of scale through the increased output produced using fewer resources. The advancements of technological innovations permeate to other sectors, thus creating a positive spillover effect that has a long-run positive impact on the broader economy (Şener, 2008).

In addition to the spillover effects, Faster Capital (2023) highlights that the endogenous theory suggests that there exists a positive feedback loop between technological innovation and factors that contribute towards economic growth. Faster Capital (2023)

makes the example of education, that the investments directed towards education result in the development of new technologies which may also spill over into the development of more education technologies. Another example made is the example of the advancements in information technology that may catalyse various sectors in the economy such as digital communication and exposure to the global footprints, which all have a long-run economic impact on growth (Jones, 2022).

Pack (1994) argues that the endogenous theory echoes the importance of strong institutions and relevant frameworks that foster a friendly environment for technological innovations to prevail. The study recommends that, according to the endogenous theory, strong property rights, regulatory frameworks and processes, and patent procedures that encourage as well as protect intellectual property, play a significant role in the progression of technology that has a long-term impact on the economy. Strong institutional structures provide technological incentives to firms to create a conducive environment that ensures that investors reap the rewards of the innovation invested, encouraging further injections towards innovation, resulting in a feedback loop that fosters a conducive landscape for long-term progress and growth (Yi & Xiaoman, 2012).

Overall, the endogenous theory is cemented in sustainable growth through the intrinsic self-perpetuating nature of technological innovation (Akcigit & Howitt, 2019). The theory stands on the principle that institutional frameworks, human capital, investment in R&D, and feedback loops create an environment that is conducive to promoting the progression of technological innovation (Jones, 2022), thus resulting in a continued cycle of technological advancement, heightening of production and its processes, and long-term economic growth. The endogenous growth theory remains pivotal, even through the never-ending evolution of economies and technologies, as it provides an understanding of a sustainable economy in a modern digital era.

Despite the endogenous growth theory's elucidation on R&D, institutions, and human capital, the theory still faces several criticisms. One key criticism is the assumption that markets operate perfectly. In reality, sectors and industries are often dominated by a few large firms with significant market share (Faster Capital, 2023). According to Chukwuemeka (2015), the theory assumes that information spillovers occur naturally

across different sectors and industries, whereas due to intellectual property rights, non-disclosure agreements, geographical location and trade secrets, spillovers are often difficult to attain. Additionally, Chukwuemeka (2015) highlights that due to the theory's assumption on knowledge spillover, the theory also accents that investments in technological innovation yield constant returns of scale. Chukwuemeka (2015) further argues that despite the constant positive returns, diminishing returns do occur in industries such as semiconductors, which are driven by initial innovation that drives significant growth; however, additional investments in the industry yield smaller gains. Chirwa and Odhiambo (2018) argue that the theory fails to account for the role institutions play in creating an environment conducive for economic growth and innovation. The argument emphasises that countries with strong frameworks of property rights, legal fraternities and strong regulatory bodies are better able to realise investments in innovation.

According to Acs and Sanders (2021), the endogenous growth theory assumes that increased focus towards innovation and human capital automatically results in economic growth. Though true, however, the theory overlooks the role of how poor institutions hinder technological progress, with factors such as corruption, frail legal systems, and ineffective governance structures, which all stifle a conducive environment of growth and innovation (Acs & Sanders, 2021). Goksel and Ozturkler (2021) postulate that one of the limitations of the theory is the assumption that improvements in productivity occur coincidentally as a by-product of the accumulation of capital, whereas improvements occur by means of deliberate efforts towards new technologies and deliberate efforts towards R&D. Lastly Goksel and Ozturkler (2021) argue that the theory does not fully account for the effects of political instability in countries which may influence trade, investments and economic growth.

2.4.4. Unified Growth Theory

According to Campante *et al.* (2021), the Unified Growth Theory (UGT) was formulated to address the failures associated with the endogenous growth theory. The unified growth theory is explained as a theory that seeks to establish a single framework to elucidate why growth accelerates. The theory suggests that economic growth and development in

the long-run and over the course of human history can be explained by one model that is more consistent than other various models customised for specific time periods (Madsen & Strulik, 2023). This means that technological innovation is driven by consistent and gradual growth in education, skills, and population (Madsen & Strulik, 2023).

Perrin (2011) simplifies the theory by explaining that it aims to conceptualise the transition from stagnant economic growth to sustained growth, and to understand the role of technological innovation and change in demographics. According to Galor (2005), the transition from stagnation to sustainable economic growth is segmented into three phases based on the theory; phase one is the Malthusian Regime followed by the Post-Malthusian Regime and lastly, the Modern Growth Regime. Madsen and Strulik (2023) also highlight that the model can be identified using three variables, namely education, fertility rate, and skills development, which all drive technological progress.

Ashraf and Galor (2011) and Campante *et al.* (2021) highlight the model phases as: the Malthusian stagnant regime in terms of technological innovation is that technological innovation results in a growth in population but not an increase in income per capita, or standard of living. This is because technologies were developed in sectors such as farming that only served to support larger populations rather than improving the standard of living. Due to a fixed amount of land, and diminishing returns to labour, the standard of living remained stagnant (Ashraf & Galor, 2011).

Jensen *et al.* (2022) explained the Post-Malthusian Regime as a phase that witnessed the impacts of technological innovation cumulatively grow above population levels, thus boosting the standard of living. Following this, investment towards human capital in relation to education and skills development was encouraged and resulted in a demographic transition with lower birth rates, as families became smaller and smaller.

Campante *et al.* (2021) denoted the last phase as the Industrial Revolution/Modern Regime, which encapsulates a turning point in technological innovation, which resulted in drastic and sustained growth in technology and in the economy. Campante *et al.* (2021) further allude that the phase is characterised by the development of industries, advanced health care, and improved communication and information. This phase further echoes

that institutions play a pivotal role in the development of technologies and growing economies. The three phases set a base of the theory's framework in understanding that technological innovation is driven by continuous evolution of the population and education.

Kawalec (2020) exemplifies the model for better understanding by focusing on the industrial revolution, specifically on the first industrial revolution, as part of the modern industrial revolution regime. The transition witnessed technological progress in textiles, steam engines, and manufacturing, which resulted in significant growth in the economy. Additionally, during the period, demographic transition began to shift, as more focus and investment towards education and skills development were echoed as a key driver of technological innovation (Kawalec, 2020). According to Strulik (2017), the unified growth theory has amplified the economic development of emerging economies like China and South Africa, nudging the countries towards more industrialised, technologically novel and technology-based economies, shifting from an agrarian economic approach with substantial investment in human capital and technology, supported by a change in demographics.

Madsen and Strulik (2023) postulate that the theory is founded on a number of assumptions, such as the assumption that technological innovation is a continuous process that has a significant impact on the economy in the long run. Galor (2005) also further suggests that the theory assumes that there exists a critical link between demographic transition and economic growth, in which the continued development in technology results in reduced fertility rates and alters the population dynamic, as witnessed from the first industrial revolution.

Temin (2012) emphasises that one of the key assumptions of the theory is that there is a significant emphasis on human capital as economies grow, specifically in education, skills development, and training, to sustain economic growth by balancing different phases in the growth of the population and the economy. Lastly, Temin (2012) noted that the theory assumes that institutional frameworks, such as property rights, play a significant role in augmenting an environment that fosters technological innovation and economic growth, and having strong institutional frameworks amounts to sustainable economic growth.

Contrary to the aforementioned assumptions, the unified growth theory falls short in accounting for some of the assumptions and assertions of the model (Galor, 2005). Nielsen (2015) argues that unified growth theory is backed up by theoretical stories that makes it difficult to narrow down which story is accurate. According to Diebolt and Perrin (2016), the unified growth theory was developed to address the shortcomings of the exogenous and endogenous growth theories, as the model is argued to oversimplify transitional dynamics of the regimes. Diebolt and Perrin (2016) argue that unified growth theory does not fully capture the transition dynamics, leaving out crucial and nuanced factors that result in a transition such as urban crowding, economic crises, and poor working conditions. Cervellati *et al.* (2023) further allude that though the theory acknowledges the role of institutions, it does not factor in the uniqueness of institutional frameworks of different countries in different historic timelines.

Campante *et al.* (2021) criticise that the theory assumes and treats technological progress as an exogenous variable, whereas in reality, technological innovation is an endogenous factor influenced by institutional frameworks. Despite its shortcomings, the theory plays a role in framing the study's model by factoring education as a key variable towards technological innovation.

2.5. EMPIRICAL STUDIES

The importance of technological innovation on economic growth has attracted a number of studies seeking to establish their significance in different economies. This section discusses empirical studies on the link between economic growth and technological innovation. The first subsection discusses studies focusing on developing economies. Next, studies focused on developed economies are discussed.

2.5.1. Developing Countries Context

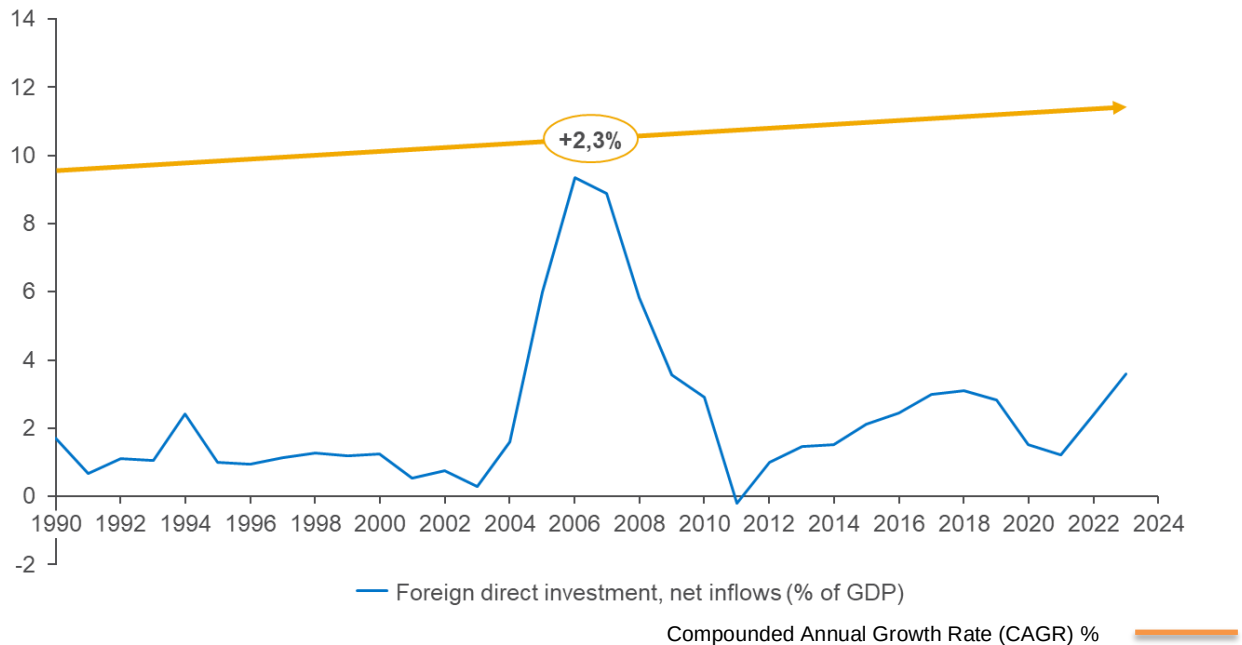
Mohamed *et al.* (2021) conducted a study assessing whether technological innovation and FDI can boost economic growth in Egypt. The study aimed at examining the relationship between technological innovation and foreign direct investment with economic growth in Egypt, for the period spanning from 1990 to 2019. The research paper

adopted an Autoregressive Distributed Lag (ARDL) model to answer the research objective question, What is the impact of technological innovation and foreign direct investment on economic growth in Egypt? And whether there is a long-run or short-run relationship between the variables of interest and economic growth. The study of Mohamed *et al.* (2021) adopted two hypotheses; i) “There is a positive significant relationship between foreign direct investment and economic growth in the long and short term for the Egyptian economy.” and ii) “There is a positive significant relationship between technological innovation and economic growth in the long and short term for the Egyptian economy.” Objectively, the study aimed to utilise the findings to develop a long-term sustainable strategy to support Egypt’s economic growth. The main findings of the study denote a positive relationship between FDI and economic growth in the long-run but it is negative yet statistically insignificant in the short-run; the innovation index that served as the measure for technological innovation interestingly revealed a negative relationship with economic growth in the long-run, and a positive insignificant relationship in the short run.

The key findings of the study on technological innovation are contrary to the endogenous growth theory assumption, that there is a positive relationship between technological innovation and economic growth in Egypt. The results of the negative relationship are associated with Egypt’s failure to meet the Global Innovation Index requirements, and Egypt’s inability to create an environment that encourages investment towards scientific research and developments in technology to build and optimise global competitiveness. The study further developed recommendations on how technological innovation can be encouraged and how a conducive environment that fosters scientific research can be emulated through collaboration between public institutions and private global institutions, encouraging the creation of products that may be exported, and increasing focus towards green initiatives. Assessing the FDI trend in Egypt from 1990 to 2023 using the data from the World Bank (2023) (See Figure 6), it is evident that FDI as a percentage of GDP has been relative, with an average growth rate of 2.3 percent from 1990. The trend corresponds with the study of Mohamed *et al.* (2021), as low FDI also affects technology transfers through fewer absorbed opportunities of skills, knowledge and management practices, hindering the development and adoption of new technologies denoting the

negative/slow relationship between technological innovation and economic growth in Egypt, as accented by the study.

Figure 6: FDI, Net Inflows (%GDP): Egypt



Source: World Bank (2023)

Looking at the study by Mohamed *et al.* (2021) is essential for this study, because Egypt is one of the top three large economies in Africa alongside Nigeria and South Africa, and therefore, the results of its movement towards the impact of technological innovation and economic growth may be essential to understand how economic strategies of the largest economies in Africa impact growth in the domestic country and also the continent. Though the countries may have different economic sizes, population, diverse economic structures, and economic challenges such as inequality, unemployment, and political instability, the countries, however, also share similar issues related to infrastructure deficits, and high dependence on specific industries. Therefore, comparing these countries is essential to understand which economic strategies work best.

Sulaiman *et al.* (2015) investigated the impact of human capital and technology on economic growth in Nigeria. Similar to Mohamed *et al.*'s (2021) study, Sulaiman *et al.*'s (2015) study also adopted the ARDL in its methodology in investigating the empirical

evidence using time series annual data for 35 years. The study adopted different variables in assessing the impact of technological innovation with economic growth. The study by Sulaiman *et al.* (2015) stressed that there was a continuous debate over the years on the role human capital and technology play in determining economic growth, thus resulting in the study's aim of investigating the short-run and long-run impact of human capital and technology on economic growth.

The study by Sulaiman *et al.* (2015) used two different models with two different proxies for human capital, one being secondary education, and the other being tertiary enrolment. Both models were estimated, both in the short-run and the long-run. The main findings of the study elucidate that there is a positive cointegration relationship between human capital and economic growth for both models, and similarly, the results for both tests showed a positive significant short- and long-term relationship between technology and economic growth. The study's results are in correspondence with the Human Capital Theory and Endogenous growth theory, that education plays an essential role in the development and growth of a country. The human capital theory suggests that continued investments in education enhances skills, productivity, and knowledge, which spills over to innovation potential, and in case of Sulaiman *et al.* (2015), saw a positive spillover in technology, which also resulted in economic growth as argued by the endogenous growth theory. The difference between the studies of Sulaiman *et al.* (2015) and Mohamed *et al.* (2021) is that Sulaiman *et al.* (2015) centred on human capital development as the key driver of technological innovation, whereas Mohamed *et al.* (2021) centred their argument on foreign direct investment being the key driver of technological innovation. This resulted in contrary results, despite the methodologies being similar. The study by Sulaiman *et al.* (2015) further expounded policy recommendations, suggesting that the Nigerian government should increase the supply of both secondary and tertiary facilities, as well as encourage R&D that promotes technological innovation as the variables both theoretically and empirically drive economic growth in Nigeria.

Equally, Chiemeké and Imafidior (2021) conducted a study investigating the adoption of digital technology and its impact on economic growth in Nigeria. The study primarily aimed at examining the relationship that exists between digital technology adoption in

labour productivity and economic growth from 1990 to 2019 in Nigeria. The study by Chiemeke and Imafidor (2021) elucidated a broad agreement that a positive impact of digital technology and economic growth existed. However, the misalignment between academic consensus and empirical results of the study highlighted the impact between economic growth and digital technology adoption. Though theoretical literature such as the endogenous growth theory supports the positive relationship, empirical results from the Chiemeke and Imafidor (2021) study provided contrary and inconsistent results, thus creating the objective of this study.

In attaining the empirical results, the study employed structural vector autoregressive (SVAR) and the impulse response function (IRF) to measure the shock responses from digital technological adoption. Additionally, the study conducted forecast error variance decomposition (FEVD) and the VAR Granger Causality. Overall, the empirical aspect of the study aimed at developing an economically well-interpreted impulse response and decomposition that deciphered the short-term impact of digital technological adoption shocks on labour productivity and economic growth in the Nigerian economy (Chiemeke & Imafidor, 2021).

The results suggested that in the short run, the adoption of digital technology shocks on labour productivity and economic growth have a negative significant impact. By contrast, in the medium to long term, digital technology shocks have a positive and significant impact on economic growth and labour productivity. The results from the Granger causality revealed that in Nigeria, the causality direction is unidirectional as it moves from digital technology to economic growth and labour productivity. The Chiemeke and Imafidor (2021) study postulated that the negative impact of the shock in the short-run is economically plausible, because in an economy like Nigeria that has low digital literacy, adoption of new digital technologies may be slow, resulting in the delayed reflection of its impact in the short-run. To this point, Abiodun (2024), Olufeni (2024) and Nkwunnowo (2023) emphasise that Nigeria has been slow in the adoption of technological opportunities in comparison to countries like Ghana, Rwanda, and South Africa, with the implementation of technologies such as blockchain, which would aid the country's challenge about financial inclusion, and technologies such as Terrestrial Laser Scanning

(TLS) to enhance Nigeria's surveying expertise. The current delays in the adoption of digital technologies in Nigeria validates the study's empirical results.

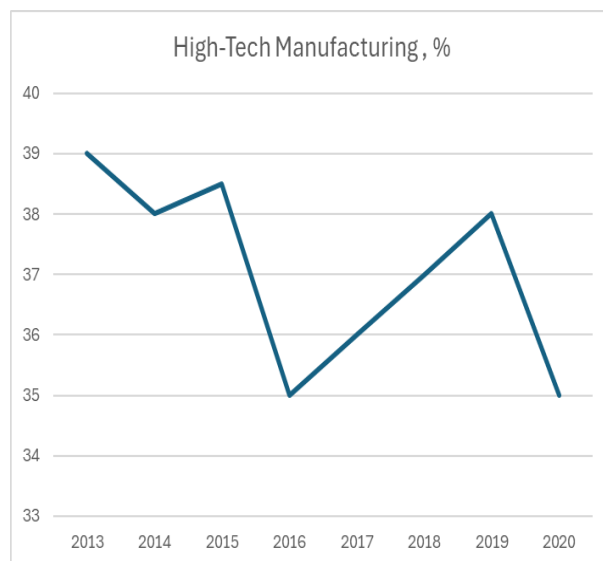
After the results, Chiemeké and Imafidor's (2021) research paper submitted recommendations to policymakers that an increased sense of focus towards the promotion of ICT is essential; institutions should further promote the utilisation of digital technologies within the teaching and learning process; regulatory-friendly frameworks should be promoted to correct market failures and improve Nigeria's access to digital technology and infrastructure, that complements that digital technologies should also be prioritised. The findings from three studies, by Sulaiman *et al.* (2015), Mohamed *et al.* (2021) and Chiemeké and Imafidor (2021) are essential for this study, as they are aligned with the objectives of the study and will help with understanding South Africa's stand in terms of driving technological innovation against the three economic giants in Africa. Also, the results from the three studies will add to the literature by indicating the current technological standpoint of the three economic giants in Africa by assessing variables related to digital technological adoption, education and technology transfers.

To further augment the depth of the study, the study assessed global developing countries that share the same economic and historic characteristics as South Africa, and in doing so, the study looked at a study by Pio (2020), with the primary aim of analysing the level of influence of innovation activities on economic growth in Brazilian states. Furthermore, the analysis aimed to look at the effects of social capital in contributing towards increasing productivity networks. The Pio (2020) study highlighted that general theoretical and empirical evidence have argued that there is a positive influence of innovation activities on economic performance. However, such conclusions for Brazilian states were not conclusive, thus resulting in the study creating two hypotheses i) "Innovation in Brazil has a positive effect on economic performance" and ii) "Social capital positively affects Brazilian economic growth" which serve the purpose of answering the research question and attaining the study's objective.

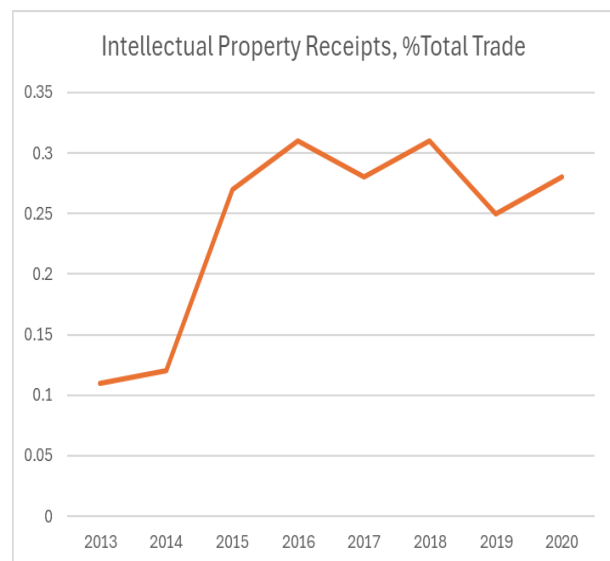
Pio's (2020) study adopted two methodological procedures to attain the empirical objectives. The first method adopted was the generalised moments method (GMM) followed by the system generalised moments method (SGMM). The research study

explains that the first methodology uses explanatory variable differences which are not solely exogenous at their available lag, and the second methodology is references to traditional ordinary least squares (OLS), fixed Effects, and Random Effect methods. Pio's (2020) study dataset comprised 297 observations over 10 years; this was due to the lack of data with a long periodic structure.

The main findings from Pio's (2020) study indicated that human capital is a viable indicator that explains Brazil's economic growth which has a positive significant impact on Brazil's economy, and an increase in the average schooling leads to an increase in productivity and production. The position of the first results are aligned with the Human Capital Theory, and also follows Sulaiman *et al.*'s (2015) study, through different methodologies were utilised. The second key finding denotes that social capital shows a positive relationship between cooperatives, different forms of non-profit institutions and Brazil's GDP. Finally, innovation was found to be significant in contributing towards economic growth. Pio's (2020) study highlights that interest in innovation activities has intensified over the years, the activities have not yet yielded positive results, and the levels of production have not yet been met. Despite the delay in the investment made in technological initiatives (See Figure 7 and 8), Brazil has continued to invest in technological initiatives, with the industrial policy that saw an investment of \$600 billion being directed towards the technology sector in 2023 for the development of chips, biotechnology, and national systems (Mari, 2023; Global Innovation Index, 2023). Though the fluctuations in the manufacturing of high technology and intellectual property receipts is evident, Brazil is focussed on driving technological innovation through the industrial policy intended to stimulate technologies that will enhance competitiveness and attract investments (Mari, 2023).

Figure 7: High-Tech Manufacturing, %

Source: Global Innovation Index (2023)

Figure 8: Intellectual Property Receipts

The reason for the lag was associated with Brazil's lack of technological innovation absorption capacity and its inability to integrate technological innovations into society. Brazil, as a country with similar economic dynamics to South Africa, is propelling benchmarking the country in terms of comparing technological innovation outcomes. Pio (2020) study's results on Brazil's economy towards technological innovation may be similar to South Africa's technological outcomes, as the two countries share similar economic dynamics. Second to that, Pio's (2020) study acceded to the study conducted by Aldieri *et al.* (2020) on the relationship between R&D and innovation activities as well as labour migration inflows as a form of human capital, and the impact the variables have on economic growth in Russia. The authors adopted a multi-regional economic geographic model in over 85 Russian regions for 6 years. Aldieri *et al.* (2020) study's contribution added to the existing literature on the effects of migration inflows and innovation within the Russian economy and also added to the political topic of how to manage policies. The authors' assumption stood on pre-existing literature on the endogenous growth model, that technological innovation and knowledge formation play an essential role towards an increase in production and growth.

Aldieri *et al.* (2020) developed two hypotheses to obtain the empirical evidence, i) "There exist positive externalities between human, knowledge and physical capital." ii) "There

exist positive importance of migration inflows on R&D and technological innovation activity". The methodology part of the study highlights that two OLS regression analyses were conducted, with innovation and migration being two separate variables. The primary results from Aldieri *et al.*'s (2020) study show a positive causality link between technological innovation and migration inflows, which boosts production and economic growth. The study's results are aligned with the theoretical framework adopted from the endogenous growth model. Moreover, the authors state that the results posed useful insights in formulating Russia's science and innovation policies to favour technological innovation activities. The study further suggests increased focus towards investments in higher education for residents in Russia to increase the flow of technological innovation activities as accounted for by the human capital theory. Russia, as one of the developing countries that is part of BRICS (Brazil, Russia, India, China, and South Africa), the results from Aldieri *et al.*'s (2020) study will assist with understanding which of the BRICS countries are more receptive to technological innovation activities.

Lastly, Zhou *et al.* (2021) wrote a research paper investigating the direction between technological innovation and structural change in driving China's economy. The authors utilised a nonlinear model using provincial data within the period from 2000 to 2014. The authors' primary aim of the study was to investigate the level of influence that technological innovation and structural change have on economic growth in China. The study's findings were to be applied in the process of redesigning strategic policies that advocate and promote the focus towards sustainable economic growth through structural changes and technological innovation activities in China. The research paper developed three hypotheses, i) "Different types of technological progress have different effects on promoting economic growth, and there is regional heterogeneity in these effects" ii) "Structure optimisation has an indeterminate effect on economic growth, and there is regional heterogeneity in its effect" iii) "Technological progress can promote industrial structural change, but the economic-promoting effect of industrial structure is uncertain; therefore, the structure effect of technological progress on economic growth is uncertain".

The theoretical foundation of the Zhou *et al.* (2021) study emanates from Schumpeterian theory, which elaborates that economic growth is promoted through technological

innovation activities. To attain the empirical objectives, the authors conducted several analyses using a variety of models such as the Stochastic Frontier Analysis (SFA), the Data Envelope Analysis (DEA), and the Semiparametric Method. As a way of avoiding unobserved variables and removing multicollinearity, the study's data utilised annual panel data inclusive of China's 30 provinces. Moreover, the model of the study was regressed using the System-Generalized Method of Moments (SYS-GMM) to reduce estimation bias. The results of the study of Zhou *et al.* (2021) denote that there is an inverted U-shaped relationship between technological innovation and economic growth and reveal the need to shift from technological imitation to a more innovative drive environment in which structural changes will stimulate China's emerging economy. Zhou *et al.* (2021) further postulate that a premature focus towards deindustrialisation may lead to the reduction of a country's economy. Comparing the study's results with the outcomes that will come from this research paper will assist in understanding which BRICS countries are responsive to technological innovation activities and which ones are not. Currently, China has the highest adoption rate of technological adoption, especially in the artificial intelligence space, with over 83 percent of the internet users having used artificial intelligence in their day-to-day life (SCMP, 2024).

2.5.2. Developed Countries Context

The selection criteria adopted for singling out developed countries was looking at countries that share similar historical and colonial background, countries that equally evince investments towards a knowledge-based economy, and countries that largely invest in education. Contextualising developed countries aids the study with understanding how countries with similar characteristics have mapped technological innovation and how it may mirror the study. Three key studies were singled out based on the criterion above to better answer whether a definitive link exists between economic growth and technological innovation.

Petelski *et al.* (2020) wrote a research paper on the support of the public sector in financing technological innovation and its impact on economic growth in the Argentinian economy. The objective of the study by Petelski *et al.* (2020) was to evaluate the impact of the public sector's funding on technological innovation to intensify R&D, labour, and

economic growth. Additionally, the research paper aimed to evaluate the firm's accumulated capacity based on the intensified focus on R&D through increased public sector funding. Petelski *et al.*'s (2020) research paper developed two hypotheses to attain the empirical objectives i) "public financing for innovation has a positive impact on R&D intensity measured as a share of current income."; ii) "public financing for innovation has no positive impact on the share of total employment of the firms dedicated to formal R&D activities". The theoretical foundation of the study stated that public sector funding created crowding-in benefits towards R&D, which enhanced innovation activities.

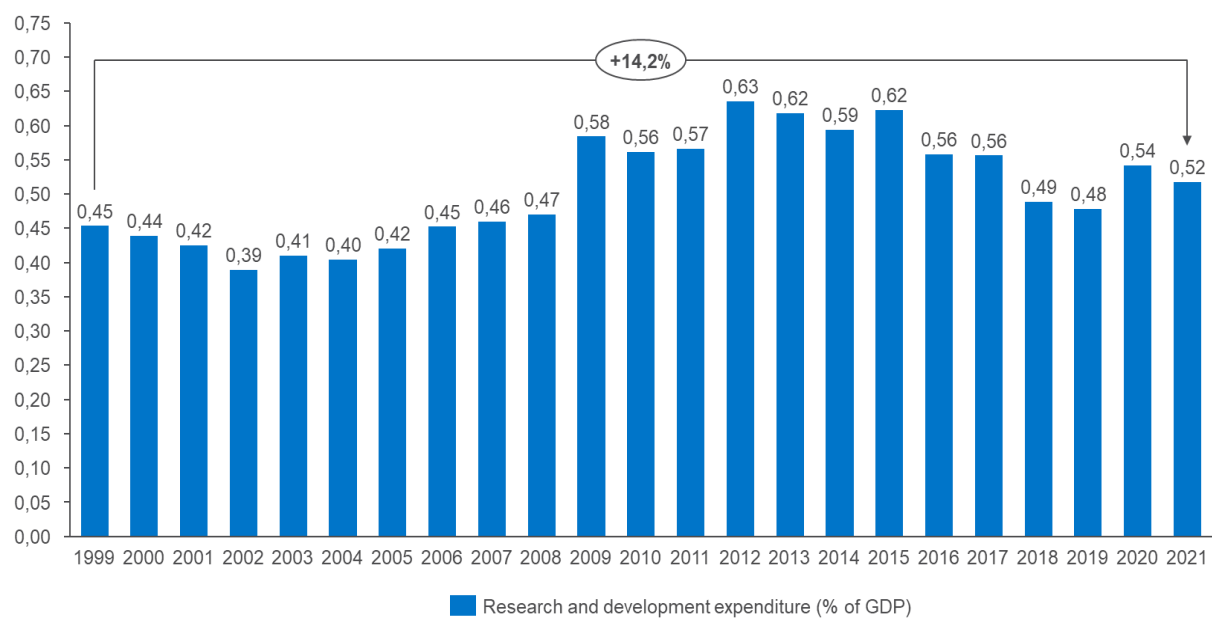
The data analysis was conducted using data from National Survey of Employment Dynamics and Innovation (ENDEI) which covered Argentina's industrial sectors nationwide, concerning 3691 firms, for the period between 2010 and 2012. To solve the problem of dimensionality, the study adopted the Propensity Score Propensity (PMS) method to ensure that subsidised firms and non-subsidised forms from the ENDEI survey are one. Secondly, to test the second hypothesis, the study analysed the impact using the DREmploy variable outcome which measured the number of employees engaged in R&D activities.

The primary results from the study indicated that public policy that supports increased technological activities measured by R&D has had a significant impact in intensifying R&D expenditure, as well as outcomes in the case of the Argentinean economy. The primary results are aligned to the endogenous growth theory, that R&D plays a crucial role in the development of technological initiatives. For the second hypothesis, the study found no positive impact of the evaluated public policy support towards R&D activities with total employment. The study then concluded that public sector policy that supports technological innovation activities is fundamental in intensifying Argentina's firms' productivity as well as performance. World Bank (2021) highlights that R&D expenditure in Argentina has increased by 14.2 percent from 1999 to 2021 (See Figure 9), accentuating the study's results, that continued R&D expenditure intensifies innovation initiatives resulting in economic growth. The spike in R&D expenditure from 2009 is followed by a positive spike in growth rate in Argentina's economy; in the following years,

economic growth reached highs of 4.33 percent in 2010 Q2 and an increase of 10.94 percent in 2020 Q3 (Trading Economics, 2024).

South Africa and Argentina share a similar colonial history and Argentina’s drive towards drafting public policies that encourage technological innovation activities is similar to South Africa’s agenda in creating efficient industries. The results from the study by Petelski *et al.* (2020) highlight a positive impact of such policies. Therefore, the results from the study may be used to influence the public policies that support innovation activities as witnessed in Argentina. In South Africa, the policies may foster an environment that boosts employment numbers.

Figure 9: R&D Expenditure (%GDP): Argentina



Source: World Bank (2021)

Following the study by Petelski *et al* (2020), the research paper further looked at the study conducted by Ben-Hassen (2021), which examined the current standpoint of a knowledge-based economy (R&D) in two of the distinct Arab countries, Qatar and Lebanon, as case studies. Ben-Hassen’s (2021) study was drafted based on five primary knowledge-based economy aspects, namely human capital development (education); ICT; entrepreneurship; innovation; and institutionalism, to provide a rigorous view of the challenges faced by Qatar and Lebanon in becoming knowledge-based economies. The

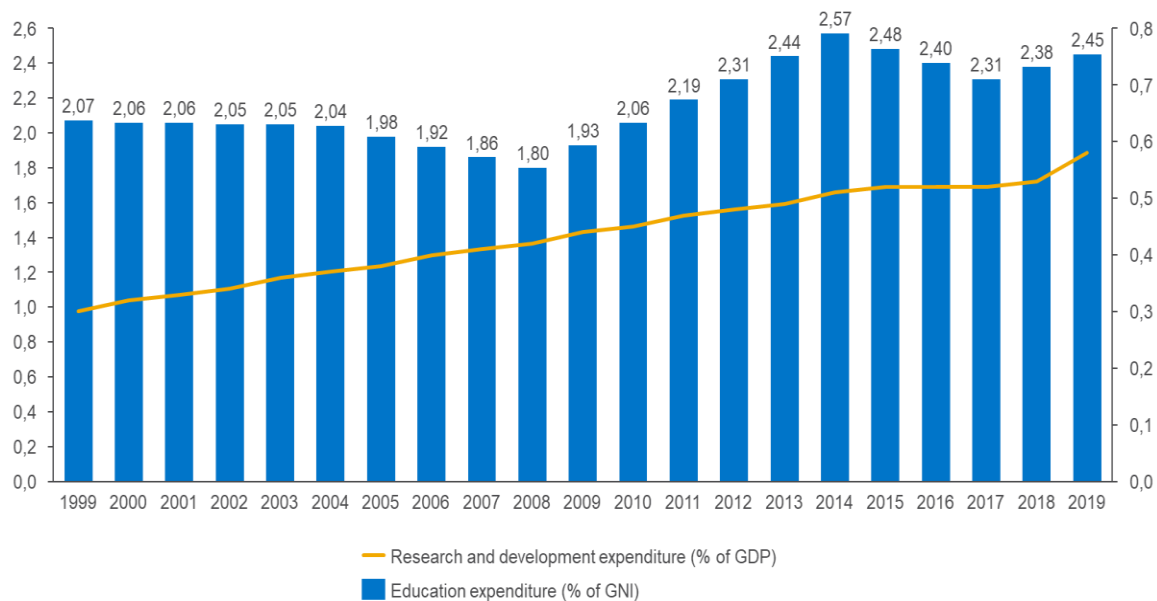
authors of the study adopted a semi-structured interview data method for different stakeholders, focusing on a knowledge-based economy as well as existing literature, in attaining the results of this study. Two sets of questions were set for this study, i) “what are the main drivers and constraints of the knowledge-based economy in Qatar and Lebanon?” ii) “how are these constraints hindering the transition toward a knowledge-based economy?”.

The research paper’s contribution was to clarify and highlight Qatar and Lebanon’s state in being a knowledge-based economy, which would have policy contributions. Ben-Hassen’s (2021) research paper sets out the premise that Arab countries have placed emphasis towards diversifying and moving to a more knowledge-based economy, and the promotion of this economy has become a key policy goal. The methodology part of Ben-Hassen’s (2021) study first began by reviewing scholarly articles, government reports and white papers on the current state of the knowledge-based economy, which assisted with determining economic characteristics and the crucial stakeholders involved in the diversification process in both countries. Secondly, the author conducted two sets of in-depth interview sessions, which were carried out either face-to-face or telephonically, and via semi-structured questionnaires. The interviews were held with Qatari and Lebanese experts in education, ICT, innovation, entrepreneurship, and R&D, as well as industry representatives, in the first series of interviews. The second phase of interviews was with ICT firms in both Qatar and Lebanon, as ICT was deemed a crucial sector in deriving a knowledge-based economy.

According to the study, a variety of variables influence Qatar and Lebanon's knowledge-based economies. The primary strength of Qatar's knowledge-based economy is the government's focused determination to diversify the economy through “top-down interventions”, while the main challenge is the lack of qualified human capital, resulting in poor performance of the innovation system and activities. The findings support the need for a systematic approach that takes into account all of these aspects, as well as their linkages and associated consequences, to increase our understanding of the possible hurdles for the Arab region's transition to a knowledge economy. Looking at the findings of the study, Qatar is increasing expenditure on R&D to move towards a more knowledge-

based economy, with increased expenditure on education by citizens over time (See Figure 10). According to the World Bank data (2021), Qatar directed the same expenditure on R&D as South Africa, and South Africa undrilled comparison between South Africa and Qatar, there is a similar focus towards investing in a knowledge-based economy for both countries. Results from the study by Ben-Hassen (2021) may aid with cementing the need to for South Africa to prioritise such an economy, based on the results of the study from Qatar, a developed country.

Figure 10: R&D Expenditure (%GDP) vs Education Expenditure (%GNI)



Source: World Bank (2019)

Lastly, the research evaluated the research by Raunio *et al.* (2018) which was conducted to explore the role of open innovation platforms (OPIs) in the orchestration of innovation activities. The authors of the study highlight that OPIs are a new tool that fosters convergence of innovation, research and development, and education activities. The authors further noted that OPIs play a fundamental role in orchestrating the interactions between education, science, and innovation activities. The “Six Cities Framework” model was adopted for the analysis of the data, as the study was explored within the smart city framework. Raunio *et al.*’s (2018) research paper stresses that the orchestration of OPIs brings about three questions i) “How does the ownership of the intangible and tangible assets on the platform impact the orchestration and its focus?” ii) “How can one create

network effects by utilizing the platform model?” iii) “How does one foster inclusive qualities in OIPs, especially when the approach is transferred to urban development and more active citizen engagement?”. The participatory action research (PAC) guided the authors in the development of the strategy.

The theoretical arguments of the study echoed that knowledge triangles and OPIs are integrated and overlapping, therefore, knowledge triangles emphasise the existence of a linkage between education, innovation, and research and development activities, which all increase the flow of information and collaboration spilling over to the creation of new business models, processes, ideas, products, systems, and ultimately economic growth. The study's theoretical framework aligns with the human capital development theory and the endogenous growth theory. As mentioned, the study utilised the participatory action research (PAC) method to answer Raunio *et al.* (2018) study's research question that attains the study's objective. The authors postulated that the PAC provides solutions and knowledge on practical problems that may hinder the attainment of given objectives or goals. Data was gathered through 14 interviews, 12 workshops, 100 meetings, 13 platforms, and 25 platforms nationally.

Results of the study show that prioritising the development of new technological techniques that incorporate societal knowledge and responsible attributes into processes and outcomes is critical to creating fair and long-term economic growth. Additionally, the authors note that an internet-powered multilateral platform is intended to use network effects to supply novel services, improve industrial scalability, and lower marginal costs. This, in turn, promotes the development of new products, the success of businesses, and general economic growth. Competitive advantages that significantly differentiate organisations are frequently based on organisational qualities like good management, simplified procedures, or innovative software, rather than physical and tangible characteristics. Raunio *et al.*'s (2018) study paints a positive narrative between innovation, education, and economic growth in Finland, a developed country that spends approximately over 70 percent of its capital on education, according to the World Bank (2021), data similar to South Africa. Additionally, Getzoff (2023) postulated that Finland is one of the technologically advanced countries with the highest rate of absorption due

to its positive correlation between education, innovation, and economic growth. The study by Raunio *et al.* (2018) sets a level of comparison and benchmarking between Finland and South Africa as countries that spend equally on education, and whether South Africa will experience the same level of correlation between education, innovation, and economic growth.

Table 1: Empirical Studies Summary

Authors	Year	Title	Data and Methods	Main Findings
Developing Countries				
Mohamed, M.M.A., Liu, P. & Nie, G.	2021	Are technological innovation and foreign direct investment a way to boost economic growth? an Egyptian case study using the autoregressive distributed lag (ardl) model.	Autoregressive Distributed lag model time series data from 1990 to 2019.	Positive relationship between FDI and economic growth in the long-run but a negative yet statistically insignificant in the short-run. Negative relationship between innovation and economic growth in the long-run and positive but insignificant relationship in the short run.
Sulaiman, C., Bala, U., Tijani, B.A., Waziri, S.I. & Maji, I.K.	2015	Human capital, technology, and economic growth: evidence from Nigeria.	Autoregressive Distributed ARDL time series data for 35 years	Positive cointegration relationship between human capital and economic growth; positive significant short- and long-term relationship between

				technology and economic growth.
Chiemeke, S.C. & Imafidor, O.M.	2020	An assessment of the impact of digital technology adoption on economic growth and labour productivity in Nigeria.	Structural Vector Autoregressive (SVAR); Forecast Error Variance Decomposition (FVED) and the VAR Granger Causality, time series from 1990 to 2019.	The research concludes that digital technology adoption in Nigeria positively impacts both economic growth and labor productivity. The results advocate for further digital investment to enhance productivity.
Pio, J.G.	2020	Effects of innovation and social capital on economic growth: empirical evidence for the Brazilian case.	Generalised Moments Method (GMM); System Generalised Moments Method (SGMM); Ordinary Least Squares (OLS), dataset comprised of 297 observations over 10 years	Human capital as a viable indicator that explains Brazil's economic growth has a positive significant impact on Brazil's economy and innovation was found to be significant in contributing towards economic growth.
Aldieri, L., Kotsemir, M. & Vinci, C.P	2020	The role of labour migration inflows on R&D and innovation activity: evidence from Russian regions	OLS regression analysis using data from 85 Russian regions for 6 years.	Positive causality link between technological innovation and migration inflows which boosts production and

				economic growth.
Zhou, X., Cai, Z., Tan, K.H., Zhang, L., Du, J. and Song, M	2021	Technological innovation and structural change for economic development in China as an emerging market.	Stochastic Frontier Analysis (SFA); Data Envelope Analysis (DEA); Semiparametric Method. Utilised annual panel data inclusive of China's 30 provinces.	U-shaped relationship between technological innovation and economic growth and reveal the need to shift from technological imitation to a more innovative drive environment in which structural changes will stimulate China's economy
Developed Countries				
Petelski, N., Milesi, D. & Verre, V	2020	Public support to innovation: Impact on technological efforts in Argentine manufacturing firms	Propensity Score Propensity (PMS); DRemploy; Data from 3691 firms in Argentina for a period between 2010 to 2012	Public policy that supports increased support of technological activities through R&D has had a significant impact in intensifying R&D expenditure thus resulting in economic growth.
Ben-Hassen, T.	2021	The state of the knowledge-based economy in the Arab world: cases of Qatar and Lebanon.	Literature review; Primary data through semi-structured interviews	A knowledge-based economy is driven by educational systems in Lebanon, and Qatar is determined to

				diversify into a knowledge-based economy, but due to the lack of human capital resources, innovation performance is low.
Raunio, M., Nordling, N., Kautonen, M. & Räsänen, P.	2018	Open innovation platforms as a knowledge triangle policy tool—evidence from Finland	Participatory Action Research (PAC), data collected over 14 interviews; 12 workshops; 100 meetings; 13 platforms; and 25 platforms nationally.	The development of new technological techniques that incorporate societal knowledge into processes and outcomes is critical to creating fair and long-term economic growth.

Source: Author computation (2024)

2.5.3. Developing vs Developed Countries: Empirical Findings

A comparison of the empirical findings of developing and developed countries, based on section 2.5.1 and 2.5.2, highlights that the assessed countries share similar growth patterns and distinct challenges in terms of technological innovation. In the assessed developing economies, such as Egypt, Nigeria, Russia, China and Brazil, technological initiatives are often fuelled by factors such as foreign direct investment, human capital, and the reliance on continuous absorption of digital initiatives. To expand on this, the study on Nigeria's economy highlights that human capital augmented by technological initiatives plays a critical role in boosting economic growth, particularly through the integration of digital technologies in labour productivity environments. Additionally, the Egyptian study emphasises the importance of FDI (technology transfers) and technological innovation as a key driver to growth. A case study on countries such as

Brazil and Russia exhibited similar patterns, where innovation and social capital contribute to R&D initiatives and economic performance. In China, technological initiatives are attached to the nation's structural changes which has enabled and positioned China to be an emerging market. The studies showcase how developing economies are heavily reliant on capital flows, technology transfers, and digital adoption to drive innovation and economic transformation.

In contrast, the assessed developed countries such as Finland, Qatar, Lebanon, and Argentina all demonstrated a more refined approach in fostering technological innovation. These countries are more focused on expanding to a more knowledge-based economy with an innovative ecosystem. The economies place more emphasis on endogenous innovation strategies supported by aligned public policy frameworks, educational programmes, and technological platforms. Finland sticks out for its use of open technological innovations to drive a knowledge-based system that fosters collaboration across different sectors. Moreover, the Argentinian study underscores the role of government's support in strengthening technological efforts in its sectors, reflecting an intended national policy to enhance competitiveness. To implement strategies that lead to a more knowledge-based economy, Qatar and Lebanon are leveraging intellectual human capital, digital infrastructure, and directed R&D. Developed countries assessed for the study's discussion are noted to be focused on endogenous innovation capabilities supported by strong public policy frameworks and global collaborations, compared to relying on exogenous factors.

While countries that are developing confront the task of establishing basic infrastructure and strengthening human capital to enable technological innovation, industrialised economies focus on optimising and growing their existing sophisticated innovation systems. Both groups share the awareness of technology as a crucial engine of economic progress, but their paths diverge dramatically. Developing countries prioritise catching up through FDI, technological adoption, and capacity building, whereas established economies emphasise maintaining and expanding their technical advantage through innovation programmes, knowledge networks, and public-private partnerships. These divergent dynamics demonstrate how economic growth is driven, not just by the

availability of technology, but also by the institutional and regulatory settings that foster innovation at various times.

2.6. CONCLUSION

This chapter highlighted three crucial sections (2.1-2.3) which were all collectively crucial in framing the theoretical and empirical foundations of the research paper. Section one provided an overview on the evolution of all industrial revolutions to provide a systemic view of what led to the 4th Industrial revolution and what constituted each industrial revolution. Though each industrial revolution resulted in positive attributes economically, the section further highlighted the shortcomings of each industrial revolution, such as how the first industrial revolution resulted in increased pollution, child labour, and the transmission of diseases. The following sub-section accented the role technological innovation plays in supporting economic growth. The section highlighted the intricacies associated with technological innovation and its impact on economic growth, from a theoretical understanding. The section dissected theoretical foundations, that technological innovation creates new industries and introduces new markets that create an opportunity for employment, facilitate global integration of economies, support economic spillovers that boost and encourage domestic investment, increase in production processes and enhance research and development in key sectors of the economy.

The second section primarily focused on the theoretical framework associated with technological innovation scrutinising the theory assumptions and limitations. The section scrutinised four theories: Schumpeterian theory; Solow growth theory; Endogenous growth theory; Unified growth theory. The theories aimed to provide a theoretical understanding that conceptualised the study's assumption. The last section of the chapter provided empirical evidence on the studies conducted, assessing the impact between technological innovation and economic growth to build parallel to the study's results, with countries that share similar economic, historic, and geographical characteristics. The studies provided a possible frame for the outcomes of the study.

The study's empirical evidence was categorised into two: developing and developed countries, which were selected based on a specific characteristic the country shares with South Africa. Some of the previous studies conducted in different countries similar to South Africa show contrary results to the theoretical assumptions, and some share similar results.

The results build a base for the study that the results may or may not be similar to theoretical assumptions. The empirical studies from developing countries highlighted that the country is heavily dependent on factors such as foreign direct investment, capital injection, education, and the level in which digital technologies are absorbed. The empirical findings in developing countries lean more towards exogenous factors in technological innovation. Contrastingly, empirical findings on developed countries highlight a heavy reliance on endogenous factors such as education and continuous investment in R&D, leading to a more knowledge-based economy. Similar and contrasting evidence towards technological innovation resulting in economic growth was observed to be present in both developing and developed countries

Expanding on these observations, the divergent reliance on exogenous and endogenous factors reflects the varying stages of economic and technological maturity between developing and developed nations. In developing economies, the dependence on foreign direct investment (FDI) and technology transfers underscores the critical role of external support in bridging gaps in domestic capabilities. However, this reliance can lead to vulnerabilities, particularly when global economic conditions fluctuate or when FDI inflows are inconsistent. In contrast, developed countries' emphasis on fostering innovation through education and R&D investment demonstrates a proactive approach to sustaining economic growth through internal capacity building. This approach enables developed nations to maintain resilience against external shocks while fostering a self-reinforcing cycle of innovation. Notably, while the pathways differ, both sets of economies reveal the fundamental importance of aligning policy and investment strategies to their specific economic contexts, ensuring that technological innovation can effectively drive sustainable growth.

CHAPTER THREE: TECHNOLOGICAL INNOVATION IN SOUTH AFRICA

3.1. INTRODUCTION

This chapter presents the profile of South Africa's technological innovation environment by assessing the conditions and trends of technological innovation based on the theoretical objectives stated in section 1.4.2. In so doing, the chapter will answer the following questions: i) What are the technological innovations conditions in South Africa; ii) What are the technological innovations trends in South Africa?. The study will achieve the objectives by firstly assessing government policies and regulations to understand the conditions innovation operates under. Theoretical assumptions discussed in section 2.4 highlight that institutions play a fundamental role in creating a conducive environment that augments technological innovation and economic growth. Therefore, this section will profile the role different institutions play in supporting technological innovation in South Africa. Secondly, the study will evaluate the emerging technologies in South Africa to understand the trends shaping South Africa's technological current trends. Understanding emerging market trends in technological innovation reflects the institutional environment in adopting new technologies.

3.2. TECHNOLOGICAL INNOVATION CONDITIONS IN SOUTH AFRICA

This section of the chapter aims to assess the environment surrounding technological innovation activities in South Africa operate. It will provide an understanding of how public and private institutions support technological creativity and research and development.

3.2.1. Government Policies and Regulations

According to the Department of Science and Innovation (DSI) (2021), South Africa has adopted a long-term approach to encouraging the country's advancement in science, technology, and innovation. In doing so, the DSI derives its mandate from the 1996 White Paper on Science and Technology which was a concept introduced to set policies and organisations across the country to create, diffuse, and acquire new knowledge practices

that attain institutional and individual goals related to technological innovation. According to Andoh (2019), the DSI, as per their mandate, espoused the 2019 White Paper on Science and Technology, which aimed to expand the role of science, technology, and innovation in various key sectors and subsectors, which accentuated initiatives such as reindustrialisation, as the world is becoming increasingly digital and knowledge-based, modernising the agricultural sector, attenuating the degradation of the environment, and improving service delivery.

After the adoption of the 2019 White Paper on Science and Technology, the DSI (2021) postulated that ratifying the 2019 White Paper is driving the coordination and efficiency of national systems to attain the nation's development objectives through innovation. The stance by the DSI echoes the sentiments of Srivastava (2023), that a technology-friendly government fosters an innovation environment that encourages R&D, supports entrepreneurship, develops strong frameworks of intellectual property, builds digital infrastructure and regulatory support, and encourages collaboration and international cooperation.

According to the DSI (2019), the 1996 White Paper on Science and Technology was met by a number of successes, such as the increase in the number of black people and women in the R&D workforce and increased the number of doctoral graduates. Additionally, the DSI (2018) further alludes that the 1996 White Paper on Science and Technology was successful in establishing institutions like the Technology Innovation Agency that aimed at advancing technological inventions and expanding international networks. The study will further elucidate the institutions established to ensure a conducive technological environment. The 1996 White Paper on Science and Technology managed to build international relationships that contributed towards strong global engagements and participation in global initiatives towards research and development, which aids towards knowledge spillovers (DSI, 2018).

By contrast, the 1996 White Paper on Science and Technology was met with a number of limitations, which led to the introduction of the 2019 White Paper (DSI. 2019). According to the DSI (2019), the 1996 White Paper on Science and Technology is not fulfilled. Although it has increased the number of black people and females, it has not

achieved inclusivity. Additionally, the Science, Technology and Innovation (STI)'s performance is hindered because it is underfunded, limiting its full capabilities. The implementation of the objectives of the 1996 White Paper on Science and Technology has been argued to be slow, resulting in slow socio-economic advancements, and is argued to be a result of the lack of policy coherence, as the objectives of the 1996 White Paper on Science and Technology are fragmented across different governmental departments, civil societies and businesses, leading to the lack of policy coherence (The Conversation, 2018). The DSI (2021) alludes that the shortcomings of the 1996 White Paper on Science and Technology yielded the revisiting of the policy to introduce the 2019 White Paper on Science and Technology.

Boghan and Jonash (1993) state that though the role of the government is multifaceted and crucial for innovation progress, the government must facilitate innovation activities through collaborations and product development. Additionally, Modara *et al.* (2020) found that for technological innovation processes and product development to occur, government should play a much stronger role in facilitating, endorsing, and incentivising the development of processes and products. The DSI, alongside the 2019 White Paper, set a target of 365 knowledge products, developing and approving 12 science, technology, and innovation policy directives; and maintaining nine interventions set to improve government services delivery over the medium-term period (DSI, 2021).

According to Kim and Castillejos-Petalcorin (2020), the government's policy framework plays a role in establishing standards and guidelines that provide security to public academic institutions and businesses, as well as facilitating long-term investments and planning related to innovation activities. Additionally, Radosevic (2018) states that friendly and flexible regulatory frameworks set by the government encourage product development while safeguarding ethical standards that stimulate creativity and risk-taking around innovation activities. Given this, the DSI established entities that facilitate and execute different regulatory frameworks to ensure a friendly and flexible environment of technological innovation activities, and section 3.2.2 elucidates institutional entities that aim to create a conducive environment for technological innovation.

3.2.2. Technological Innovations Entities in South Africa

According to Gao and Fan (2023), institutional entities are fundamental, as they play a crucial role towards advancing the science, innovation, technology and knowledge of a country. The DSI (2021) argues that entities such as the Academy of Science of South Africa (ASSAf), Council for Scientific and Industrial Research (CSIR), Human Sciences Research Council (HSRC), National Research Foundation (NRF), South African Council for Natural Scientific Professions (SACNASP), South African National Space Agency (SANSa) and Technology Innovation Agency (TIA) are collectively directed towards enhancing the country's research capacity, recognising and promoting scholarly achievements, facilitating the development of global and local innovation, and promoting evidence-based decisions by collaborating and engaging with policy makers. Additionally, technological institutions cultivate an environment conducive enough to promote cutting-edge research and innovation that supports and ensures scientific development is effortlessly disseminated (Su *et al.*, 2023). Institutional agencies are instrumental in driving and addressing socio-economic issues with specified targets, for instance the CSIR seeks to support 56 registered patents, and publish 960 journal papers in the medium term, and The TIA over the following three years seeks to licence 70 technical breakthroughs, introduce 101 items into the market, and guarantee that 24 technological advances are operational and functional (DSI, 2021). Though the institutions established prior or post the 1996 White Paper on Science and Technology as listed on Table 2 may carry different mandates, the entities all share a similar goal of promoting innovation, through research and development, scholarly achievements, development of human capital and providing policy recommendations all assist towards positioning South Africa as a key player in technological innovation on the local and global stage (DSI, 2018).

Table 2: Technological Innovation Entities

Entity Name	Mandate
Academy of Science of South Africa (ASSAf) – 1996	To be an apex organisation for science and scholarship in South Africa. To bring forth sustainable provision for a professionally

	managed company capable of mobilising the greatest brains, knowledge, and experience.
Council for Scientific and Industrial Research (CSIR) – 1945	To be the leading science and technology research organisation that engages in research, development, localisation, and innovation to enhance South Africa's socio-economic prosperity
Human Sciences Research Council (HSRC) – 1968	To initiate strategic and applied research in human sciences, as well as address developmental challenges through data collection, analysis, and publication, particularly through public-sector collaborations.
South African Council for Natural Scientific Professions (SACNASP) – 2003	Promote the practice of the natural science professions in South Africa; ensure and administer the mandatory registration of natural scientists as required in terms of The Natural Scientific Professions Act of 2003; exercise control over the standard of conduct of professional natural scientists
Technology Innovation Agency (TIA) – 2008	To promote the development of public interests, innovations, inventions, and discoveries, alongside fulfilling the organisation's mission of translating the nation's knowledge resource into opportunities that are sustainable for the socio-economic environment.
South African National Space Agency (SANSa) - 2010	To co-ordinate and integrate national space science and technology programmes and conduct long-term planning and implementation of space related activities in South Africa, for the benefit of the citizens of South Africa

Source: Authors' compilation

According to DSI (2021), research entities have had notable successes and failures, and among the successes, the entities have contributed significantly towards the advancement of knowledge, science, and technological innovation. For instance, the NRF supported research projects in fields such as health, energy, biotechnology, and agriculture, which resulted in knowledge breakthroughs (NRF, 2024). The CSIR has been instrumental in the development of technological innovations that address national challenges related to low cost solar-powered energy, and supporting industrial development (DSI, 2021). The DSI (2018) further alludes that the entities have further pioneered policy recommendations, supported by empirical research evidence, to provide valuable insights to critical societal issues. However, the technological innovation entities have faced a number of challenges (DSI, 2018). The DSI (2019) states that one of the key challenges the entities have faced is the challenge of inconsistent funding that has hampered long-term research and retention of projects. Similar to the 1996 White Paper on Science and Technology, research entities have faced a challenge of administrative bottlenecks due to misalignment, and the lack of policy coherence that has resulted in delayed research initiatives over the years (DTI, 2018). Additionally, the DTI (2018) and the DSI (2019) highlight that the mismatch between research outputs do not always reflect tangible societal outcomes, with different mandates given to technological innovation entities, clashing regulatory frameworks, and governmental objectives resulting in concerns over regulatory frameworks, influencing technological progress. Despite the setbacks faced by the technological innovation entities, the DSI (2021) alludes that the entities continue to play a pivotal role in augmenting an environment that supports technological innovations with more focused targets as set by 2019 White Paper on Science and Technology and promoting variables that augment technological innovation such as property rights.

3.2.3. Intellectual Property Rights (IPR)

Neves *et al.* (2021) assert that intellectual property rights have played a fundamental role in the invigoration of innovation, proselytising technological progress, and espousing economic growth. Arrow (1972) further states that the protection of IPR encourages the progression of technological innovation, by granting successful inventors and innovators

the assured safeguard that the efforts of their creations will be rewarded and given a temporary monopoly over their creative innovations. Additionally, the protection of IPR is suggested to be a significant determinant of economic growth that boasts a conducive environment of technological innovation (Gould & Grube, 1996).

According to Falvey *et al.* (2006), individual countries acquire development and advances in technology through a variety of channels that are channelled by either direct or indirect spillover. These channels include technological innovation, patents, licencing, trademarks, foreign direct investment, copyrights, and piracy and imitations that are all tools that foster an environment favourable for technological innovation. Falvey *et al.* (2006) further state that the effects of strong IPR protection towards technological innovation and aggregate growth are dependent on the level of development, and on the nation's ability to imitate. The World Intellectual Property Organisation (WIPO) (2017) postulates that channels such as patents ensure that groundbreaking inventions by innovators are protected, and innovators are granted exclusive rights to commercialise and gain from the utilisation of the inventions created. Additionally, successfully commercialised technologies generate revenue, which may finance research and development activities or be redirected towards the discovery of new technologies, thus creating a viable environment driven by technological innovation (WIPO, 2017; Baker, 2022). Global economies are increasingly and predominantly being driven by innovations and technology, and are knowledge-centric, thus accentuating the crucial role of the protection of IPR as a tool that fosters growth and technological innovation (African Union Development Agency (AUDA-NEPAD), 2023).

Similarly, the creation of copyright protection in industries related to art and culture is as progressive as the creation of patent protection of technological innovations, as the protection of both rights yields positive spillovers (Watt, 2009). Watt (2009:24) argues that "if an industry based on copied copyright-protected products were allowed to function, then there would be a creation of employment and correspondingly a certain generation of income locally, so long as the copied products were not depriving local authors of remuneration"; Kilbride (2023) highlights that robust frameworks are essential, because

in today's global economy, translating creative ideas to the market fuels productivity and fosters a hospitable environment for economic growth.

Overall, striking a balance in Intellectual Property Rights (IPRs) is critical for mitigating potential negative repercussions, such as limiting access to crucial new technologies and creative arts, and diffusion and transmission of information. Several developing countries face the difficult task of balancing intellectual property protection with the urgent need for inexpensive access to innovations, particularly in crucial sectors such as healthcare, education, and energy. Intellectual property rights have a significant influence on both innovation and economic progress. IPRs actively contribute to the growth of an inventive ecosystem by providing legal protection and incentives to innovators and creators. Nonetheless, careful consideration is required to ensure that intellectual property regulations strike a prudent balance between encouraging innovation and permitting accessibility for greater social benefit.

3.2.4. Intellectual Property Rights (IPR): South Africa

The South African legal environment constitutes of a hybrid of mixed common law systems which are drawn from various legal frameworks that include Roman-Dutch Law, English common law, Germanic law, and Roman law. However, primarily, the main source of South African domestic law includes the Constitution, common law, legislation, customary law, and case-law, which all guide and explain different intellectual property rights (European Commission, 2022). The Department of Trade and Industry (DTI) (2018) postulates that in recent decades, strides have been taken to protect, administer and manage the deployment of IPR. European Commission (2022) and DTI (2018) list statutes in South Africa that are related to IPR including: "Intellectual Property Rights from Publicly Financed Research and Development Act 51 of 2008; National Environmental Management: Biodiversity Act 10 of 2004; Patents Act 57 of 1978; Merchandise Marks Act 17 of 1941; Copyright Act 98 of 1978; Designs Act 195 of 1993; Plant Breeders' Rights Act 15 of 1976; and the Trademarks Act 194 of 1993".

According to Spoor and Fisher (2018), Phase I of the intellectual property policy of 2018 echoes that following the National Development Plan (NDP), South Africa placed priority

on technological innovation, pursuit of knowledge, exploration of comparative and competitive advantages and fostering efficient production; IPR is stated to play a crucial role in instrumenting the promotion of technological innovation, technology transfers, R&D, industrial development, and creative expression, which cements economic growth. According to the DTI (2018), South Africa's technological innovation and dynamic research environment requires a well-coordinated and balanced approach towards IPR protection, and the IP policy should be engraved in South Africa's Constitution. In doing so, the DTI (2018) IPR 2018 policy primarily focused on 11 key issues which were aimed at cultivating and promoting an environment of growth and development. The 11 key issues drafted by the DTI (2018) IP policy phase 1 are:

- I. Local manufacture and export in line with industrial policy
- II. Substantive Search and Examination (SSE)
- III. Patent Opposition
- IV. Patentability Criteria
- V. Disclosure Requirements
- VI. Parallel Importation
- VII. Exceptions
- VIII. Voluntary Licences
- IX. Compulsory Licences
- X. IP and Competition Law
- XI. Rule of Law, Legal Certainty & Security of Investments

The suggested key focus areas seek to improve the legal clarity and framework on patents and other types of intellectual property, beyond the current status quo (DTI, 2018). Furthermore, the proposed patent system aims to increase and diversify investments in the country through enhanced legal clarity in intellectual property, notably patents. According to the DSI (2021), reflecting on the depository system of existing intellectual property policies, the DSI alludes that the policies lack substantial patent review, are frequently deferred to the courts with the determining criteria for patent

eligibility and ineffectiveness, leading to costly litigation processes. The restated focus key policy areas aim to rectify the shortcoming by providing patent applicants with heightened assurance pertaining to the merits of their applications from the onset of the patent application process in South Africa (DSI, 2021).

Additionally, in resolving socioeconomic issues, the policy aims to develop a fair IP management system that appeals to a wider spectrum of IP companies (DTI, 2018). In the healthcare sector, for example, the Policy seeks to attract investment from a wide range of manufacturing countries throughout the world, notably North America, Europe, Brazil, Israel, and India, as well as original and generic manufacturers (DSI, 2019). Simultaneously, the Policy seeks to promote domestic investment by encouraging the growth and expansion of the current pharmaceutical firms in the country, which is an important sector of the national economy (DSI, 2018 & 2019).

The policy programmes correspond with multiple incentives established by the South African government to draw foreign investors, such as individuals under Section 12I of the Income Tax Act, the Critical Infrastructure Programme (CIP), the Support Programme for Industrial Innovation (SPII), and the Strategic Partnership Programme (SPP), and the benefits associated with investing in Special Economic Zones (SEZs), including preferential corporate tax, building allowances, employment tax incentives, and income received from the use of intellectual property rights according to the International Property Rights Index (IPRS): South Africa. However, despite the strides and initiatives taken by the South African government to increase the IPR protection footprint, the IPR benchmark comparison highlights that South Africa's IPR globally has declined. The Property Rights Alliance (PRA) (2023) reports that, according to the IPRI 2023 report, South Africa's IPRI score declined by over -0.34 to a score of 5.19, dropping to number 55 in the world and third in Africa. Additionally, the PRA (2023) adds that the Legal and Political Sub-index of South Africa also declined by over -0.08 to 5.22. South Africa further declined in scores related to Judicial Independence; Rule of Law; Political Stability; Copy Right Protection and Trademark Protection. Table 3 highlights South Africa's regional and global IPRS scores.

Table 3: IPRS Scores – South Africa

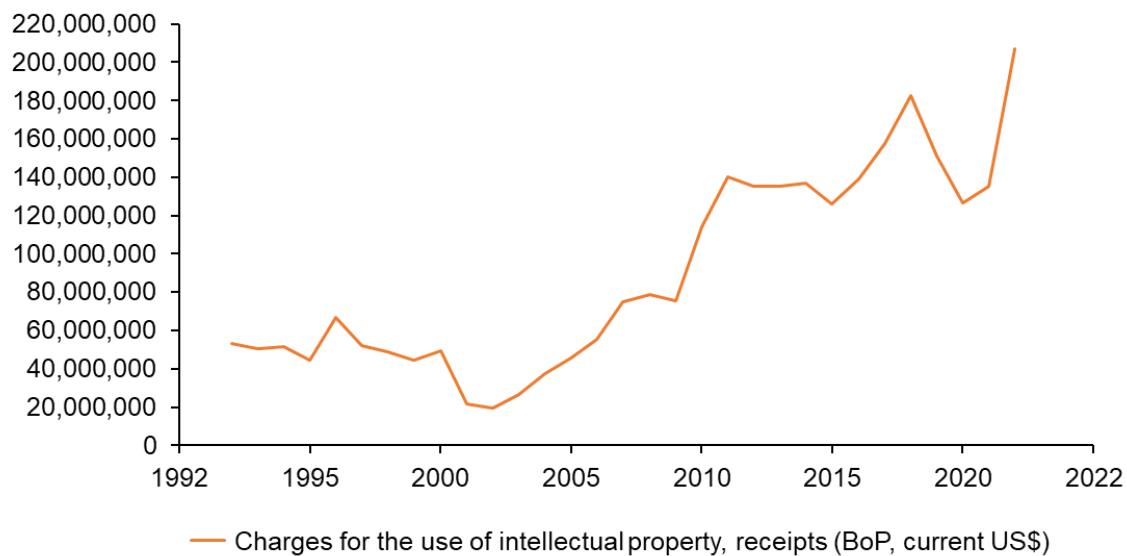
Statistic	Overall Scores	Position	
		Regional	Global
Overall IPRS	5.19	3	55
Legal and Political	5.12	4	52
Physical	4.95	5	61
Intellectual	5.40	1	52

Source: Property Rights Alliance PRA (2023)

In South Africa, the protection and enforcement of intellectual property rights face several challenges (Ncube *et al.*, 2014). Similarly, South Africa's decline in global rankings in terms of IPRs may be associated with the nation's inability to address prominent aspects related to creating an environment for technological innovation. Dell (2011) highlighted that South Africa's IPR framework made it difficult to protect local researchers and innovators from global competitors, and local frameworks do not confer global IP protection.

In addition to this analysis, Van Zyl (2023) highlighted that despite the progress made in terms of improving IPR protection, South Africa still struggles with aligning IPR frameworks with international standards, while addressing objectives related to research and development domestically which has created an environment susceptible to counterfeit and piracy, spilling over negatively to technological innovation and healthcare. Similarly, according to the World Bank's (2022) data, South Africa's charges from the use of intellectual property have only had a 5 percent compounded annual growth rate CAGR from 1992 to 2022, and Figure 11 depicts South Africa's charges for the use of intellectual property over the years.

Figure 11: Intellectual property use charges, receipts – South Africa



Source: World Bank (2022)

South Africa's challenges further include high levels of counterfeiting and piracy; inadequate resources and capacity for enforcement agencies; limited public awareness and understanding of intellectual property rights; and the need to balance the rights of creators with the users' access to affordable goods and knowledge. Additionally, there is a need for South Africa to effectively utilise the flexibilities provided by international IP agreements to promote development and ensure affordable access to IP-protected goods (Ncube & Yemurai, 2020). Moreover, there is a need for South Africa to actively engage in international IP law regimes and take into account the protection of traditional knowledge and biodiversity. Furthermore, it is crucial for South Africa to tailor its intellectual property policies to its socio-economic status and utilise evidence-based approaches in policy formulation (Ncube & Laltaika, 2013).

In addition, Anti (2023) echoed that despite adoption of the TRIPS Agreement and being part of the WIPO, South Africa still encounters struggles related to IP infrastructure, as some of the offices dedicated to IPRs still utilise paper-based methods to process patent applications; another evident challenge is the shortage of skilled expertise. Africa Business (2023) noted that there is a need for the government to highlight the importance of IPR to the general public, as the enforcement of IP framework presents challenges due

to a differential and misalignment of global and regional IP regulations and policies. In light of these challenges, it is important for South Africa to develop a comprehensive and coordinated approach to intellectual property that aligns with its development goals (Ncube *et al.*, 2014). This will involve addressing counterfeiting and piracy, strengthening enforcement agencies, and raising public awareness of intellectual property rights.

3.2.5. Education and Research Institutions

3.2.5.1. Role of Education and Research Institutions

Education and research institutions play an epoch-making role in the boosting of technological innovation, and they serve as a nucleus and a proponent of knowledge creation, skills development, socio-economic development, and collaborative research, which all serve as key determinants of sustainable economic growth and development (Li & Liu, 2021; Lassnigg *et al.*, 2017). According to Cheng and Ge (2005), research institutions are not exclusively centres of knowledge development but are also hubs of cultivating an erudition of curiosity, high-level talent, and critical thinking, which erupts in an educational environment that allows students as well as researchers to explore ideas that are innovative with positive spillover effects. Similarly, Zhang *et al.* (2023) further note that cultivated individuals who are highly educated create a novel stock of knowledge that espouses technological innovation, by channelling individuals and firms to engage in technologically intense industries.

Kitaura and Yakita (2010:1) allude that educational programmes provided by research institutions equip individuals with crucial skills to address complex challenges that advance technological innovation activities; additionally, “educational progress increases the income of individuals and encourages physical capital accumulation, which enlarges productive knowledge through implementation and operations.” Akolo *et al.* (2023) cite that research institutions engage in innovative projects that push known boundaries of knowledge and translate them to discoveries that are practical and applicable, which links research institutions with standards, models, and tools that project educational research that links with intellectual capital used in the labour market, contributing to new competencies.

Overall, the OECD (2004) emphasised that the collaboration among academics, industry, and government creates a climate receptive to technological innovation. The collaboration enables the translation of research discoveries into concrete products and services, hence promoting economic growth and societal improvement; and aids the government in responding to the continuous change in the technological processes. Beyond information transmission, education and research institutions serve as catalysts for nurturing a dynamic and inventive ecosystem that drives nations ahead in the ever-changing technological world.

3.2.5.2. Education and Research Institutions: South Africa

The Department of Science and Innovation's (DSI) (2022) annual report in 2020 stated that the department aims to boost South Africa's socioeconomic environment through research and development, by providing its leadership and cultivating an environment conducive to science, technology, and innovation. The role of the DSI highlights Moloi and Salawu's (2020) research, echoing that education and research institutes play a crucial role in advocating for the advancement of technological innovation activities that contribute towards economic growth and global competitiveness. Van Zyl (2011) noted that research institutions serve as hubs of knowledge generation; cultivating an environment that promotes inquiry, creativity and problem-solving in South Africa.

One of the research institutions established by the DSI following the White Paper of 1996 is the CSIR (DSI, 2021). The CSIR conducts interdisciplinary research in collaboration with educational institutions, industry, and government organisations (CSIR, 2024). According to De Jager (2022), the CSIR has provided significant advances in key sectors, including renewable energy, healthcare, and refined manufacturing. The CSIR's role in the development of the Pebble Bed Modular Reactor, a revolutionary nuclear technology, demonstrates how research institutions may lead ground-breaking initiatives with transformational potential (Ingersoll, 2015). Additionally, the TIA provides financing and strategic guidance in transforming research results into economically viable goods and services (TIA, 2024).

For example, the TIA funded research at the University of the Witwatersrand to help develop a low-cost, solar-powered hearing device (Mjimba *et al.*, 2022). Mjimba *et al.* (2022) further note that the invention addresses a major healthcare need while demonstrating how partnerships among academic organisations and funding bodies may produce significant outcomes. Furthermore, universities within South Africa play a substantial part in defining the innovation environment (Moloi & Salawu, 2020). Another prominent example is the UCT's H3D (Drug Development and Development Centre), which is distinguished as an example of a research institution that interacts alongside industry partners to promote the development of medicines and solve essential health concerns (Nkwanyane, 2023). The university's dedication to connecting academics and industry exemplifies how educational institutions may spur innovation by turning research findings into practical applications.

Collaboration plays a pivotal role in supporting and initiating innovative technology activities. For example, South Africa's MeerKAT radio telescope initiative effectively reflects inter-institutional cooperation (Moyo, 2022). Moyo (2022) and Iderawumi (2022) state that the project is led by the South African Radio Astronomy Observatory (SARAO) in partnership with numerous research institutions such as the University of the Western Cape, European Research Council-funded MeerTRAP, University of Pretoria, and the South African government; the telescope aids in worldwide astronomical advances and emphasises the importance of sharing knowledge and resources to reach significant technical milestones.

Additionally, Webb *et al.* (2018) echo that education and research institutions are pivotal for the sustainable development of human capital for innovation. For example, the Square Kilometre Array (SKA) Human Capital Development Programme shows how scientific undertakings spur skill development, correspondingly contributing towards the advancement of science's capabilities (South African Radio Astronomy Observatory (SARAO), 2022; OECD, 2023). Echoing the initiatives, Cai, Morris, Hohensee, Hwang, Robison and Hiebert (2019) argue that supporting training programmes and offering opportunities for students and researchers aid in producing a workforce capable of

driving technical improvements in key sectors of the economy that accent economic growth.

The role of educational and research institutions in fostering technological innovation in South Africa is multifaceted, as institutions play a significant role in the country's development ecosystem, by performing pioneering studies, espousing cooperation, and generating human capital. The examples such as the CSIR, and universities, or joint initiatives like MeerKAT and SKA, demonstrate how numerous mechanisms have been adopted in which South Africa's education and research institutions have continuously contributed towards the country's technical growth and global stature.

3.3. DIGITAL TECHNOLOGICAL TRENDS: SOUTH AFRICA

South Africa, across copious industrial revolutions, has produced significant technological innovation trends throughout its history, and South Africa's innovative activities followed a line-forward model that encompassed a process from research direct to the market, or from the market back to research, which shaped sundry sectors contributing towards overall development following the adoption and implementation of the White Paper 1994 (Jegade & Ncube, 2021; Flowerday, 2015). Africa Mining (2018) and Casey (2019) highlighted that one of the key historical technological innovation trends in South Africa that have been influential for over a decade was the advancement of the mining industry in the fields of diamond and gold extraction. African Mining (2018) further states that the advancements in technological innovation in the industry have resulted in large-scale mining operations and the development of high-level innovation.

Pretorius, Du Plessis and Gonsalves (2017) postulated that another key trend in technological innovation historically was the advancement of the telecommunications sector, which included the adoption and development of mobile communication technologies such as Global System for Mobile Communications (GSM) networks; proliferation of smartphones; and internet connectivity. The advancements historically transformed communication within the country and also opened various pathways for individuals and businesses. Moreover, technological innovations in the renewable sector have been experienced with the development and implementation of solar systems, wind

farms, and biomass energy (Ahem & Amankwah-Amoah, 2021; Department of Energy, 2015). The Department of Energy (2015) further highlights that innovations have helped to diversify the country's energy sources, reduce reliance on fossil fuels, and contribute to a more sustainable future.

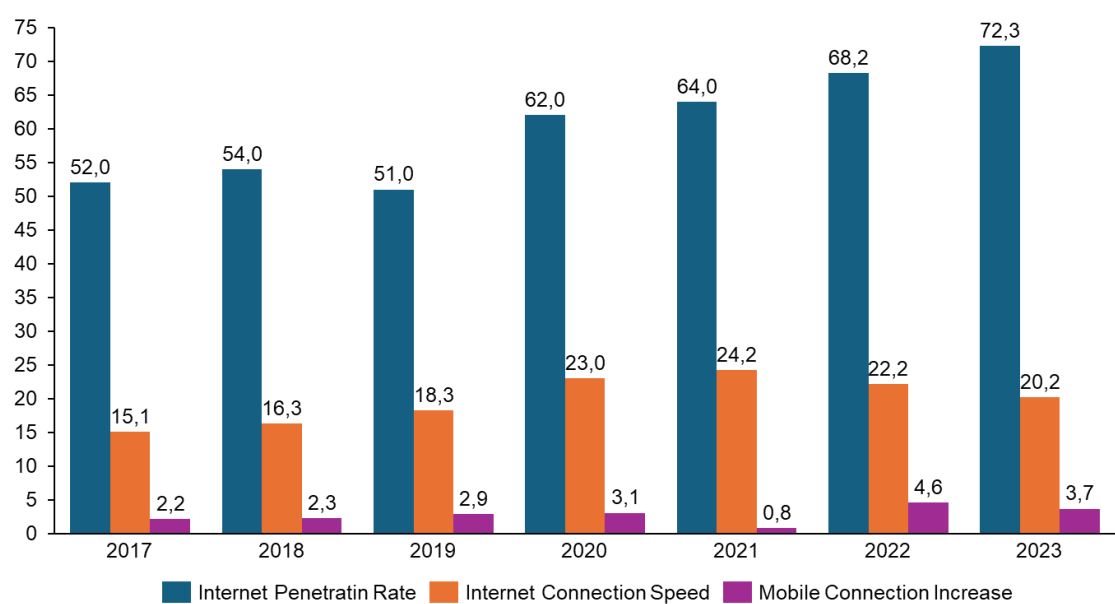
The DSI (2019) highlights that South Africa, since the adoption of the 1996 White Paper as the government's commitment to advance science, technology, and innovation, and since the advent of democracy in 1994, has resulted in South Africa making progress in the technological landscape. However, the DSI (2019) further states that the 1996 White Paper still posed challenges, as the performance and innovation landscape has been flat, resulting in the adoption of the 2019 White Paper, which particularly aimed to be inclusive, respond to the global science, technology, and innovation environment that is propelled by 4IR, to realise the country's STI potential, and proselytise partnerships and transformation in the STI landscape.

Following such, the DSI (2021) adopted various initiatives, policies, and systems to match global trends in technology, recognising that the availability of research infrastructure is fundamental for robust technological development, and cementing South Africa as a global competitor. DSI (2021:1) further explained that strengthening research infrastructure included "constructing large national infrastructure platforms and facilities; acquiring scientific equipment; and developing pilot plants, technology demonstrators and specialised facilities such as drug development and aerospace platforms."

Primarily, the key trend highlighted by the DSI's (2021) report was the development of human capital as the key development towards being globally competitive and establishing national systems, and in so doing, the DSI reports that to date, the department has awarded 257 research chairs of which 240 are operational; and set up hubs that allow universities and science councils to partner and tackle challenges in key sectors such as health, energy, biodiversity, food security, and human development. Additionally, the DSI (2021) accentuated the need to advance technological innovation activities to address global challenges over the medium term, through supporting 15 commercial outputs in areas of health, 85 technological demonstrations, products and services, and prototypes over the prescribed medium term.

Currently, according to Hello Yes (2024), South Africa is experiencing a surge in digital penetration, amounting to a 74.7 percent penetration rate as of 2024 with continued growth of approximately 1,122 newly registered internet users from 2023. The growth in digital adoption in South Africa is largely driven by mobile dominance, the boom in social media, data driven marketing, e-commerce, and FinTech (Hello Yes, 2024). Discover (2024) further highlights that South Africa is currently experiencing a digital revolution trend that requires the adoption of digitisation across different sectors to compete in the global economy. BizCommunity (2024) postulates that, according to the 2024 Global Digital Report, the average South African between the ages of 19 and 64, spends 9 hours and 38 minutes per day on the internet.

Figure 12: Digital Adoption South Africa



Source: DataReportal (2017-2023)

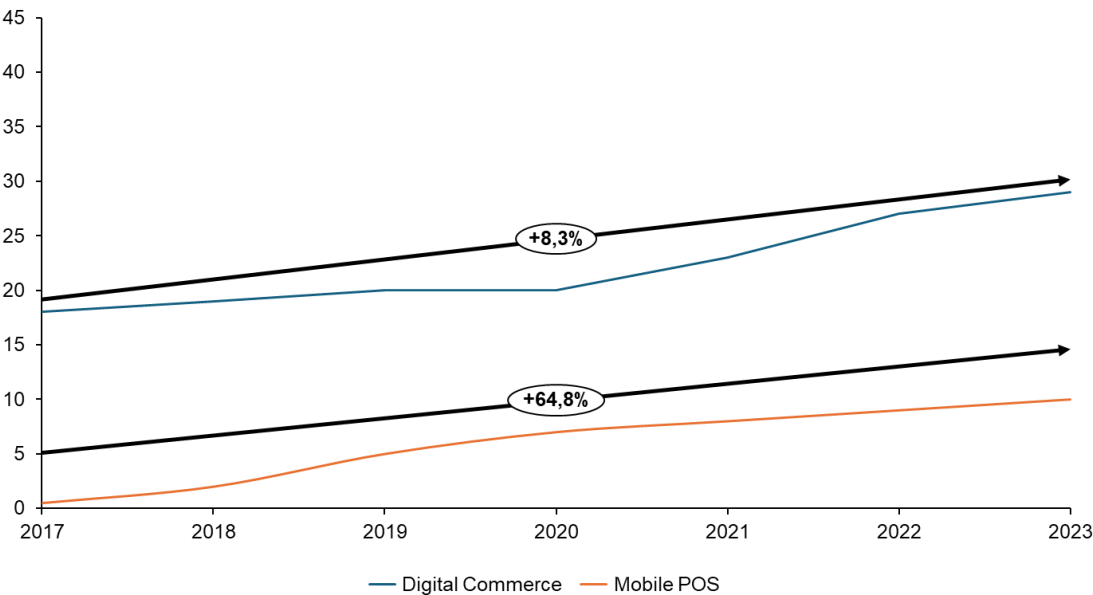
Moreover, the report indicated that approximately half of the internet users use online banking, investment, and insurance, exceeding global averages, and South Africa has an active online brand engagement with approximately 64.5 percent of social media users interacting (BizCommunity, 2024). The digital penetration is largely driven by the expansion of mobile usage of the internet, and continued investment in infrastructure (DataReportal, 2023). Figure 12 highlights South Africa's trends in digital adoption, reaching highs of 72.3 percent in internet penetration in 2023, an increase in 20.2 percent

in internet connection speed, and an increase of 3.7 percent in internet connection in 2023. According to Meltware (2024), South Africa’s continued investment in the rolling out of fibre has been crucial in the continued adoption of digital technology.

3.3.1. Current Digital and Emerging Technological Trends

South Africa’s technological landscape has been experiencing numerous technological trends, aiding the country’s evolution and competence to compete within the digital space associated with the 4th Industrial Revolution, with over 43 million of the population being internet users in 2023 (Kemp, 2023). UJ-TRCTI (2022) highlights that disruptive technologies have transformed global sectors in manufacturing and agriculture with advancements in artificial intelligence, the Internet of Things (IoT), smart sensors, big data analytics, robotics, 3D printing, and virtual reality (VR), resulting in improved efficiencies and global competitiveness. The adoption of the 4th Industrial Revolution has been noted to be significant due to its ability to espouse industrial development and contribute towards socio-economic conditions (Bayode *et al.*, 2019).

Figure 13: Digital Commerce vs Mobile POS (\$Million)



Source: Digital Virgo (2023)

Digital Virgo (2023) notes that South Africa’s penetration rate in digital adoption has been evident in the commerce, digital economy and digital consumption landscapes. Figure 13

highlights the growth of digital commerce and mobile payments from 2017 to 2023, as reported by Digital Virgo. The compounded annual growth value of digital commerce in the defined years is 8.3 percent, growing from \$18 million to \$29 million, and Mobile POS compounded annual growth value grew by 64.8 percent from 2017 to 2023. The growth highlights South Africa's surge in digitisation, aiding the study's objective to re-model the measure of technological innovation as more and more people are adopting digital instruments. Digital commerce and Mobile POS have reached their highest value in 2023, denoting the linear growth revenue in the technological and digital space, further accenting the study's objective to remodel the measure of technological innovation.

Similar to institutions highlighted in section 3.2.2, Bayode *et al.* (2019:344) add "The government has been preparing for the 4IR through various agencies such as the Department of Trade and Industry (DTI); Department of Science and Technology (DST); the Council for Scientific and Industrial Research (CSIR) and the Department of Higher Education and Training (DHET) to develop policies and initiatives for the fourth industrial revolution. The Industrial Policy Action Plan (IPAP) and Future Production Technologies Initiative." Fieldbus and Industrial Networking (2023) note that despite the limitations posed by the pandemic, South Africa was able to adopt hybrid models and new technologies as a countermeasure toward the pandemic and adapt to the changing environment of technological innovation. Below are some of the key notable technological trends in South Africa.

3.3.2. Hydrogen Society Roadmap (HSRM)

The DSI (2021) report highlighted that to support the energy markets, the HSRM was to be launched in February 2022 as a measure to unlock and facilitate clean energy and promote a carbon-neutral economy. The DSI (2021) pledged to register the Hydrogen Valley Programme with Infrastructure South Africa as part of the Strategic Integrated Projects set for December 2022. The hydrogen economy dates back to 2007, as approved by the National Hydrogen and Fuel Cells Research, Development, and Innovation Strategy, also known as HySA Strategy.

3.3.3. Artificial Intelligence (AI) and Machine learning (ML)

Rapanyane and Sethole (2020) postulated that globalisation is gradually becoming the key source of interaction amongst countries and economies, and products, technologies, and processes are rapidly becoming more accessible. Correspondingly, Artificial Intelligence has been able to provide industry-based solutions in key sectors such as information technology, health, and security, due to the noticeable manifold ability to process large quantities of data into practical and actionable reports (Fieldbus and Industrial Networking, 2023). Machine learning, on the other hand has been reported to play a pivotal role in optimising energy consumption, turbine maintenance, price prediction and assessment of the energy demand as a way of responding to fluctuating trends (Mhlanga, 2023).

The AI and ML seriatim markets have significantly experienced exponential growth in the South with an estimated market adoption value of US\$8.74 billion in AI and US\$6.22 billion in ML by 2030 (Statista, 2023; Go-Globe, 2022). Go-Globe (2022) further highlights that AI and ML in South Africa are expected to have a CAGR of 27.73 percent from 2023 to 2030, and the 2021 AI Readiness Index highlights South Africa as having high AI and ML absorption amongst African countries. According to Tshukudu (2023), in South Africa, across numerous industries, including banking, healthcare, and agriculture, AI and ML are being aggressively adopted as part of operational structures to gain a competitive and comparative advantage. Additionally, technological activities are adopted in a variety of activities, including the analysis of large databases, assessment of consumer behavioural patterns, and the optimisation processes.

Artificial Intelligence and Machine Learning integration processes are significantly contributing towards enhancing diagnoses, optimising agricultural production, and ameliorating effectiveness in identifying fraudulent activities in the systems, as a result demonstrating the tangible benefits that AI provides to businesses as well as society at large. The use of AI-powered diagnostic tools, particularly in the medical sector, has resulted in a significant increase in accuracy in diagnostics and efficacy, hence speeding up the diagnosis process and allowing for prompt treatments (BusinessTech, 2019). Marrie, Lakic, Anteghini, Valley, Rosman, Bekker and Shongwe (2023) add that the

widespread application and the pervasive utilisation of AI and ML technologies across these sectors underscores the transformative potential in augmenting operational capabilities and fostering innovation within South Africa.

3.3.4. Internet of Things (IoT)

Lindquist (2024) notes that despite continued shortages due to supply chain constraints and constantly changing demand in sectors like manufacturing, the use of the Internet of Things has enabled such sectors to surpass pandemic levels. The successful adoption of IoT hints at the implementation of cost effective, fluent communication, and ease of processing information through cheaper costs associated with sensors and processing, optimised big data processing, extended use of smart devices, and ultralow alternative energies (Ndubuaku & Okereafor, 2015). According to Digitising Africa (2024), the Internet of Things (IoT) has continued to grow and gain popularity across many sectors, notably the agricultural sector, energy, transportation, healthcare, and insurance and finance, in South Africa. Digital Africa (2024) further adds that within the agriculture sector, IoT devices help boost harvest levels by monitoring soil and climate variables, as well as controlling animals.

According to IOnline (2023), South Africa is well-positioned to connect with the growing international IoT industry, with research by Mordor Intelligence (MI) (2023) estimating a US\$5.1 billion value for South Africa's IoT sector by 2022. The estimated Compound Annual Growth Rate (CAGR) of 13.28 percent is expected to boost the global market's valuation to \$11.3 billion by 2028 (Statista, 2023). Additionally, administrations in the field of connected cities are progressively using IoT technology to improve urban administration and resource utilisation. Fortune Business Insights (2022) postulates that concurrently, industrial manufacturing is embracing IoT for automated upkeep and simplified manufacturing processes, mirroring the larger global trend towards an integrated and fuelled-by-data economy.

A scrutiny of the energy sector revealed IoT is used for smart power system administrations, and tracking and regulating energy use (Macrocomm, 2024). Furthermore, the Internet of Things aids health through monitoring of patients remotely,

efficiently tracking and administering health care equipment like nebulizers, oxygen pumps, and defibrillators (WIPRO, 2022). Van Schalkwyk (2023) highlighted that the development of IoT in South Africa reinforces the potential to improve efficiency, sustainability, and the standard of living in a rapidly changing environment of interconnected devices. Digitising Africa (2024) further cements that South Africa's IoT developments mirror a larger worldwide trend towards a more interconnected and informed-by-data society as a whole, with an opportunity to improve productivity, environmental sustainability, and our overall standard of life.

3.3.5. Square Kilometre Array (SKA)

According to the DSI (2021), South Africa is primed to facilitate a new batch of scientists with the creation of the Square Kilometre Array (SKA) Observatory, which will make a substantial contribution to the nation's technological environment. As of mid-2023, development on the SKA project has begun, representing a combined effort with Australia to produce perhaps the most comprehensive radio telescope array built to date, with a projected cost of US\$2.2 billion. These stations are expected to create a remarkable 710 petabytes of science data when completely operational in 2029, facilitating transformational astronomical study for more than 50 years.

The South African segment consists of adding 133 dish antennas to the pre-existing 64-dish MeerKAT predecessor telescope, establishing the SKA's mid-frequency telescope array. Notably, the SKA bursary plan will assist 1,400 students by mid-2023, promoting scientific study. The facilities deployment, which includes the development of the new SKA Exploratorium in Carnarvon, Northern Cape, is expected to provide significant advantages to South African businesses and the South African Radio Astronomy Observatory. Despite the scientific impact, the programme is positioned to increase science awareness, stimulate science tourism, and offer job possibilities. The MeerKAT telescope, an affirmation of South African inventiveness, will continue to make ground-breaking scientific advances up until it is fully integrated into the SKA throughout the next five to seven years, as demonstrated by the forthcoming appearance of over 180 scientific papers centred on MeerKAT assessments in prominent journals by mid-2023.

3.3.6. Fintech and Insurtech

According to Sanni (2022) and Cover (2023), South Africa's financial technology (Fintech) and insurance technology (Insurtech) landscapes boast apparent technological innovation trends, altering the business environments and dynamics. Insurtech, in particular, with technological breakthroughs in artificial intelligence (AI) and data analytics has improved risk assessment models and enabled a more precise and agile underwriting process for personalised and business insurance solutions, both in life insurance and non-life insurance (Cover, 2023). In addition to AI and data analytics, Instanda (2023) further adds that telematics following IoT technology are becoming increasingly incorporated into insurance models, providing real-time data that enables dynamic personalised pricing and product coverage. The growing usage of smartphones has fuelled the growth of mobile banking and digital payment solutions in the fintech area. Notably, Go-Globe (2023) and Cover (2023) note that the application of blockchain technology is gaining popularity in improving security and transparency within the financial services space. The ascendancy of robo-advisors and automated investment platforms signifies a shift toward more accessible and technologically driven wealth management services (RMB, 2019). According to McKinsey & Company's (2022) monthly insight, the transformative frenzy in South Africa's Insurtech and fintech sectors is propelled by the forces of digitalisation, data analytics and innovative financial service solutions.

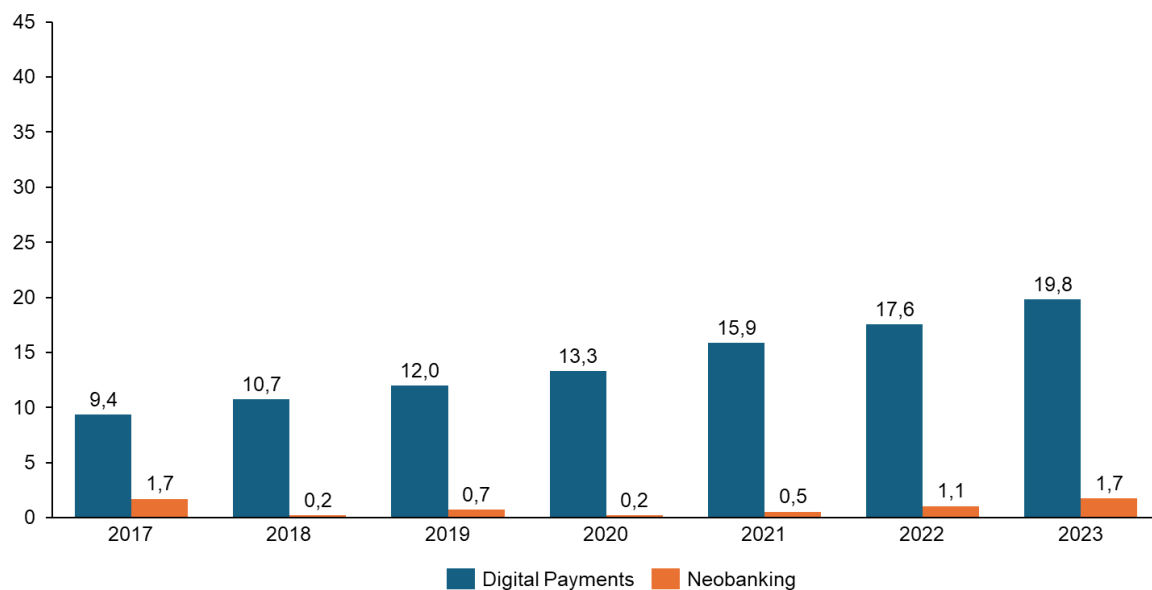
Furthermore, BDO South Africa (2022) explains that the relationship between conventional banks and mobile network operators (MNOs) is briskly developing to match the ceaseless changing environment. BDO South Africa (2022) further states that MNOs recognise the exigency for financial transactions to shift away from traditional banking systems and towards more accessible technological infrastructure, particularly smartphones, as Kemp (2023) reported that over 112 million smartphone connections were active in the first quarter of 2023. The change in the financial services space has resulted in innovations in APIs, software, and other technologies throughout the continent (BDO South Africa, 2022).

The virtual currency market's volatility in recent years divulges the advent of Fintechs, and with the expansion of firms such as Luno, we may expect cryptocurrencies to become more widely used in the future (Santosdiaz, 2022; BDO South Africa, 2022). According to Kemp (2023), South Africa's internet penetration stands above 72 percent, primarily signalling high utilisation of digital services, cementing an industry trend, and eliminating the necessity for conventional banking facilities. With the proliferation of reliance on digital platforms, cybersecurity has emerged as a top priority due to finance, insurance institutions, FinTech, and Insurtech firms aligning significant investments in cybersecurity to protect client data and ensure secure transactions (PR Newswire, 2023; Fernandes, 2023).

In addition to the surge in virtual currency, neo-banking and digital payments have transformed South Africa's financial landscape, driven by the continued increased adoption in the use of smart phones, consumer preference, and the innovations in the banking and insurance sector (Ngwenya, 2024). Volschenk (2024) further alludes that neobanks – banks without any branches that are fully digital – are gaining traction in South Africa, with banks such as African Bank and Bank Zero offering low cost, custom features and a client-centred approach. According to KLA (2024), banking application installation increased by 55 percent in 2023, and 42.31 percent of South Africa's population with access to the internet and a smartphone use mobile cell phones to access digital apps and make payments.

Additionally, digital payment platforms such Yoco, Ozow, Zapper, Ikhokha, PayPal, SnapScan, etc. are becoming more integral in the daily transactions of citizens (KLA, 2024). South Africa's transactional value in digital payments and neo-banking has been positively growing from 2017, with the compounded annual growth rate of 13.3 percent from 2017 to 2023 in digital payments and a 0.3 percentage growth rate in neo-banking in the same time frame (See Figure 14). The value of transactions in 2023 in digital payments reached \$19.8 million which is a 12.8 percent increase from 2022 value of transactions, and the value of transactions in neo-banking reached \$1.7 million in 2023, a 64.2 percent increase compared to 2022's value, which further echoes and aligns with the study's objective.

Figure 14: Digital Payments vs Neo-banking



Source: Statista (2024)

Fernandes (2023) notes that innovative firms leverage innovation to improve consumer experiences, boost efficiency, and provide avant-garde insurance products, and in South Africa, notable Insurtech disruptors include Naked, Lumkani, Pineapple, Pula, and Yalu. Companies across industries are adopting digital strategies, not only to save money and increase operational efficiencies, but also to improve customer communications and happiness. Practically, the majority if not all aspects of financial services may now be completed online, minimising the need for actual branch visits. Similarly, the insurance sector is digitising, atomising traditional methods like paper-driven procedures related to claims logging, processing, and underwriting, and loss assessments to help clients get their claims resolved faster (Norton Rose Fulbright, 2017; Go-Globe, 2023; BDO South Africa; 2023). This multidimensional technological shift highlights the rapid growth of South Africa's banking and insurance industries in response to the digital age.

3.3.7. Technological Innovation Adoption Challenges: South Africa

South Africa, like many other countries, faces various technological innovation challenges, and the challenges comprise limited access to funding, lean resources for research and development, lack of skilled professionals in key sectors of the economy, inadequate infrastructure to support innovation activities, and ineffective coordination and

collaboration between academia, industry, and government (Burger; 2023; Siriram, 2022; Andreoni & Avenyo, 2021). Additionally, Ramoroka (2023) and Mudombi and Muchie (2014) allude that South Africa also faces challenges in terms of intellectual property rights protection and enforcement, which discourages innovation and hinders the growth of technology-based sectors.

Furthermore, there is a need to address the digital divide and ensure equitable access to technology and information for all South Africans; the technological innovation challenges in South Africa are multi-faceted and require comprehensive strategies and investments to overcome (Malele *et al.*, 2019). Malele *et al.* (2019) further notes that South Africa also grapples with issues related to technology transfer and commercialisation; despite notable research and development efforts, there is often a gap between the creation of innovative technologies and their successful application in the market. This poses a barrier to the economic impact of technological advancements and hinders the growth of tech-based industries in the country.

Moreover, the fast-paced nature of technological evolution presents a continuous challenge in keeping up with global innovation trends. South Africa needs to not only focus on local innovation but also integrate with international advancements to remain competitive and relevant in the global technology landscape (Ng'ambi *et al.*, 2016). Addressing these challenges requires a holistic approach that involves collaboration between government, academia, and industry, as well as strategic investment in research and development. By fostering an environment that supports innovation, South Africa can overcome these obstacles and emerge as a leader in technological advancement, thereby unlocking new opportunities for economic growth and societal advancement.

3.3.8. CONCLUSION

Though South Africa is facing a number of challenges and is lagging in terms of creating a conducive environment that fosters technological innovation, challenges such as limited funding, lean R&D resources, skilled labour and inadequate infrastructure, the South African government however has implemented initiatives and established a number of institutions to set up policies across the country to create, diffuse, and acquire new

knowledge practices that attain institutional and individual goals related to technological innovation. Following the 1996 White Paper on Science and Technology, the DSI reprioritised the focus on technological innovation by espousing the 2019 White Paper aimed at expanding the role science, technology, and innovation in various key sectors and subsectors.

The 2019 White Paper and the DSI set a target of 365 knowledge products, developing and approving 12 science, technology, and innovation policy directives; and maintaining nine interventions set to improve government services over the medium term, highlighting the government's active participation in creating a conducive environment for technological innovation.

The study highlighted seven institutions established by the DSI to facilitate and execute different regulatory frameworks to ensure a friendly and flexible environment of technological innovation activities. Despite the initiatives and institutions established by government, the IPR benchmark comparison highlights that South Africa's IPR global ranking has declined, and South Africa's IPRI score declined by over -0.34 in 2023. Though the DTI policy phase one framework highlighted 11 key issues which were aimed at cultivating and promoting an environment of growth and development in South Africa's technological innovation environment, the policies' framework has not yielded positive results. In cultivating an environment conducive for technological innovation, the DSI's 2019 White Paper on Science and Technology has noted the essence of prioritising education as a key driver for technological innovation by encouraging and pioneering constant collaboration between public and private educational institutions.

The study further highlights that amongst the seven institutions established by the government, institutions such as CSIR and the TIA have augmented collaboration with educational institutions, industry, and government organisations to finance and provide guidance in transforming research results into economically viable goods and services. Though South Africa's level in education is not level with those of countries like China and Finland, there is however, continued regulatory support towards the advancement of the sector to ensure it is at par.

Despite the decline in IPRI score and decline in IPR global rankings, South Africa's technological adoption of new technology is on par with those of developed countries, reflecting the adoption of advancements in artificial intelligence, the Internet of Things (IoT), smart sensors, big data analytics, robotics, 3D printing, and virtual reality (VR), resulting in improved efficiencies and global competitiveness. Additionally, South Africa's banking and insurance sectors are growing exponentially indicating a high absorption rate of technological invention in the aforementioned sectors. South Africa's technological condition in absorption of digital technology highlights a positive linear growth trajectory despite a lag in the policy, with 72.3 percent in internet penetration, an increase in 20.2 percent in internet connection speed, and an increase of 3.7 percent in internet connection in 2023.

Moreover, due to the increased adoption of digital technology, digital commerce has increased by 8.3 percent from 2017 to 2023, and POS Payments have increased by 64.8 percent in the same period, highlighting South Africa's consumer acceptance of digitisation in their day-to-day lives.

In answering the primary questions of the section that read: i) What are the technological innovations conditions in South Africa; ii) What are the technological innovations trends in South Africa? South Africa has a complex technological innovation environment. Policies and regulations are established to support a conducive technological innovation environment with the introduction of the 2019 White Paper on Science and Technology, followed by the IPR phase two policy framework focusing on 11 key issues. However, the regulations and policies are lagging as the IPR ranking and IPRI score have declined in 2023, and yet the technological trends in South Africa reflect a very active and receptive adoption of technological innovations, especially in the financial services sector, thus, resulting in South Africa having an active adoption appetite towards technological innovation inventions and digitisation.

CHAPTER FOUR: METHODOLOGY AND DATA

4.1. INTRODUCTION

The study of technological innovation has consistently centred on its status as an economic phenomenon, emphasising the essential alignment between technological innovation and economic growth and development. This alignment holds significant implications for the effective formulation and coordination of policies within any given economy. Nevertheless, a notable challenge in the study of technological innovation lies in the establishment of a comprehensive, conclusive, and appropriate measure of technological innovation. This measure must account for previously excluded components, which are technology transfers, human capital development, and digitisation, measured using the IRTII index, amongst others (Chiffi *et al.*, 2021). Consequently, the primary empirical objective of this study is to construct an adjusted 4th Industrial Revolution Technological Innovation Index (IRTII) tailored to the 4th Industrial Revolution and assess its impact on economic growth in the context of South Africa over time.

The significance of this study arises from the limitations of traditional methods employed to assess the impact of technological innovation, limitations such as not factoring in elements related to digital absorption. Traditional approaches such as looking at technology solely as a Total Factor of Production (TFP) has resulted in the use of diverse proxies and classifications, yielding inconsistent results, and overlooking crucial variables (Kahn, Sithole, & Buchanan, 2022; Chiffi *et al.*, 2021; Koh *et al.*, 2016; Souitaris, 1999). In response, this study seeks to transcend conventional methodologies to offer a more comprehensive understanding of technological innovation. In doing so, a more holistic measure is anticipated to facilitate the development and adoption of new technological innovations, offer extensive insights into the requisite structures and processes for technology development, extend the purview of policies governing technological innovation, and ultimately contribute to economic growth (Pokala, 2023; Ponta *et al.*, 2021).

Against this backdrop, this chapter seeks to present the data and method used to accomplish the objectives of the study. Essential to this presentation is highlighting the chosen theoretical and empirical models employed in the study. The first section of this chapter introduces the chapter. The second section presents the theoretical framework of the study. The third section presents the data used in the study. The fourth section presents the models used in the study and the fifth section presents the economic estimation approach of the study.

4.2. RESEARCH DESIGN

In pursuit of its empirical objectives stated on section 1.4.3., this study will employ a quantitative methodology utilising secondary data, with a specific focus on Principal Component Analysis (PCA) for the construction of the index and for further detailed economic analysis. The study will conduct short-run and long-run estimation techniques. The adoption of a quantitative approach is integral to this study as it allows for the objective measurement and analysis of various dimensions of technological innovation. This encompasses the identification of patterns, trends, and relationships among variables, thereby affording valuable insights into the efficacy and efficiency of technological advancements.

4.3. THEORETICAL FRAMEWORK

The study is grounded on the principles of various theories of macroeconomics, especially the neoclassical and endogenous growth theories. According to Todaro and Smith (2014), the neoclassical growth theory is founded on one of the principles of neoclassicism that states that international trade (trade openness) attracts domestic and foreign investments, which increases capital accumulation, which will improve the country's domestic savings rate and improve the country's capital-labour ratios and income per capita. The Solow neoclassical growth theory, developed by Solow (1954) is famously known for improving on the shortcomings of the Harrod-Domar model (Prescott, 1988). In addition, this theory assumes that population growth and savings rate are the key determinants of income per capita (Ahuru & James, 2015). Solow (1956) employed

the traditional Cobb-Douglas (1920; 1928) production function that considers labour, capital, and technology as the determinants of long-run economic growth.

The Solow model was criticised by many scholars and economists for various reasons, including that the model describes a developed economy more than a developing one (Todaro & Smith, 2014), and that the model ignores distinctive features that explain long-run growth (Ahuru & James, 2015). Furthermore, Nafziger (2005) critiques the model's assumptions of perfectly competitive markets, and the idea that technological levels are assumed to be the same across the world. Against the backdrop of these criticisms, Mankiw *et al.* (1992) augmented the Solow model by including human capital as one of the determinants of growth and development, arguing that human capital is a factor that explains productivity disparities between countries.

The shortcomings of the neoclassical growth theory gave birth to the endogenous growth theory, which was firstly conceptualised by Paul Romer in the late 1980s (Ahuru & James, 2015). The endogenous growth theory differs from the neoclassical growth theory on the basic fundamental argument that technology as a determinant of growth is endogenous in nature, meaning that technology, or rather technological progress, is assumed within the model, or rather, economic system (Lucas, 1988). Moreover, according to Todaro and Smith (2014), the endogenous theory discards the assumption of diminishing returns to the use of capital investment; on the contrary the model is grounded on the assumption of increasing returns to scale. According to Aghion and Howitt (1992), the contribution of the endogenous theory is to explain the disparities in the growth rates observed between countries, and furthermore, to explain the determinants of growth that are not explained by the Solow (1956) growth model. This study will ground its empirical framework on these macroeconomic theories, because they align with the study's objectives.

4.4. MEASURING TECHNOLOGICAL INNOVATION

Principal component analysis (PCA) initially conceptualised by Wold, Esbensen, and Geladi (1987), operates as a statistical matrix method aimed at analysing and simplifying large datasets. It achieves this by extracting dominant patterns within the dataset, consequently reducing dimensionality while preserving essential information. Although

PCA is conventionally employed in fields like population genetics due to its proficiency in simplifying complex datasets (Elhaik, 2022), this study will utilise PCA to gauge technological innovation. This adaptation aligns with the growing popularity of the use of PCA in assessing the complex dynamics relating to technological innovation (Azubuike, 2013; Akinradewo *et al.*, 2022; Boran *et al.*, 2022).

Using the PCA to construct an index offers distinct advantages, foremost among them being the capacity to reduce data dimensionality while retaining essential information about the underlying variables (Wold *et al.*, 1978). This dimensionality reduction streamlines the analytical process and enhances result interpretation. Furthermore, PCA proves valuable in mitigating issues related to multicollinearity among the variables integrated into the index. By creating a linear combination of the original variables, PCA effectively mitigates the impact of multicollinearity, thereby enhancing the accuracy and stability of the constructed index. The incorporation of PCA in index creation contributes to the production of more reliable and robust outcomes, accurately encapsulating the fundamental factors influencing the phenomenon under investigation.

The study will follow a similar approach to that used by Gui and Zhou (2022), as well as by Azubuike (2013), which utilises the PCA to aggregate variables into a single index that captures the dynamics that each of the variable represents. The PCA method encompasses the use of covariances and correlations of variables in a data series to construct the index. The IRTII is to be constructed by aggregating the average weight of the eigenvectors of each variable representing technological innovation; the formula to construct the index is presented as follows:

$$IRTII = \alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3 + \alpha_k X_k \quad (2.1)$$

The study will use the variables that are often used by the International Telecommunications Union to construct the index of technological innovation. The variables are: mobile cellular phones, telephone lines, and internet access. The variables are substituted into equation 2.1 and equation 2.2 is computed as follows:

$$IRTII = \alpha_1 TELEPHONE_1 + \alpha_2 CELLPHONE_2 + \alpha_3 INTERNET_3 \quad (2.2)$$

Where $\alpha_1 - \alpha_k$ represents the average weight of the eigenvectors of each technological innovation indicator, $X_1 - X_k$ denotes the variables that measures technological innovation. *IRTII* denotes the name of the index derived from the indicators of technological innovation. The selected variables of technological innovation that will be utilised in this study have been employed by similar studies like Ali and Bujari (2016), Pala (2019), Mohamed *et al.* (2021) and Awan and Yaqoob (2023).

4.5. SHORT-TERM AND LONG-TERM RELATIONSHIP

The study will further conduct short-run and long-run estimations to comprehensively answer the research question and attain empirical objectives of the study by using the ARDL model to assess the short-run and long-run dynamics. Nkoro and Ukro (2016) assert that the autoregressive distributed lag (ARDL) is a statistical model that suggests the existence of a long-run relationship between variables in question. Kripfganz and Schneider (2023) further highlight that the ARDL is crucial for exploring the connection between a dependent variable and one or more independent variables within a time series context. The model gained its popularity through the work of Pesaran between the period from 1997 to 2001 (Baharin & Al-Hadi, 2019).

The ARDL model adeptly accommodates short-term and long-term effects of independent variables on the dependent variable, enabling a comprehensive longitudinal analysis of the relationship between the variables. The econometric model has flexibility to handle various lag structures (Inglesi-Lotz & Pouris, 2013). Another feature of the ARDL model is its ability to address collinearity concerns by incorporating the lag of the dependent variable within the model itself (Inglesi-Lotz & Pouris, 2013). Furthermore, the presence of stochastic trends in the data might cause the ARDL model to reflect these trends rather than capturing the authentic dynamics.

The study will follow the principles adopted by Sulaiman *et al.* (2015), Mohamed, Liu and Nie (2021), Awan and Yaqoob (2023) and Mussaiyib and Pradhan (2023) in using the

ARDL, because these studies considered both the advantages and disadvantages of the ARDL models, ensuring that their findings are reliable and valid.

4.5.1. Empirical Model Specification

The study proposes to utilise the ARDL model to investigate the relationship between technological innovation and economic growth. This empirical model is chosen because of its ability to reduce endogeneity and controlling for serial correlation (Nkoro & Ukro, 2016). Nkoro and Ukro (2016) further indicate that the use of the ARDL technique is prominently attributed to its ability of conducting long-run and short-run estimates, as the technique can identify dependent variables from an independent variable. The aptitude of the ARDL technique allows the examination of cointegration between variables asserting long-run and short-run equilibrium relationship (Kripfganz & Schneider, 2023). In addition, the proposed empirical model is considered a good technique to estimate the coefficients in the presence of integrated variables (Ghouse *et al.*, 2018).

The study adopts the principles of Sulaiman *et al.* (2015) and Mohamed *et al.* (2022) of the ARDL model, as the studies are aligned with the objectives of the study with regards to methodology use and objectives in a different context. The empirical model of this study builds on the assumptions of the endogenous model and neoclassical model by adding other determinants of economic growth. The study will apply a linear equation including target variables, namely: Real GDP (GDP), Capital (CAP), Labour (LAB), technological innovation (IRTII); Research and Development (R&D); Human Capital Development (HCD); and Technology Transfer (TT), represented as:

$$GDP = f(CAP; LAB; IRTII; R\&D; HCD; TT) \quad (2.3)$$

The function expressed as a linear econometric model is presented as:

$$GDP_t = \beta_0 + \beta_1 CAP_t + \beta_2 LAB_t + \beta_3 IRTII_t + \beta_4 R\&D_t + \beta_5 HCD_t + \beta_6 TT_t + \varepsilon_t \quad (2.4)$$

The model is transformed and expressed as a dynamic econometric model as:

$$\begin{aligned}
GDP_t = & \beta_0 + \beta_1 \sum_{i=1}^p \Delta GDP_{t-1} + \beta_2 \sum_{i=1}^p \Delta LAB_{t-1} + \beta_3 \sum_{i=1}^p \Delta CAP_{t-1} \\
& + \beta_4 \sum_{i=1}^p \Delta IRTII_{t-1} + \beta_5 \sum_{i=1}^p \Delta R\&D_{t-1} + \beta_6 \sum_{i=1}^p \Delta HCD_{t-1} + \\
& + \beta_7 \sum_{i=1}^p \Delta TT_{t-1} + \lambda_1 GDP_{t-1} + \lambda_2 CAP_{t-1} \lambda_3 LAB_{t-1} \\
& + \lambda_4 IRTII + \lambda_5 R\&D_{t-1} + \lambda_6 HCD_{t-1} + \lambda_7 TT_{t-1} + \varepsilon_t \quad (2.5)
\end{aligned}$$

Where: real GDP represents a gross domestic product which is a proxy for economic growth, CAP represents physical capital stock, LAB represents employment, IRTII is used as a proxy for the technological innovation, R&D represents expenditure on research and development; HCD denotes human capital, proxied by number of general pupils enrolled in secondary education; TT represents technology transfers which refers to knowledge and information sharing amongst nations, and ε_t denotes the stochastic component. The short-run dynamics are denoted by the summation sign and the long-run dynamics are represented by the lambda.

The study proposes to employ the error correction model (ECM) should the results of cointegration test detect the existence of a long-run equilibrium relationship between economic growth and technological innovation, and other determinants of growth. The ECM will be used to capture the speed of adjustment when the long-run equilibrium is corrected in the short-run (Mohamed *et al.*, 2021).

The error correction model of this study is stipulated as:

$$\Delta Y_t = \alpha_{oi} + \sum_{i=1}^p \gamma_i Y_{t-i} + \sum_{i=1}^p \alpha_1 X_{t-i} + \lambda ECT_{t-1} + \mu_t \quad (2.6)$$

4.6. DATA SELECTION

This study will employ econometric techniques, utilising secondary data gathered from international databases the World Bank. The study sourced the data from the World Bank due to its reputation as a globally recognised and reliable repository of economic and development data and datasets from the World Bank is widely used in academic and

policy research, enhancing the credibility and comparability of the study's findings across different contexts and regions. The dataset encompasses annual observations spanning a comprehensive 30-year period, ranging from 1992 to 2022. This extensive temporal scope has been chosen deliberately to ensure that the data series is normally distributed. The 30-year period provides a sufficient timeframe to capture long-term trends and dynamics, allowing for a more robust analysis of the relationship between variables. Additionally, the extended period enables the identification of structural changes, cyclical patterns, and the sustained impacts of key drivers such as technological innovation and economic growth. The expanded database incorporates the components of digitalisation, echoing the methodologies observed in analogous studies (Pachys, 2014; Stavbunik & Pelucha, 2019; OECD, 2020; Zhang *et al.*, 2022). Alongside the components of digitalisation, the study retains familiar variables frequently employed in the evaluation of technological innovation-growth nexus, including capital, labour, and research and development (R&D) expenditure.

4.6.1. Justification of selected variables

The variables to construct the index that measures technological innovation are selected particularly because they reflect the use of technology to facilitate economic growth by improving end-user base, market expansion, and sharing of knowledge and information (Ruger *et al.*, 2022; Tian *et al.*, 2023). The variables that will be used to construct the IRTII index include use of internet, mobile cellular phones, and fixed telephone subscriptions. According to Thales (2021), mobile cellular subscriptions play a pivotal role in facilitating innovation, enhancing business communication and collaboration, and act as a crucial gateway to the digitalisation of the economy, particularly by facilitating remote retail markets and trade. Furthermore, Amaghionyeodiwe *et al.* (2011) emphasise that the contemporary significance of advanced communication systems is a cornerstone for the establishment of a well-developed communication infrastructure that underpins sustainable growth and development.

Rajagukguk *et al.* (2021) highlighted that mobile subscriptions provide a diverse spectrum of communication activities, encompassing the sharing and receipt of essential information that is instrumental in fields such as education, the global economy,

healthcare, and the facilitation of innovation. Lastly, technological innovations on telephone subscription, including corded and cordless telephones, exerted a substantial influence on competitiveness and expansion of economies in developing countries (Portillo *et al.*, 2021). This complexity necessitates the consideration of telephone subscription as a fundamental measure of technological innovation.

Table 4: IRTII Variable Summary

Variable description	Variable description	Source
Internet use	Internet users are individuals who have used the Internet in the last 3 months. The Internet can be used via a computer, mobile phone, personal digital assistant, games machine, digital TV etc.	World Bank
Telephone subscriptions	Fixed telephone subscriptions refers to the sum of active number of analogue fixed telephone lines, voice-over-IP subscriptions, fixed wireless local loop subscriptions, ISDN voice-channel equivalents and fixed public payphones.	World Bank
Mobile Cellular phones	Mobile cellular telephone subscriptions are subscriptions to a public mobile telephone service that provide access to the PSTN using cellular technology.	World Bank

Source: World Bank (2021)

To assess the evolving behaviour of key variables over time, this study will employ the ARDL method, focusing on variables such as real gross domestic product, capital, labour, and 4th Industrial adjusted Technological Innovation Index. These variables are adopted from the Cobb-Douglass (1928) production function that considers physical capital,

labour, and technology as key determinants to economic growth. In addition to these traditional determinants that foster economic growth, this study will include expenditure on research and development and technology transfers, as well as human capital development. The rationale for including these variables is that they are often neglected by existing literature (Thi & Do, 2021; Mohamed *et al.*, 2021) despite being important towards economic growth.

Table 5: Variable Summary

Variable	Variable Description	Source
Real GDP	Annual percentage growth rate of GDP at market prices based on constant local currency	World Bank
Capital	Gross capital formation consists of outlays on additions to the fixed assets of the economy plus net changes in the level of inventories.	World Bank
Labour	Labour force participation rate is the proportion of the population aged 15 and older that is economically active: all people who supply labour for the production of goods and services during a specified period.	World Bank
Research and Development	Gross domestic expenditures on research and development (R&D), expressed as a percent of GDP.	World Bank
IRTII	The Industrial Revolution adjusted Technology	Author's computation

	Innovation Index which accounts for the digitisation in the economy.	
Technology Transfers	TT measured in terms of FDI are the net inflows of investment to acquire a lasting management interest in an enterprise operating in an economy other than that of the investor.	World Bank
Human Capital Development	Measured in terms of education and is the percentage of population ages 25 and over that attained or completed lower secondary education.	World Bank

Source: World Bank (2021)

4.7. Econometric Techniques

The research methodology adopted in this study follows a multi-step approach, designed to comprehensively investigate the relationships and dynamics within the dataset. Unit root tests are conducted first, employing both the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests. These tests play a pivotal role in determining the stationarity of the time series data, a fundamental prerequisite for ensuring the reliability of the empirical findings. Subsequently the study will test for the presence of the long-run relationship between the variables, using the Johansen-Fisher cointegration technique. Should the findings of the Johansen-Fisher indicate the presence of a long-run equilibrium relationship among the variables, this study will employ the Bound-test as well as the error correction model (ECM) and the Bounds-test long-run estimator to capture the adjustment process.

4.6.2. Stationarity Tests

Mohamed *et al.* (2021) asserts that studies that adopt time series data have the assumption that the data is characterised by stationarity, which implies that the mean and variance of the variables stabilises over time. Non-stationary data series often affects the validity of the empirical evidence. Unit root tests will be conducted to verify the level of stability of the variables and the order of integration; the study will utilise the Augmented Dickey-Fuller test (ADF) (1979) and the Phillips-Perron test (PP) (1988) to test for stationarity. The equations that will be utilised to test for stationarity are presented as follows:

4.6.3. Augmented Dickey-Fuller (ADF)

The ADF test is estimated using the model as:

$$\Delta Y_t = \alpha_0 + \alpha_1 t + \alpha_2 Y_{t-1} + \sum_{j=1}^p \alpha_j \Delta Y_{t-j} + \varepsilon_t \quad (2.7)$$

Where: t represents the number of the year, p is the length/number of lagging gaps, Y_t represents the value of the variables that are to be tested in t , and $\alpha_0, \alpha_1, \alpha_2$ represent the estimated study parameters, and ε_t is the value of the error term at time t .

4.6.4. Phillips and Perron (PP)

The PP test considers serial correlation issues nonparametric correction process, as it assumes that time series data is generated through autoregressive integrated average moving average. Therefore, the model equation is specified as:

$$\Delta Y_t = \partial_0 + \partial_1 t + \partial_2 Y_{t-1} + \varepsilon_t \quad (2.8)$$

4.7. LONG-RUN BOUND TEST

The long-run bound test will be conducted to assess the presence of a long-term equilibrium relationship amongst the selected variables and ascertain whether variables

are integrated in the same order and the variables move together despite the short-run fluctuations.

The long-run bound test equation is expressed as:

$$H_0: \delta_1 = \delta_2 = \delta_3 = \delta_4 = \delta_5 = \delta_6 = 0 \quad (2.9)$$

against the alternative

$$H_1: \delta_1 \neq \delta_2 \neq \delta_3 \neq \delta_4 \neq \delta_5 \neq \delta_6 = 0 \quad (2.10)$$

4.8. ROBUSTNESS CHECK

To ascertain the reliability and validity of the empirical findings, the study will conduct robustness checks on the empirical model. The model robustness check will aid in determining any errors in the model adopted; this study will use the variance decomposition and impulse response techniques.

4.8.1. Impulse Response

The impulse response will aid the study's results by allowing the examination of how the index responds to shocks of variables over time, highlighting the dynamic interaction that exists amongst the index and the variables. Understanding the shocks of endogenous variables provides a clearer explanation on what drives the relationship between the variables. In doing so, the Structural Vector Autoregression (SVAR) impulse model was adopted due to its ability to identify structural shocks and its dynamic interaction with selected variables.

The structural form of SVAR is expressed as:

$$AY_t = BY_{t-1} + \varepsilon_t \quad (2.11)$$

Reduced form

$$Y_t = CY_{t-1} + \mu_t \quad (2.12)$$

4.8.2. Variance Decomposition

Additionally, the variance decomposition will enhance credibility and reliability of the study's results due to its ability to evaluate the model's stability and provide policy recommendations, as it provides understanding of the interaction between variables over time without imposing restrictive assumptions on the direction of causality.

Variance decomposition model is expressed as:

$$Y_t = A_1Y_{t-1} + A_2Y_{t-2} + \dots + A_pY_{t-p} + \mu_t \quad (2.13)$$

4.9. CONCLUSION

This section outlined the methodology and data adopted to attain the objective. The study follows the PCA principles to create the IRTII and adopts a multi-step approach to attain a comprehensive measure of the impact of technological innovation and economic growth. To investigate the impact of technological innovation on economic growth, the study aligns with the principles of an ARDL model due to its ability as a linear model to deal with time series data, and deal with reducing endogeneity. The ARDL model is further highlighted to be aligned with the study's objectives due to its ability to denote short-run and long-run relationships amongst the variables of interest.

In addition to the ARDL model, the study incorporated pre-estimation techniques, including Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests for unit roots, as well as correlation analysis, to assess the stationarity and relationships among the variables. The subsequent ARDL cointegration test and Error Correction Model (ECM) will be employed to examine long-run and short-run dynamics. The analysis ensures a thorough examination of the research question and contributes to the study's empirical objectives. Furthermore, the methodology includes post-estimation tests such as serial correlation tests, heteroskedasticity tests, impulse response analysis, and variance decomposition. These tests are designed to verify the robustness and reliability of the model, thus solidifying the credibility of the findings and ensuring that the study's results are both valid and reliable.

CHAPTER FIVE: EMPIRICAL RESULTS

5.1. INTRODUCTION

This section presents the results of the tests conducted to address the primary question outlined in section 1.4.1. The first section includes the pre-estimation tests which feature trend graphs, descriptive statistics, and stationarity tests. The following section details the estimation results, encompassing cointegration tests, autoregressive distributed lag (ARDL) model, error correlation model (ECM), and long-run bounds tests. Finally, the last section discusses post-estimation results, including serial correlation tests and heteroscedasticity tests.

5.2. PRINCIPAL COMPONENT ANALYSIS: RESULTS

The PCA is used in this study to construct the IRTII. Furthermore, the section discusses how much each variable used in the study contributes to the IRTII and how much these variables relate to each other. Table 4 presents the results. Table 4 highlights a substantial level of correlation amongst the variables which are mobile cellular subscriptions, internet usage, and telephone subscription. All correlations exceed 0.70 (see the third section of Table 6). The correlation of the three variables validates the use of PCA to construct a single index that measures technological innovation. The findings from the principal component show that internet use and mobile cellular subscription have a correlation coefficient level above 0.93, while telephone subscription and mobile cellular subscription exceed 0.72, and internet use and telephone subscription are above 0.85. These high correlation levels validate the use of the PCA to derive a single index because it is evident that the variables are highly collinear and could impact the empirical findings when modelled individually in a linear regression.

The second section of Table 6 reveals the PCA loadings, which highlight how much each variable contributes to each of the three principal components. PC1 represents the highest proportion of the variances in the dataset. Mobile cellular subscription and internet usage depict a positive loading of 0.57 and 0.60 respectively, suggesting that both contribute positively to the index. Contrastingly, telephone subscription has a negative

loading of -0.55, suggesting that as PC1 increase, telephone subscriptions decrease. PC1 captures the contrast between traditional communication technologies, such as telephone subscriptions, and modern technologies, such as internet usage and mobile subscription, which are positively correlated to technological digitisation. PC1 may be interpreted as a shift from traditional technologies to modern digital technologies. Thejaasri (2023) and Wavetec (2024) state that as new technologies are introduced, traditional technologies began to be phased out.

PC2 represents the second largest proportion of the variance and denotes a different aspect of the data. PC2 highlights that the loads of the three variables, mobile cellular subscriptions, internet usage, and telephone subscription, contribute positively to the index (0.61, 0.14. and 0.78, respectively). However, internet usage has a low loading, suggesting that PC2 is less associated with internet usage. PC2 may represent areas where both telephone subscriptions and mobile cellular subscriptions are prevalent but lagging in internet penetration. According to Geldenhuys (2019), areas such as Limpopo and the Eastern Cape have low internet penetration (46.2 percent and 55.3 percent respectively) as households' members are most likely to have access to the internet while at work or while in metropolitan areas.

PC3, the last PC, explains the lowest amount of variance amongst the PCs. Internet usage has the highest loading of 0.79 suggesting that internet usage is the dominant variable of the index. Telephone subscription has a positive yet relatively low loading of 0.28 denoting a minute role. However, mobile subscription has a negative loading of -0.55, highlighting an inverse relationship with internet usage. PC3 may be argued to represent the contrast between mobile subscription and the use of the internet, where the increased use of the internet decreases mobile subscription. The decrease may be associated with the shift from mobile based services to more internet-based services by consumers/users. The criterion utilised to select PC1 is that the loadings explain the largest proportion of the variance in the dataset as it captures the most significant relationships amongst the variables (Mobile Cellular Subscription, Internet Usage, and Telephone Subscription)

Table 6: PCA Results

Eigenvalues: (Sum = 4, Average = 1)					
Number	Value	Difference	Proportion	Cumulative Value	Cumulative Proportion
1	2.68	2.39	0.89	2.68	0.89
2	0.28	0.24	0.09	2.96	0.99
3	0.04	-	0.01	3.00	1.00
Eigenvectors (loadings):					
Variable	PC 1	PC 2	PC 3		
Mobile Cellular Subscription	0.57	0.61	-0.55		
Internet Usage	0.60	0.14	0.79		
Telephone Subscription	-0.55	0.78	0.28		
Ordinary correlations:					
	Mobile Cellular Subscription	Internet Usage	Telephone Subscription		
Mobile Cellular Subscription	1.00				
Internet Usage	0.93	1.00			
Telephone Subscription	-0.72	-0.85	1.00		
<i>Note: ***, 1%, **, 5% and *, 10% significance level</i>					

Source: Author's Computation

5.3. PRE-MODELLING DIAGNOSTICS

5.3.1. Summary statistics

This section discusses summary statistics of the main variables used in the analysis of the effectiveness of the IRTII for the South African economy. Figure 15 depicts the trends results of the variables of interest. The first trend graph, titled GDP, highlights an upward trend in GDP from 1992 to 2022. GDP is used as representative for economic growth in South Africa. The growth in the economy from 1992 may be associated with a number of

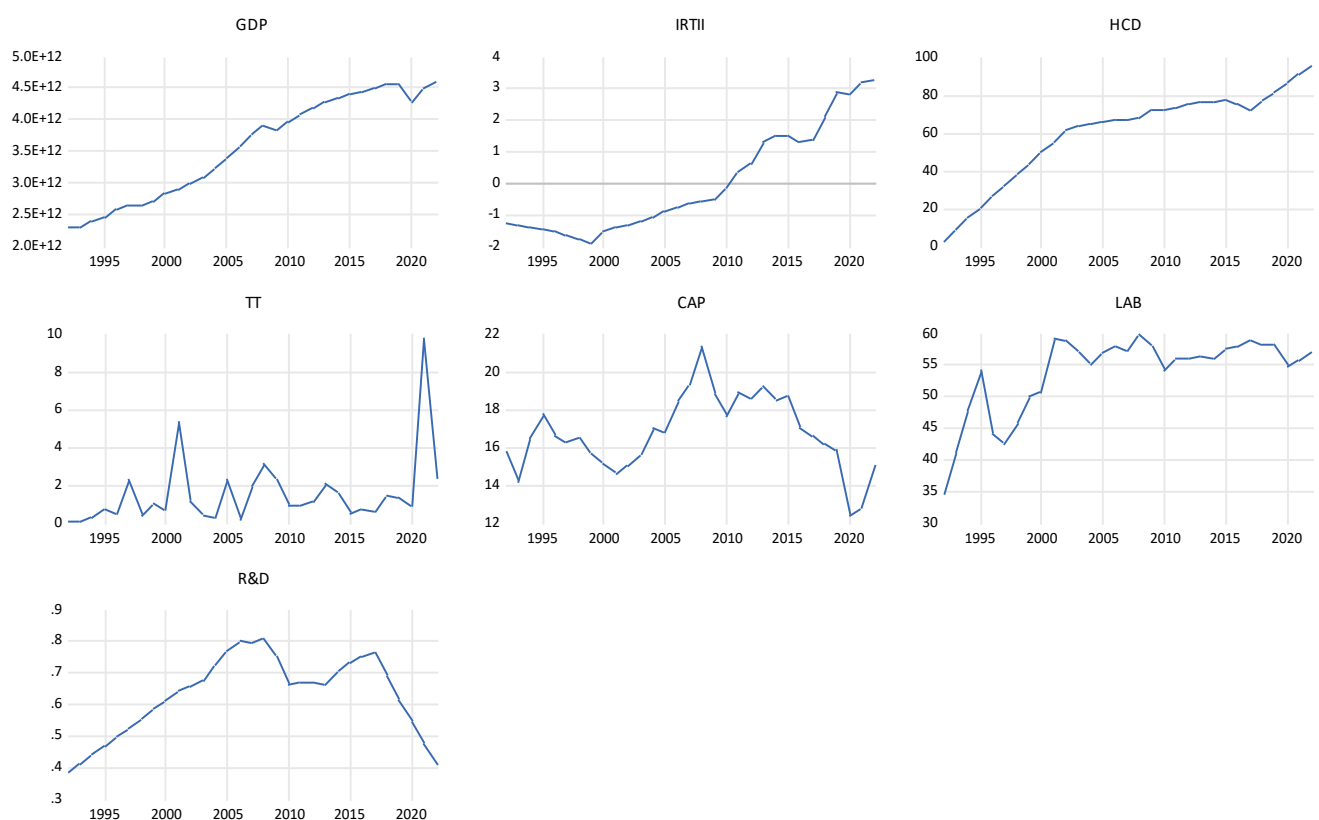
events, such as the beginning of the end of the Apartheid regime; the introduction of the new government which resulted in the adoption of new policies such as trade liberalisation and an open economy policy; the development of infrastructure in industries such as telecommunication, energy, and transportation; the tourism and natural boom as well as the financial liberalisation (Department of Planning, Monitoring and Evaluation, 2014; South African Reserve Bank, 2020; Layton-Matthews & Landsberg, 2022). According to the DPME (2014), the introduction of the new government in 1994 augmented political stability, inclusive policies and economic reforms that fostered a conducive environment for investments.

The economic and political reforms coupled with the development of industries, attracted foreign investment that supported the industrial growth that contributed to overall economic growth. The graph further depicts economic decline between 2008/09, which may be attributed to the global financial crisis that crippled economies across the globe. Post the global financial crisis, growth levels continued to increase due to the global recovery phase from the crisis, and the 2010 Federation Internationale de Football Association (FIFA) World Cup, which led to an increase in foreign direct investment and technological advancement in the country. The decline from 2019 could be associated with the Covid-19 pandemic, domestic challenges such as unemployment levels, and inequality, power supply shocks as well as commodity prices fluctuations.

The second graph of Figure 15 depicts a positive growth pattern from 1999 in the IRTII. The growth patterns may be associated with the increase in technological advancements globally, such as semiconductor innovations, telecommunication infrastructures and wireless connectivity (ACL Digital, 2023; Hart, 2023; Pasdar, 2024). The growth may further be associated with the introduction of the internet and the increase in the rollout of broadband services, which led to an increase in internet usage contributing to digitisation. DataReportal (2024) highlights that over 45 million South Africans are internet users, reflecting a 442,000 percent increase in the past 10 years, with approximately 70 percent of the total internet users going online daily. Additionally, DataReportal (2024) reports that mobile broadband is increasing at approximately 30 percent a year, with a penetration of 26 percent as of 2024. The development of technological advancements

such as semiconductors, telecommunication infrastructure and broadband enables a faster and more reliable communication, with enhanced data processing, and increased internet accessibility in South Africa (WonderNet, 2022). Technological advancements support the digital economy, facilitate innovation, and foster technology-driven sectors such as e-commerce and fintech. The expansion of policies and economies resulted in a positive increase in labour, with increased affordability of telephones, cell phones and internet usage, furthering the competitive landscape, globalisation, and exchange of information, as well as consumption and entrepreneurship.

Figure 15: Visual Data Analysis



Source: Author's computation (2024)

Figure 5 displays a positive trend in the growth of capital. From 1993 to 1995, there is an upward/positive trend which was triggered by the dawn of democracy in South Africa and the reintegration of South Africa's economy into the global economy, opening the economy to international markets (Jacobs, 2024). However, from 1996 to 2001, South Africa experienced a downward trend in capital. According to Makrelov, Davies and Harris

(2021), the decline in capital may be associated with structural economic challenges which included battling with unemployment, inequality and stagnant economy growth. From 2002 to 2008 there was an upward trend in capital inflows; the inflows may be associated with the stability in investors' confidence, augmented by improved macroeconomic policies that characterised positive fiscal management, low inflation and prudent economic policies that were growth-oriented, such as maintaining a budget surplus. The global financial crisis increased public debt, and the global economic slowdown posed challenges that resulted in a decline and a downward trend in capital inflows from 2008 to 2020; however, capital inflows began to increase from 2021.

The results from Figure HCD highlight that HCD has been on a positive trend from 1992 to 2022, with a slight decline from 2014 to 2018. The positive upward trend in HCD may be attributed to the increased investment in human capital development as a key area of social development, which resulted in an increased budget in building new schools and allocating more educational resources. Additionally, expansion in higher education and Technical and Vocational Educational and Training (TVET) was prioritised to accommodate more students. The establishment of the White Paper on Post-School Education and Training targets accelerated human capital development. Lastly, Figure F on Technology Transfers highlight a sideways trend on technology transfers from 2002 to 2020, which spikes in between these years. The sideways trends may be attributed to the slow adoption of technologies in the private sector, with many industries in manufacturing, services, and SMMEs facing challenges in the adoption of technologies due to skills mismatch, lack of financial resources, and infrastructure challenges. Additionally, governmental support and implementation of policies that support technological innovation have been lagging. Though policies and strategies have been adopted, the lack of streamlined focus, funding and governmental coordination may have resulted in the sideways trend in technological innovation. However, there was an upward spike in 2021, which may have been a result of increased global coordination due to the pandemic.

The descriptive statistics results of the Jacque-Bera were conducted using raw data and are expressed in two decimal places. The Jarque-Bera test results indicate the data series

is normally distributed, as the p-values of five of the seven variables are greater than 0.05. Labour and Technology Transfers are the two variables with p-values less than 0.05, making the two variables statistically significant, and for the two variables, the null hypothesis rejected that the dataset is normally distributed. A further analysis of the descriptive statistics of South Africa's GDP shows that there is a mean average growth of 3.57 since 1992, and volatility rate of 8.18. The economic growth levels may be associated with the political transition from an Apartheid-led regime to a democratically led government, which introduced new policies and confidence towards economic growth (South African History Online, 2014).

Moreover, the growth may also be linked to trade liberalisation agreements (i.e. Export Marketing and Investment Assistance (EMIA), Development, and Cooperation Agreement (TDCA), Southern African Development Community (SADC)) that opened up the economy and reduced trade barriers, boosted international trade and exposed South Africa to information transfers; the focus on infrastructure development (i.e. Reconstruction and Development Programme (RDP), National Infrastructure Plan, Expanded Public Works Programme (EPWP)) in specific areas such as telecommunications, energy and transport (Ngepah & Udeagha, 2020; Mojapelo & Ngoepe, 2020; Kumo, 2012). Moreover, the implementation of sound fiscal and monetary policies helped shape the economy and investments on human capital development to ensure skills development and a skilled labour force.

Similar attributes may be attested towards a mean of 0.63 in R&D, and a volatility of 0.38. Technology transfer has a mean of 1.46 and volatility of 1.88. The results show that labour and capital have the highest standard deviation amongst other variables, of 6.24 and 1.96 respectively, depicting that they are more volatile, and a mean average growth of 53.79 and 16.72 individually, implying that they have an active role to play in terms of economic growth. Though other variables are not as volatile as labour and capital, the variables still have an active role to play towards economic growth.

Table 7: Descriptive Statistics

	GDP	IRTII	R&D	LABOUR	CAPITAL	TT	HCD
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Mean	3.57	-1.72	0.63	53.79	16.72	1.49	4614156.
Median	3.80	-0.67	0.66	56.17	16.57	0.93	4687958.
Maximum	4.60	3.29	0.81	59.69	21.29	9.70	5606487.
Minimum	2.29	-1.89	0.38	34.52	12.40	0.00	3241006.
Std Dev	8.18	1.66	0.13	6.24	1.96	1.88	563728.9
Skewness	-0.20	0.71	-0.44	-1.55	-0.05	3.03	-0.660305
Kurtosis	1.49	2.10	2.06	4.55	2.96	13.14	3.188517
Jarque-Bera	3.16	3.62	15.46	15.46	0.02	179.99	2.2985
Prob.	0.21	0.16	0.34	0.00	0.99	0.00	0.3169
Observations	31	31	31	31	31	31	31

*Note: ***, 1%, **, 5% and *, 10% significance level*

Source: Author's computation (2024)

5.3.2. Correlation Analysis

The study conducted the correlation test to note the strength and direction of the variables of choice. The results from the analysis show that there is a strong positive correlation between GDP and IRTII, with the strength of correlation of 0.8860. Moreover, GDP has a strong positive correlation with HCD and Labour (0.9136 and 0.7084 respectively), GDP has a positive yet low correlation with TT and Capital represented by correlation coefficient of 0.2736 and 0.2076 respectively. R&D has a moderate correlation relationship with GDP with a coefficient of 0.46, which may be associated with economic cyclical factors such as domestic and global instabilities, and institutional challenges.

Analysing IRTII, the results show that IRTII has the highest positive correlation relationship with HCD amongst all other variables, with a 0.7953 strength measure, indicating that the two variables have positive collinearity among them. IRTII has a positive correlation with TT with strength measure of 0.3225, a strength measure of 0.0364 with Labour, and 0.4615 with R&D, denoting a low and moderate strength of correlation depicted by the measure of strength. Contrastingly, IRTII has a negative correlation relationship with Capital with a strength measure of -0.1432 which could be associated with the resistance to change, regulation challenges, and high cost relating to innovation. The results of the TT reflect a positive, and weak correlation relationship with

HCD and Labour, depicted by the strength measures of 0.3317 and 0.278 respectively. However, TT has a negative correlation relationship with capital, at -0.2325 strength measure. The negative relationship may be argued to be as a result of the substitution effect, where the increase in TT may result in the decrease in capital, and technology advancements may also result in less capital input.

A further analysis on capital shows that capital has a positive correlation with the majority of the variables which are not strong, as highlighted by the strength of measure. However, R&D has the strongest correlation relationship with capital amongst the variables, with a correlation strength of 0.6034. HCD has a strong correlation relationship with Labour, with the measure of strength of 0.7516, but has a moderate correlation relationship with R&D at 0.4543. Lastly, the correlation results highlight that R&D has a strong positive correlation with Labour, depicted by the measure of strength of 0.7047.

Table 8: Correlation Analysis

	GDP	IRTII	TT	CAPITAL	HCD	LABOUR	R&D
GDP	1.0000						
IRTII	0.8860	1.0000					
TT	0.2736	0.3225	1.0000				
CAPITAL	0.2076	-0.1432	-0.2325	1.0000			
HCD	0.9136	0.7953	0.3317	0.1890	1.0000		
LABOUR	0.7084	0.4615	0.2785	0.2872	0.7516	1.0000	
R&D	0.4618	0.0364	-0.049	0.6034	0.4543	0.7047	1.0000

*Note: ***, 1%, **, 5% and *, 10% significance level*

Source: Author's computation (2024)

5.3.3. Stationarity Tests

This study conducted stationarity tests using the Augmented Dickey-Fuller (ADF) and the Phillips-Perron (PP) tests in order to determine the order of integration and the level of stationarity for each of the identified data series. Both the ADF and PP test the null hypothesis, that the series has unit roots, against the alternative hypothesis that the series

is stationary. Null Hypothesis (H_0): the time series has a unit root, and Alternative Hypothesis (H_1): The time series does not have a unit root. The unit root tests were conducted on all three criteria; none, intercept, trend, and intercept level for all the chosen variables. Tables 9 and 10 display the results. In Table 9 the significance of p-values indicates the rejection of the null hypothesis. The results of the unit root reveal that the majority of the variables had unit root problems at level. Specifically, five out of the six variables had unit root problems. Technology Transfers (TT) is the only dataset that did not have a unit root problem at level. The unit root problems for the remaining variables meant that the research could not reject the null hypotheses, resulting in further stationarity tests being conducted.

Table 9: Unit Root at Level

Variable		Augmented Dickey-Fuller (ADF)		Phillips-Perron (PP)	
		T-stat	P-value	T-stat	P-value
TT	None	-3.330777	0.0016	-3.300074	0.0008
	Constant	-5.073430	0.0003	-5.061407	0.0003
	Constant, Linear Trend	-5.480675	0.0006	-5.48947	0.0005
GDP	None	4.108641	0.9999	3.735909	0.9998
	Constant	-1.056870	0.7193	-1.056870	0.7193
	Constant, Linear Trend	-0.880625	0.9453	-0.980235	0.9320
HCD	None	0.264309	0.7558	0.590804	0.8384
	Constant	-4.502296	0.0013	-4.035766	0.0041
	Constant, Linear Trend	-3.352817	0.0778	-2.327305	0.4075
Labour	None	0.766864	0.8741	0.963126	0.9068
	Constant	-3.652546	0.0104	-3.783030	0.0076
	Constant, Linear Trend	-3.410576	0.0689	-3.409814	0.0690
Capital	None	-0.286246	0.5743	-0.268799	0.5808

	Constant	-1.845448	0.3523	-1.845448	0.3523
	Constant, Linear Trend	-1.774740	0.6916	-1.774740	0.6916
R&D	None	-0.721189	0.3954	-0.271756	0.5797
	Constant	-1.531809	0.5037	0.175350	0.9083
	Constant, Linear Trend	0.260780	0.9972	0.350342	0.9980
IRTII	None	0.111626	0.7103	0.111626	0.7103
	Constant	1.788535	0.9995	2.013074	0.9998
	Constant, Linear Trend	-1.891998	0.6337	-3.248763	0.0944
<i>Note: ***, 1%, **, 5% and *, 10% significance level</i>					

Source: Author's computation (2024)

Table 10: Unit Root at First Difference

Variable		Augmented Dickey-Fuller (ADF)		Phillips-Perron (PP)	
		T-stat	P-value	T-stat	P-value
TT	None	-	-	-	-
	Constant	-	-	-	-
	Constant, Linear Trend	-	-	-	-
GDP	None	-3.225429	0.0022	-3.233658	0.0022
	Constant	-5.052228	0.0003	-5.052207	0.0002
	Constant, Linear Trend	-5.181745	0.0013	-5.180787	0.0013
HCD	None	-3.137510	0.0028	-3.137510	0.0028
	Constant	-3.151171	0.0337	-3.059096	0.0412
	Constant, Linear Trend	-4.210052	0.0126	-4.210052	0.0126

Labour	None	-5.051901	0.0000	-5.415970	0.0000
	Constant	-5.054179	0.0003	-5.905383	0.0000
	Constant, Linear Trend	-5.475619	0.0009	-10.27455	0.0000
Capital	None	-5.224985	0.0000	-5.215446	0.0000
	Constant	-5.106486	0.0003	-5.090985	0.0003
	Constant, Linear Trend	-5.236757	0.0011	-5.272658	0.0010
R&D	None	-1.844707	0.0627	-1.944384	0.0509
	Constant	-6.065756	0.0000	-6.171127	0.0000
	Constant, Linear Trend	-3.942573	0.0245	-6.113507	0.0001
IRTII	None	-2.897333	0.0053	-5.253151	0.0011
	Constant	-3.593636	0.0123	-3.451650	0.0171
	Constant, Linear Trend	-4.150856	0.0144	-5.253151	0.0011
<i>Note(s): ***, 1%, **, 5% and *, 10% significance level</i>					

Source: Author's computation (2024)

The tests were conducted to show the ADF and PP at first difference at none, intercept, trend and intercept level. The ADF and PP results present that the remaining dataset is statistically significant. Additionally, the results indicate a combination order of integration I(0) and I(1). The results emanating from the stationarity tests guided the study in selecting a suitable econometric model, as discussed in section 3.3. Thus, the study employed the ARDL model to investigate the impact of technological innovation and economic growth. This econometric technique has been employed by previous studies such as Sulaiman *et al.* (2015), Mohamed *et al.* (2021), Awan and Yaqoob (2023) and Mussaiyib and Pradhan (2023).

5.3. ESTIMATION RESULTS

5.4.1. Long run estimates

As identified from the stationarity tests, the ARDL was the selected model. The model was run on four dependent lags and two maximum linear regressors. The number of lags was selected based on the Akaike Information Criterion (AIC), as the AIC favours a fewer number of parameters and penalises model complexities, while ensuring minimal loss of information. The findings from the primary variable of interest IRTII highlight that the index depicted has a positive and statistically significant relationship with economic growth in the long run. The findings reveal a 1.58 impact on economic growth with a statistically significant p-value of 0.00. The results are aligned with the endogenous theoretical assumption noted in chapter 2, that technological innovation related to digitisation has a long-term impact on economic growth. Saba, Ngepah and Odhiambo's (2023) study solidifies the study's results, by reporting that there is long-term positive relationship between the index variables and economic growth. After adjusting for the one lag, technological innovation has a -1.02 impact on economic growth with a 0.05 significance level.

Chapter 2 discusses the Schumpeterian theory, known as the creative destruction theory, which suggests that technological innovation may have a negative impact on economic growth in the long term. Mohamed *et al.* (2022) suggest that in the majority of the developing countries, the diffused technology comes through technological transfers that may not be aligned to local economies, resulting in the negative impact of technological innovation on economic growth in the long run. The negative impact may be attributed to high initial costs associated with digitisation, regulatory barriers that impede the implementation and adoption of new technologies; also, the resistance to change may have a proportional impact on the negative impact of the index to economic growth (Zhang *et al.*, 2022; Gomes, Lopes, & Ferreira, 2022; Aleksandrova, Truntsevsky & Polutova, 2022).

The ARDL results for Research and Development depict a positive relationship between R&D and economic growth, and a statistically significant value at level. R&D has 1.45

impact on economic growth and a 0.01 statistically significant p-value in the long-run. The results are comparable with the endogenous growth theory discussed in chapter 2, asserting that investments in R&D are crucial drivers in long-term economic growth. Agezew (2024) and Pala (2019) further reinforce the study's results by denoting that in the long term, R&D results in fast economic growth due to its linkage to high productivity and improved societal standard of living. Adjusting to a one period lag, R&D has a 1.73 impact on economic growth; however, R&D has a 0.73 p-value making R&D statistically insignificant. The two-period lag adjustment reveal that R&D has a 3.92 impact on economic growth and is statistically insignificant, with p-value of 0.31. According to Ulku (2004), McMorrova and Röge (2009), the insignificant levels of R&D may be associated with the lack of linkage between R&D and industries; weak legal frameworks to protect intellectual property; or pressure caused by short-term economic objectives. The low magnitude levels in explaining economic growth may also be associated with the insignificant levels. In comparison to the IRTII, R&D has a low correlation strength measure (See Section 5.3.3). Additionally, IRTII has a strong impact relationship with economic growth, compared to R&D in the long run. The disparity may be attributed to IRTII's immediate applicability given sufficient infrastructure such as internet access, digital services, and mobile networks, whereas R&D requires a longer time horizon to generate tangible outcomes (Ishnazarov, Kasimova, Tosheva, & Isaeva, 2021; Fernández-Portillo, Almodóvar-González, & Hernández-Mogollón, 2020; Bahrini & Qaffas, 2019).

Labour results depict both a positive and negative relationship with economic growth, and both are statistically significant in the long run. The results from Labour at level denote a -2.40 impact on economic growth and is statistically significant with a p-value of 0.01. Unat (2020) highlights that the Malthusian Theory of Population suggest that labour may have a negative impact on economic growth, as overabundance of labour without the equal correspondence of income results in labour having a negative impact. The negative impact may be associated with technological shocks in specific industries such the introduction of automation in manufacturing; structural shifts in terms of the political or domestic landscape such as the end of the Apartheid regime, and skills mismatch in the long run (Badkar, 2024; Holzer, 2022; Scott, 2019. Factoring in the first period lag,

labour has a 0.81 impact on economic growth and a statistically insignificant p-value of 0.06. The first lag adjustment impact asserts the slow growth theory discussed in chapter two, as an increase in labour contributes positively to the growth in output. After the adjustment of the two-periods, labour has a -7.44 impact on economic growth, with a statistically significant. The results show that labour has a strong magnitude in explaining economic growth. In comparison with the primary variable (IRTII), at level, IRTII has a higher impact and correlation with economic growth; however, when adjusting the first lag, labour has a stronger impact or relationship with economic growth.

The ARDL results on capital depict that capital has a positive impact on economic growth. Capital has a 4.45 impact on economic growth in the long run, which is statistically significant. The study's result are aligned to the Solow growth model, suggesting a surge in capital such as machinery, infrastructure and financial capital has a long-term positive impact on economic growth. According to Ribaj and Mexhuani (2021) and Combes, Kinda, Ouedraogo and Plane (2019), capital accumulation enables research and development to take place, and capital goods result in higher output and productivity driving economic growth. However, after factoring in the adjusted one period lag in the long-run, capital has -2.15 impact on economic growth, with a statistically insignificant. Mirzayev (2023), Udugampola (2023), Spyromitros and Panagiotidis (2022) argue that the negative impact may be associated with poor institutions, which are subject to corruption, mismanagement of funds, inefficiencies, and political interferences; also excessive debt reliance which often results in debt overhaul and capital being utilised to finance debt. According to the findings, the magnitude of capital in explaining economic growth is low. Additionally, the overaccumulation theory within Marxism aligns with the results, by explaining that capital accumulation that is not met with the same amount of demand may result in overproduction, resulting in a negative economic crisis.

The evaluation of the results for TT highlights a positive relationship between TT and economic growth, which is statistically significant in the long run. A further analysis of the results show that TT has a 3.24 impact on economic growth, with statistical significance level of 0.00 at level. When adjusting to a one-period lag, TT still has a 1.84 impact on economic growth with a statistically significant. After factoring in the adjustment of the

two-period lag, TT has a 2.53 impact on economic growth and is statistically significant. Amongst the variables, TT has the highest positive magnitude overall in explaining economic growth. The endogenous growth theory (See Chapter 2) reinforces the results by highlighting that knowledge spillovers and technology transfers among countries play a crucial role in driving sustained economic growth through backward and forward spillovers. Asongu and Odhiambo (2020) postulate that technology transfers induce a positive inflow of economic growth through the transfer and diffusion of new technologies. Similarly, Human Capital Development has a positive and statistically significant relationship with economic growth. The positive impact may be attributed to the contribution of human capital in skills development that yields or fosters innovation, boosts productivity, and increased global competitiveness.

The ARDL results for R&D depict a positive relationship between R&D and economic growth and a statistically significant value at level. R&D has 1.45 impact on economic growth and a 0.01 statistically significant p-value in the long-run at level. Similar to the aforementioned variables, the exogenous growth theory solidifies the study's results by arguing that R&D has a long-term impact on economic growth, as R&D results in technological innovation and improved efficiencies, which are all crucial drivers of economic growth. Adjusting to a one-period lag, R&D has a 1.73 impact on economic growth; however, R&D has a 0.73 p-value, making R&D statistically insignificant. The two-period lag adjustment reveal that R&D has a 3.92 impact on economic growth and has a statistically insignificant p-value of 0.31. Ulku (2004) and Blanco, Prieger, and Gu (2013) suggest that the insignificance levels of R&D may be associated with the lack of linkage between R&D with industry's weak, legal frameworks to protect intellectual property, and pressure caused by short-term economic objectives. The low magnitude levels in explaining economic growth may also be associated with the insignificant levels. The magnitude levels are also lower than those of the primary model IRTII, denoting that the index has a stronger impact/relationship on economic growth

Table 11: Long-Run Estimates

Variable	Coefficient	Std. Error	t-Static	Prob.
GDP(-1)	0.27	0.24	1.13	0.00***
GDP(-2)	-0.26	0.16	-1.67	0.57*
GDP(-3)	-0.16	0.26	-0.60	0.00***
GDP(-4)	0.89	0.25	3.50	0.00***
LABOUR	-2.40	6.83	-3.51	0.00***
LABOUR(-1)	8.41	4.04	2.08	0.00***
LABOUR(-2)	-7.44	3.42	-2.17	0.00***
CAPITAL	4.45	1.03	4.33	0.00***
CAPITAL (-1)	-2.15	1.32	-1.63	0.00***
TT	3.24	7.25	4.47	0.10*
TT (-1)	1.84	7.71	2.38	0.00***
TT (-2)	2.53	8.52	2.97	0.00***
HDC	126811	57878	2.19	0.00***
R&D	1.45	4.20	3.45	0.00***
R&D(-1)	1.73	4.88	0.35	0.73*
R&D(-2)	3.92	3.70	1.05	0.00***
IRTII	1.58	4.25	3.77	0.00***
IRTII(-1)	-1.02	4.64	-2.19	0.00***

*Note: ***, 1%, **, 5% and *, 10% significance level*

Source: Author's computation (2024)

5.4.2. Long-run Bound Test

To ascertain the ARDL model results, the study further conducted the long-run bound test to assess whether the variables of interest have a long-run equilibrium. The results highlight that the F-statistics is greater than the 5 percent upper bound and 5 percent lower bound, denoting that there is a long-run relationship between the independent and dependent variables of interest.

Table 12: Long-Run F-Bounds Test

Test Statistic	Value	Significance level	I(0)	I(1)
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F-statistic	7.765204	10%	2.08	3
K	5	5%	2.39	3.38
		2.5%	2.7	3.73
		1%	3.06	4.15
<i>Note(s): ***, 1%, **, 5% and *, 10% significance level</i>				

Source: Author's computation (2024)

5.4.3. Error Correction Model

The results from the ARDL model indicated deterministic and stochastic trends in some of the variables, and therefore, the ECM was conducted to examine how short-run deviations are corrected over time, capturing the speed of adjustments. The models were noted to be deterministic, as the error correction term is significant, highlighting a stable long-run equilibrium, and the model is stochastic, as the variables are integrated at I(1) and I(0). The EC term is -0.26. The negative sign indicates that there is a long-run relationship between GDP and explanatory variables. The magnitude of 0.26 is closer to one, indicating a slow speed of adjustment back to equilibrium. In particular, following a short-run deviation from equilibrium, only 26 percent of the long-run relationship is corrected in the following year. The error correction term is statically significant, with a p-value of 0.00. Similar to the long-run estimation test, the primary variable of interest, the IRTII has a positive impact on economic growth in the short run. A 1.58 impact of the Index towards economic growth has been noted and is statistically significant. This then reinforces that the IRTII has a positive impact on economic growth in both the short-run and long-run. The study by Mwananziche, Myovella, Karacuka, Haucap and Moshi (2023) confirms the study's results by arguing that the early adopters and adapters of the index's variables get a boost in economic growth in the short and long term. The ECM results in the index are aligned with the neo-classical growth theory, that argues that technological innovation has a short-run positive impact on economic growth, as technology boosts production output and increases efficiencies that result in a boost in economic growth.

From the ECM results, Labour is noted to have a -2.40 impact on economic growth in the short-run and is statistically significant at 0.00. The negative relationship may be associated with economic shocks like the global financial crisis or the Covid-19 pandemic,

which lead to a decrease in employment or job absorption; rigid labour policies that do not encourage labour absorption techniques, and setting up below average minimum wage (Baker & McKenzie, 2023; South African Reserve Bank, 2021; Public Servants Association's Perspective (PSA) (2014). Baker and McKenzie (2023) highlight that South Africa is argued to have some of the most stringent labour laws, similar to European countries. Global economic constraints such as Covid-19 resulted in the loss of over 630 thousand jobs in the formal sector in the second quarter of 2020 (SARB, 2021). The negative impact may also be associated with the mismatch or scarcity of skills in certain sectors, such as the STEM fields. Mncayi (2021) highlights that approximately 50 percent of the working population in South Africa is mismatched, resulting in low production levels. Additionally, Mncayi (2021) states that among the 50 percent of the misplaced workers, graduates particularly are often in environments where they are under- or overqualified. After the adjustment of the one-lag period in the short run, labour has a positive 7.44 impact on economic growth and is statistically significant at 0.00. The magnitude of Labour is high in explaining economic growth.

In the short-run, capital deviations have a positive and statistical impact on economic. Capital has a 4.45 impact on economic growth and is statistically significant with a p-value of 0.00. Similarly, TT has a positive impact on economic growth in the short run with a 3.24 impact and statistically significant level of 0.00. However, after adjusting to the one-period lag, the variable exhibits a negative impact on economic growth of -2.53 and is statistically significant at 0.00 p-value level. Research and Development (R&D) in the short run at level has a positive impact on economic growth. R&D has a 1.45 impact on economic growth at level and is statistically significant with a p-value 0.00. After adjustment of the one period lag, R&D has a negative impact of -3.92 on economic growth, which is statistically insignificant with a p-value of 0.10. The negative impact may be the result of the time it takes for R&D to yield results, caused by institutional and regulatory inefficiencies and cyclical economic short-run pressures. The magnitude of R&D in explaining economic growth is relatively low. The Index has a positive impact on economic growth in the short run. A 1.58 impact of the Index economic growth has been noted and is statistically significant.

Table 13: Error Correction Estimates

Variable	Coefficient	Std. Error	t-Static	Prob.
GDP(-1)	-0.47	0.08	-5.91	0.00***
GDP(-2)	-0.73	0.09	-7.77	0.00***
GDP(-3)	-0.89	0.18	-4.83	0.00***
D(LABOUR)	-2.40	2.39	-10.03	0.00***
D(LABOUR(-1))	7.44	1.74	4.28	0.00***
D(CAPITAL)	4.45	4.77	9.33	0.00***
D(TECHNOLOGY TRANSFERS)	3.24	3.04	10.67	0.00***
D(TECHNOLOGY TRANSFERS(-1))	-2.53	4.50	-5.62	0.00***
D(R&D)	1.45	2.09	6.96	0.00***
D(R&D(-1))	-3.92	2.20	-1.78	0.10*
D(IRTII)	1.58	2.17	7.25	0.00***
COINTEQ*	-0.26	0.03	-9.91	0.00***
<i>Note (s): ***, 1%, **, 5% and *, 10% significance level</i>				

Source: Author's computation (2024)

5.5. POST-ESTIMATION RESULTS

5.5.1. Heteroskedasticity Test

To further validate the study's model, the Heteroskedasticity test was conducted to examine whether the variance of the residuals or errors in a regression model are consistent, to allow a more accurate assessment of the model's parameters. In doing so, the Breusch- Pagan-Godfrey test was conducted and the results emanating from the test highlight that the data series is homoscedastic, as the p-values from the test are greater than 0.05. Therefore, the study failed to reject the null hypothesis, that the variance of the residuals is constant.

Table 14: Heteroskedasticity

Model Tests:				
Null Hypothesis: Homoscedastic	Obs*r-squared	F-Stat	Prob. Chi-square	Prob. F
Breusch- Pagan-Godfrey	8.370137	0.449286	0.8187	0.9188
Harvey	10.99876	0.687360	0.6109	0.7457
<i>Note(s): (*) non-rejection of the null hypothesis at 1%; 5% & 10% significance level</i>				

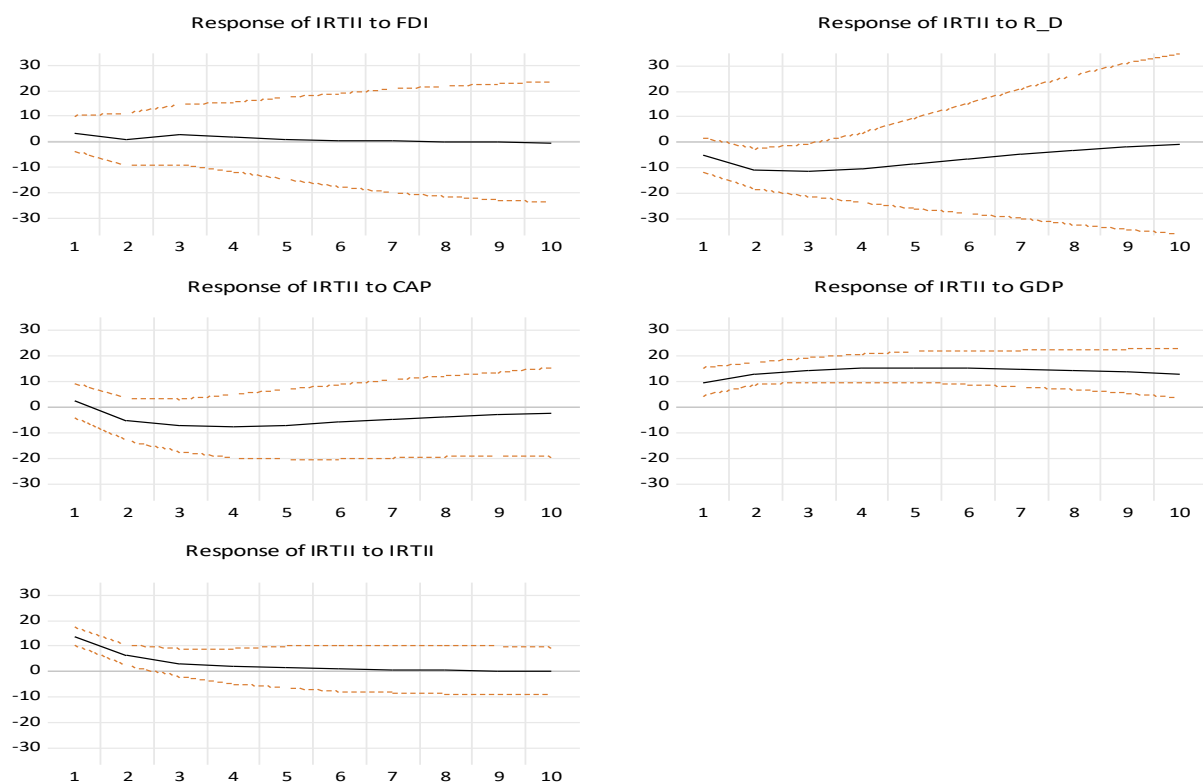
Source: Author's computation (2024)

5.5.2. Impulse Response

In order to assess the robustness of the main results, the SVAR model was estimated. This section discusses the impulse response functions (IRFs) obtained from the SVAR model. Figure 16 displays the results. The y-axis is measured in percentages whereas the x-axis is measured in quarters. The black lines are the IRFs whilst the red dotted lines are the 95 percent confidence intervals. First, we discuss the response of the IRTII to shocks to ascertain what drives technological developments in South Africa.

Figure 16 shows that a shock to technological transfers (measured using FDI) triggers a positive response from the IRTII. The positive response may be attributed to the knowledge spillovers and R&D collaboration that enables the creation and diffusion of new technologies, as well as knowledge, and the decrease on the shock may be attributed to the increase in competition and the increase towards safeguarding the technological innovation (reducing the expansion of technology).

Figure 16: Impulse Responses IRTII



Source: Author computation (2024)

The index responds negatively towards R&D shocks, but gradually starts to be positive in the long run. This may be attributed to the reallocation of resources; as new technologies are adopted, resources may need to be directed towards the integration of new technologies, which may decrease R&D initiatives. Secondly, the learning curve may also be attributed to the negative impact, due to the time it takes to learn and adapt to new technologies. However, from unit three, the shock begins to increase, which may be attributed to the positive externalities that are exuded by new technologies that encourage R&D.

Capital shocks share similar attributes to R&D, as the first unit of shock of capital generates a negative response from the index. However, the second unit of shock of capital has a positive direction on the index which may be attributed to the lag it takes for capital to be generated and adopted, denoting the idea that technology may exist but the time in generating the capital is lagging. Secondly, the negative response may be attributed to the uncertainty new technologies bring to the market, therefore a cautious

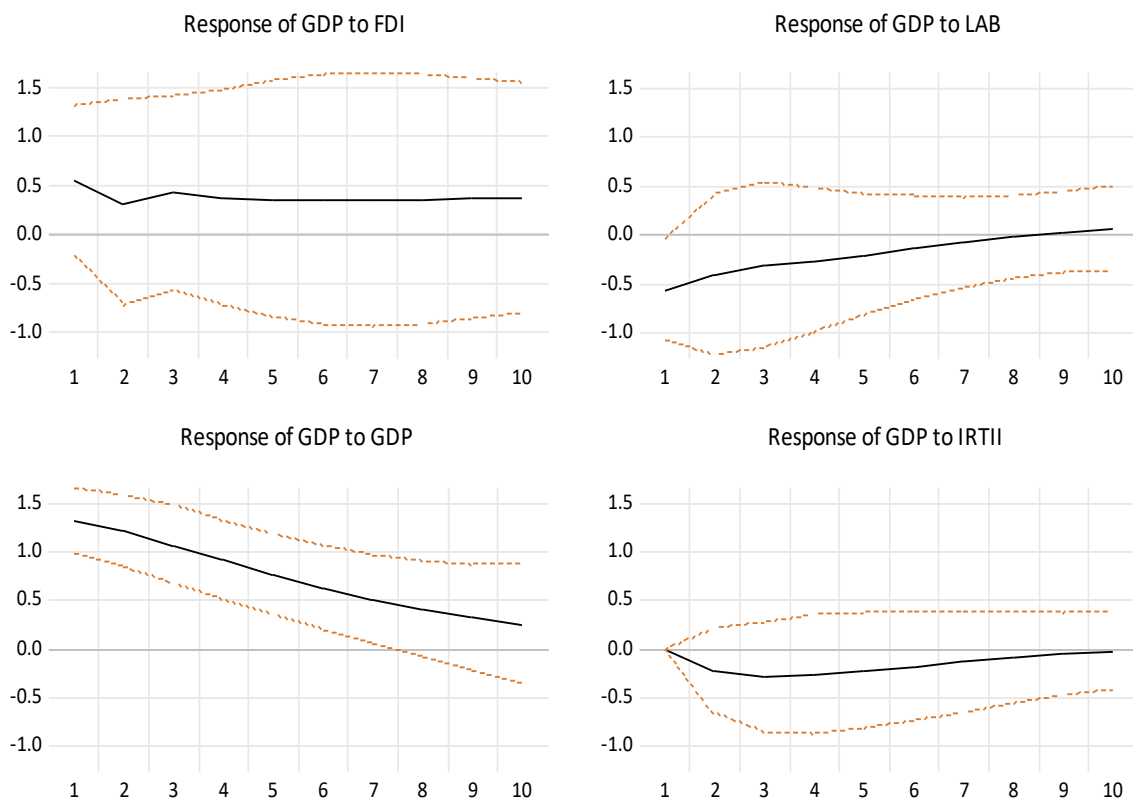
approach may be taken to allow the market to adjust. However, from the fourth shock of capital the response of the index starts to increase towards equilibrium, which may be due to the spillover effect of technological innovation attracting investments and the endorsement and adoption of the of innovation-led growth by economies further validating that the positive impact capital has on the index in the long-run and vice versa. TT and R&D also further validate the study's result, there being a positive relationship between the index, technology transfers, and R&D in the long run.

Looking at the shock of the economic growth (GDP) on the index, the results highlight that GDP shock has a positive direction/impact on the index and each unit shock of GDP is supported by an increase in the index, validating the results that there is a positive relationship and impact between the index and economic growth. The impulse response results further highlight that continuous GDP shocks are needed to push technological development as the shock begins to wear off. Lastly, the impulse response highlights that the index also has a positive shock towards itself, which may be attributed to the feedback loop as more technological innovation shocks lead to further innovations, and more innovation shocks may trigger an increase in resources directed towards R&D to encourage further technological adoption. To further deepen the results of the study, the research conducted impulse response of the GDP against selected variables to assess how GDP may respond to impact shocks of the variables.

The results of the impulse response are depicted below (Figure 17). The first figure shows that one unit of shock of TT (measured using FDI) has a positive response attribute towards GDP and shows a positive impact of the shock in the long run. The positive relationship may be attributed to the increase in the market size and domain, and as the economy grows, the market increases, attracting the demand for larger technological transfer initiatives and knowledge spillovers from different industries. Despite the shock showing a positive direction, the second unit shock shows a slight decline, which may be attributed to the lack of capacity to adopt the technologies due to inadequate implementation of IPR, as discussed in section 3.2.2, or due to market parities that may hinder the full adoption of technologies; however, the shocks of TT to GDP is positive. Secondly, a unit shock of labour is highlighted to have a negative response from GDP,

which may be attributed to structural changes caused by the adoption of new technologies in new industries resulting in loss of jobs, and income, ultimately affecting economic growth negatively. The results complement the study's results on the relationship between labour and economic growth, and the primary results of the study show the relationship adjusts positively in the long-run, which is highlighted in the impulse response that from the second unit shock of labour to GDP, the adjustment begins to increase towards the equilibrium.

Figure 17: Impulse Response of GDP



Source: Author's computation (2024)

Interestingly, the impulse shocks show a negative direction on GDP to GDP. The direction may be associated with the economic theory of creative destruction, in which some industries, markets, and sectors become obsolete due to technological innovations disrupting traditional methods of output, and may also be attributed to investment lags in technology, and transition costs towards the adoption of technological innovation initiatives. Looking at South Africa's economic environment, a number of internal and external shocks result in a negative response in economic growth. According to the World

Bank (2024) and International Monetary Fund (IMF) (2023), crippling load shedding schedules have resulted in increased operation costs that further hamper production, as South Africa experienced over 280 days of electricity cuts. Moreover, the IMF (2023) argues that the low reduction of unemployment, currently standing at over 30 percent, results in an increased inability of the government to combat socio-economic challenges. Bishop (2024) reinforces that South Africa's heavy dependence on export commodity prices exposes the country's currency to global price fluctuations. Such internal and external shocks augment the study's results on the shock and response of GDP.

Lastly, similar to the shocks of GDP to the index, the impulse response shows that the index shocks also have a positive direction towards GDP in the long run, further validating the primary results of the study. Though the first unit index shock highlights a negative response direction to the GDP, the shock adjusts from the third unit of shock. The negative direction at first may be attributed to the theory of creative destruction, regulatory frameworks toward technological innovation, and the time it takes for technology to adjust in the market; the shock begins to increase towards the equilibrium and above in the long run, which can be attributed to technology spillover. The overarching result from the IRF is that the index shock is seconded by a positive response in economic growth.

5.5.3. Variance Decomposition

To further ascertain the stability and shocks of the primary results of the study, the variance decomposition analysis was conducted. Following the study's assertion that there are traditional variables used to scrutinise the impact of technological innovation on economic growth, the study primarily focused on the technological innovation (index) shocks and its variances with other variables, to better understand the impact between technological innovation and economic growth. The study further focuses on other variables that support growth and technology advancements. Table 15 depicts the results of the variance decomposition analysis.

The results indicate that technological innovation in both the short-run and long-run has the highest explanation of GDP variations amongst other variables. Similarly, GDP shows the highest explanation of technological innovation (index). In the initial period (short run),

technological innovation is highly explained by itself, with 51.2 percent shock. However, as time progress in the long term, the shock of other variables begin to increase. GDP on the other hand is highly explained by itself in the long term, with a 54.87 percent shock, but in the short-run, GDP variations are explained by other variables. Moreover, in the short-term (year one to three), technological innovation is explained by 25.38 percent, and 39.50 percent, of variations in GDP in year one and year three respectively. It is further explained by 11.61 percent and 6.63 percent of HCD, 0.00 percent and 0.08 percent of labour, 1.30 percent and 7.51 percent of capital, 7.46 percent and 22.88 percent of R&D, and 3.00 percent and 1.75 percent of variations in TT respectively. Similarly, in the short-term, GDP explained similar variation results in the aforementioned variables.

The results suggests that in the short run, the technological innovation (IRTII) shocks are largely driven by its own intrinsic factors. Secondly, the results highlight that, out of the index explaining itself, GDP has the strongest explanation of technological innovation fluctuations in the short run. In the same timeline, GDP shocks are largely expanded by technological innovation variations. The explanation of GDP explaining technological innovation variation (vice versa) may be attributed to the increase in digital adoption in South Africa in sectors such as banking, e-commerce, telecommunications, and fintech that drive economic activity. Moreover, the explanation of HCD variations of technology in the short-term may be associated with technological spillovers and technological diffusion of the workforce, as they enhance their capabilities and adopt new technologies, improving human capital. Amongst the variables, technological innovation explains labour variance the least, which may be associated with technological innovation having a low impact in labour intense sectors and may also be associated with slow adoption of technological innovation. The short-run variance decomposition results reinforce the study's investigation, that GDP has a positive strong impact or explanation towards technological innovation in the short-run.

Moving to the medium term (year four to six), the dynamic begin to shift, as technological innovation does not largely explain its variance, but instead other external variables have a crucial role in explaining technological innovation shocks. In the medium term,

technological innovation shocks are explained by 15.03 percent and 10.19 percent variant of itself. Technological innovation shocks are explained by 42.22 percent and 47.25 percent of variance in GDP in years four and six respectively. The results suggest that GDP explanation of technological innovation variances increase over the years. Outside of the digital adoption, the increased explanation of technological innovation variances by GDP may be associated with increased policy support towards technologies, such as private sector innovation to enhance the enhancement of technological innovation. Even in the medium term, GDP has the strongest positive explanation of technological innovation shocks. Second to that, technological innovation is explained by 22.83 percent and 20.00 percent of variation in R&D. R&D has the second strongest explanation of technological innovation fluctuations in the medium term. The explanation of the variance of technological innovation by R&D may be associated with the emerging of technology hubs in places such as Cape Town and Johannesburg, the collaboration between public and private institutions which encourages the R&D outputs, and the continued focus on innovation-driven policies in the medium term.

A further analysis on the medium term depicts that technological innovation is explained by 9.18 percent and 11.63 percent of variations in HCD after years four and six. The explanation of technological innovation variation by HCD in the medium term may be associated with the increased technology-driven jobs. As new industries and sectors in banking, fintech and information technology adopt more technologies, expansion is required and they generate the demand for skilled labourers, which results in the increase in the development of human capital. Additionally, technological innovation is explained by 9.15 percent and 9.58 percent of capital, 1.47 percent and 1.07 percent of TT, and 0.08 percent and 0.23 percent of variation in labour after years four and six. The explanation of variances of labour towards technological innovation has the weakest explanation of technological innovation in the medium term, which may be attributed to technological displacement, particularly amongst low-skilled workers, as more technologies are being adopted in these industries.

In the long-term period, represented by years seven to ten, technological innovation has the least explanation of itself with a variance measure of 8.98 percent and 7.06 percent

after years seven and ten respectively. GDP, on the other hand, has the highest explanation of itself. This suggest that in the long run, technological innovation shocks becomes more dependent on other variables, and GDP becomes more dependent on its own intrinsic variations. Technological innovation shocks are explained by 49.54 percent and 54.87 percent of the variations of GDP for year seven and year ten, therefore ascertaining that GDP has the strongest explanation of technological innovation fluctuations. The results may be attributed to increased investment in R&D especially in industries that have adopted digital technologies in the short-run such as banking, telecommunications, and e-commerce; the results may be attributed to the increased FDI inflows targeting technological sectors that result in technology transfers, spillover of knowledge, and the influx in capital that drives technological innovation, and it may also be attributed to the role of the private sector in advancing and incorporating new technologies into their operations (big data, AI, automation) that may have a cumulative effect on economic growth.

Similar to the medium-term period, R&D has the second highest strong explanation of technological innovation shocks. Technological innovation shocks are explained by 18.42 percent and 14.84 percent of the variance in R&D. The explanation of R&D towards technological innovation shocks may be associated with improved focus in STEM field education due to the witnessed results of technological innovation in skills enhancement, creation of jobs in technology driven industries, and technological spillovers in the short and medium term. The explanation may further be associated with further focuses on technology-driven policies, and increased investment in R&D by multinational corporations, as well as increased public-private collaborations.

Moreover, HCD explains 12.48 percent and 13.72 percent of technological innovation shocks after years seven and ten respectively. HCD has the third strongest explanation of technological innovation shocks. Technological innovation shocks are explained by 9.26 percent and 8.07 percent of capital variance, 0.95 percent and 0.74 of TT and 0.33 percent and 0.66% of labour variance for years seven and ten respectively. Labour represents the weakest explanation of technological innovation in the long run. This low level of explanation may be associated with the theory of creative destruction, that the

adoption of new technologies may result in making labour in specific industries and sectors obsolete, but it gradually begins to create more and more labour as the technologies become more integrated in the long run. The analysis of the variance decomposition suggests that economic growth plays a crucial strong role in explaining technological innovation shocks and fluctuations. The variance decomposition findings add to the depth of the findings presented in this study with respect to understanding the magnitude that technological innovation has on influencing economic growth in South Africa

Table 15: Variance Decomposition of IRTII.

Period	S.E	TT	R&D	CAP	LAB	HCD	GDP	IRTII
1	0.1921	3.0082	7.4616	1.3095	0.0072	11.6147	25.3869	51.2109
2	0.2677	1.6673	19.7523	4.4422	0.1119	6.6813	35.4001	31.9446
3	0.3404	1.7598	22.8883	7.5149	0.0801	7.6347	39.5064	20.6155
4	0.4018	1.4759	22.8354	9.1566	0.0837	9.1888	42.2202	15.0392
5	0.4514	1.2479	21.5927	9.6549	0.1421	10.5477	44.7899	12.0246
6	0.4914	1.0775	20.0084	9.5882	0.2313	11.6398	47.2577	10.1968
7	0.5421	0.9537	18.4246	9.2698	0.3362	12.4836	49.5434	8.9886
8	0.5511	0.8637	16.9979	8.8632	0.4479	13.0978	51.5875	8.1418
9	0.5733	0.7979	15.7971	8.4523	0.5597	13.5029	53.3642	7.5258
10	0.5916	0.7443	14.8422	8.0784	0.6659	13.7241	54.8723	7.0676

Source: Author's computation (2024)

5.6. CONCLUSION

To answer the primary question of the study that reads: “what is the link between technological innovation and economic growth in South Africa?” the study first employed the PCA to construct the index that measures technological innovation. Second, the pre-estimation analysis was conducted to better understand the trend of the economic variables chosen for this study; the findings were presented in visual data format. In addition to visual data, the study presented exploratory data analysis which included descriptive statistics, correlation analysis, and unit root stationarity tests. The findings indicated an upward trend of the GDP, a fluctuation trend on labour, and upwards trend on the index from 1992 – 2022. The descriptive statistics results of the Jacque-Bera test indicate the data series is normally distributed, except for labour and TT, because of their statistical significance. The stationarity tests from the Augmented Dickey-Fuller (ADF) and the Phillips-Perron (PP) revealed a combination order of integration $I(0)$ and $I(1)$, therefore informing the decision to use the ARDL model. A strong and positive correlation between GDP and technological innovation was observed from the correlation analysis.

The study conducted empirical investigations which included the autoregressive distributed lag (ARDL) model to investigate the short run and long-term dynamics between technological innovation, economic growth, and its determinants. The Johansen-Fisher cointegration test, and the error correction model (ECM) were used. The Johansen Cointegration results indicated the evidence of a long-run equilibrium relationship among the variables in the data series. The long run estimate results revealed a positive relationship between the GDP and technological innovation. However, interestingly, after adjusting the first lag, the relationship is negative, which answers the primary question that in the long run, there is a link between technological innovation and economic growth. The ECM results showed a similar relationship in the short run. The post-estimation results show that is no serial correlation amongst the residuals using the Breusch-Godfrey serial correlation LM test and Breusch- Pagan-Godfrey test.

In addition to the Breusch-Godfrey serial correlation LM test and Breusch- Pagan-Godfrey test, the impulse response and variance decomposition analysis were conducted to validate the study's results, and from both the tests, the results validated the long-term

and short-term relationship that exists amongst the variables, especially between technological innovation and economic growth. The impulse response highlights that there is a positive statistically significant long-run and short-run impact between the shock of the index and economic growth according to the primary results of the study; additionally, the shock of GDP has a positive impact on the index in the long-run. The variance decomposition similarly echoed the primary results by indicating that the shock of the technological innovation is strongly explained by GDP variances in the short-run and long-run. The results further denoted that technological innovation shocks are well explained by other variables that contribute towards economic growth, therefore showing that technological innovation does not solely impact economic growth.

Building on these findings, the robustness of the relationship between technological innovation and economic growth is further supported by the interaction among other variables within the model. The variance decomposition revealed that, beyond GDP, human capital development and research and development (R&D) variances significantly contribute to explaining technological innovation shocks. This emphasizes the interconnectedness of these factors in fostering economic growth, where advancements in technological innovation are not isolated but are reinforced by investments in education, skills development, and R&D activities. Moreover, the impulse response analysis underlines the sustained impact of these shocks over time, showcasing that initial technological disruptions lead to amplified economic outcomes in both the short and long term. This underscores the necessity of a holistic approach to policy design, where fostering innovation ecosystems is coupled with strengthening complementary areas like education and R&D to maximize the benefits of technological innovation on economic growth.

CHAPTER SIX: DISCUSSION OF RESULTS

6.1. INTRODUCTION

Following the study by Petersen and Kruss (2019), which echoed the need for a more comprehensive approach to measuring the impact of technological innovation on economic growth in a 4th Industrial Revolution era, the study therefore, primarily aimed at constructing the 4th Industrial Revolution adjusted Technological Innovation Index (IRTII) to account for variables not included in traditional methods when measuring the impact of technological innovation on economic growth in a 4th industrial environment. The study further assessed the impact of the index and other common traditional variables, namely Gross Capital Formation; Labour; Research and Development (R&D); Technology Transfers; and Human Capital Development, on economic growth in South Africa for both the short run and long run from 1992 to 2022. To attain the empirical results, the research conducted the cointegration analysis; correlation analysis; ARDL analysis (based on the unit root results) for long-term elasticities; the Error Correlation Model for short-term elasticities; the study further conducted post-estimation results to assess the model's reality.

The key results from the research study are summarised as: 1) The constructed technological innovation index has a positive and statistically significant impact on economic growth in both the short and long-run; however, in the long-run and short-run, after adjusting the one period lag the impact is negative; 2) TT has a positive and statistically significant impact on economic growth in both the short-run and long-run; 3) R&D results show a positive and statistically significant impact on economic growth in the short and long run; however, after adjusting the first and second lag, the impact is positive but statistically insignificant in the long-run, and is negative but statistically insignificant in the short-run; 4) Human Capital Development has a positive impact on economic growth and is statistically significant for the long-run and short-run; 5) Capital has a positive and statistically significant impact on economic growth in the short and long-run, but after adjusting for the first lag in the long-run, the impact is negative and insignificant; 6) Labour has a positive impact on economic growth in the first lag for both the short-run and long-

run, which is statistically significant; however, at level, labour has a negative impact on economic growth and is statistically significant. The study will further try to provide justification and meaning towards the results obtained as summarised above.

6.2. INDUSTRIAL REVOLUTION ADJUSTED TECHNOLOGICAL INNOVATION INDEX (IRTII)

The study found a positive impact on the constructed technological innovation index that primarily looked at variables that echo the importance of digitisation in the 4th industrial revolutions in the short and long run. The results are consistent with previously reported studies by Sulaiman *et al.*, (2015), Emiru and Wajebo (2023), Begazo *et al.* (2023), Solomon and Van Klyton (2020) and Khumalo and Mongale (2015). What the results mean is that the increase and promotion of the index coefficient have a considerable impact on the growth and level of economic growth in South Africa. The policies that aim to drive digitisation in the 4th industrial revolution are most likely to drive economic growth in the short run and long run.

Mwendera (2023) highlights that South Africa has the largest Information Communication and Technology market in Africa, therefore, a continued drive on digitisation in industries such as financial services with the rise of FinTech, digital purchases and transactions, big data and artificial intelligence in banking and insurance, will not only increase access to these industries but will also increase utilisation, enhance financial inclusion to previously marginalised population and regions through credit, savings, investments, which will in turn encourage spending, increasing the financial services contribution towards the GDP.

The results mean that an increase in the technological innovation index mostly results in the increase in labour productivity through skills development that are aligned with the increase in digitisation; increasing the access to goods and services as well as lowering the price of goods; and improving industry efficiencies which increases economic growth. Additionally, the increased drive towards digitisation will foster an environment that encourages entrepreneurship, boosting Small Medium and Micro Enterprises (SMMEs) to compete in the global market, and expanding the economic domain. By contrast,

digitisation poses challenges and gaps such as cybersecurity threats, regulatory setbacks, infrastructure, and the digital divide.

Interesting yet contrary results of the study highlight that after adjusting the first lag, the impact of the technological innovation towards economic growth is negative. This means that for digitisation in a developing country like South Africa, the economies of scale begin to decrease after the adjusted first lag in the long run. There are various reasons that may be attributed to such in the South African context; for instance, in the long run, industries such as retailers may see an increase in input costs, and non-tradeable sectors may face a loss of jobs; the parity of disposable income attributes to technological innovation may not be adopted by the population as a whole, as digital products are utilised by a specific income demographic which may result in the positive impact; however, after the first lag adjustment, sustaining the use of digital products by that demographic wears off, resulting in a negative impact; the costs associated with digitisation may be attributed to the negative impact of income disparities and the boost of new businesses due to technological digitisations may lead to growth. However, due to the high rate of failures of SMMEs in South Africa, the negative impact in the first lag adjustment may be associated with the failure of SMMEs who are not utilising digital products anymore. The results of the long-run lag adjustment are interesting, as they are in contrast to the above-highlighted studies, but yet consistent with other previous studies, such as Mohamed *et al.* (2021), Emiru and Wajebo (2023), and Sabbagh *et al.* (2013).

6.3. TECHNOLOGY TRANSFERS (TT)

The key finding from the study reinforces a positive impact of technology transfers on economic growth in the short and long run. The results are consistent and are in alliance with previously published studies by Fernandes, Veiga, Ferreira and Hughes (2021), Osano and Koine (2016); Hoekman *et al.* (2005) and Damooei and Tavakoli (2006). What the results mean is, that in both the short run and long run, an increase in attraction of technology transfers creates large externalities that yield positive growth levels in South Africa.

The influx of technological knowledge enhances access to current technology market trends like artificial intelligence, 5G, FinTech, and cryptocurrencies, and attracts global experts in industries such as health, education, and medical research, enabling a country like South Africa to upgrade its technology footprint, promote efficient methods of innovation and continue being competitive in the global market. Technology transfers can result in the diversification of different sectors such as mining, which has been declining for the last decade in South Africa, through the introduction of efficient methods of processing raw materials like gold, which will extend South Africa's global competitiveness. With the current challenges faced in the energy sector, technology transfers can be used as a benchmarking mechanism in attracting methods and innovations adopted by countries like Singapore and the United Arab Emirates (UAE) in maintaining and elevating their energy sector, and the influx of knowledge will provide policymakers adequate policies to adopt to ensure a sustainable energy sector which will result in economic growth.

The KwaZulu-Natal floods can be utilised as a case study to attract technology transfers on how to deal with the increase in the climate crisis. Additionally, the transferring of technology knowledge equals the implementation of new technologies in the ecosystem, and as a result, a skilled pool of workers will be required to boost employment and skills development, elevating individual well-being which will correspond to an increase in consumption and economic growth. In the space of knowledge development, technology transfers will stimulate the collaboration of different sectors such as academic institutions, private and public institutions, and entrepreneurs, to foster a conducive and friendly environment for economic growth. An increased focus on technology transfers can elevate other industries just as it elevated the telecommunications industry from a constrained, limited cord landline connection to a wider mobile communication reach that increased accessibility, reach, communication, and spread to industries like banking and insurance. All these aspects highlight the positive impact of technology transfers on economic growth.

6.4. RESEARCH AND DEVELOPMENT (R&D)

The variable of R&D gave interesting yet contrasting results. On the one hand it showed a positive impact on economic growth in the short-run and long-run, which is consistent with other studies, but on the other hand, it highlighted a negative impact on economic growth. What the first results mean is that an increase in expenditure on R&D will equally increase economic growth, which is consistent with studies by Mussaiyib and Pradhan, (2023), Tung and Hoang (2023), Ansah-Mensah *et al.* (2023) and Bujari and Martinez (2016). Investments towards R&D initiatives act as a catalyst for innovation and fostering competition locally and globally. Such investments can be noted in industries like agriculture with biotechnology research, which has enhanced crop yields, and agricultural productivity, which has extensively contributed towards economic growth.

Policies focused on increasing the footprint on R&D help with increased diversification in different sectors, such as the energy sector, where the introduction of mixed energy production has been noted in South Africa for greener energy, with more focus on solar and wind plants with the implementation of the Independent Power Producer Procurement Programme (REIPPPP). This seeks to add additional alternative energy sources to the country's low electricity grid, which in return will yield positive economies of scale.

The positive impact of R&D on economic growth in South Africa also means that the investments in R&D result in an extended accumulation of knowledge, nurturing the country's workforce to solve complex problems in different industries such as health, manufacturing, mining, and education. Successful initiatives have led mining industries to find efficient methods in the extraction process of minerals which are safe and sustainable. Also in the health sector, the increased focus on biotechnology is finding alternative treatments to various diseases. Increased endeavours on R&D may further result in a positive outlook on the citation of intellectual property, that will attract investment and encourage an entrepreneurial environment. The positive impact of R&D plays a pivotal role in encouraging growth in South Africa.

By contrast, the results highlight that after adjusting for the first and second lag, the impact of R&D on economic growth is negative. The results are consistent with studies by Acharya and Pathak (2019); Dessus *et al.* (2017), and Inekwe (2015). What the results mean is that R&D investments can result in a negative impact due to several layers such as misdirection of R&D; for example, sufficient investments were not directed to SMMEs which are key players towards economic growth in South Africa, and this resulted in little to no yield on R&D. The negative results may be associated with the lack of application of R&D results to practical implementations such as the misalignment between theoretical results with industry needs, which results in underutilisation of resources. Moreover, the results mean that the disproportional allocation of resources between low-impact areas and high-impact areas could impede innovation and competitiveness of R&D; moreover, the lack of skills, infrastructure, and regulatory limitations may also impede the adoption and implementation of R&D results.

6.5. HUMAN CAPITAL DEVELOPMENT (HCD)

Human Capital Development shows a positive relationship with economic growth. The results are consistent with published studies by Awan and Yaqoob (2023), Molaodi (2022), Sulaiman *et al.* (2015), Pelinescu (2015), and Glewwe, Maiga and Zheng (2014). A positive impact of human capital development highlights the transformative population landscape of South Africa that shapes not only the individual but the nation's parity. The results mean that an educated population is capable of cultivating the adoption and implementation of technological innovation, driving entrepreneurship, and increasing productivity across numerous sectors.

An increase in access to and quality of education, largely in previously neglected areas, will not only empower individuals but will also increase the human capital landscape. Investments in attracting individuals into STEM fields have the potential to drive and foster larger technological innovation advancements, propelling South Africa to be a knowledge-based economy which will fuel economic growth. Having a large population being educated also means that the utilisation of technological innovations is increased; for instance, the introduction of banks such as the Tyme Bank has witnessed a full virtual bank in which everything is operated electronically, and the bank has been successful.

The success of the bank may be directly linked to the educated population that can operate, adopt, and utilise innovation. The impact of education may contribute towards the reduction of inequality through the creation of upward mobility opportunities, which may be associated with creating a more inclusive economic growth trajectory. A skilled labour force is more likely to participate in high-value, high-growth economic activities, contributing to economic diversification. The positive impact between human capital development and economic growth underscores the imperative for sustained investments in education, to ensure the long-term prosperity and development of South Africa.

6.6. CAPITAL

Similar to some studies, the results highlight that there is the presence of a positive relationship between capital and economic growth both in the long run and short run. Studies by Sijabat (2022), Pasara and Garidzirai (2020), Meyer and Sanusi (2019), and Jalilian, Kirkpatrick and Parker (2007) are consistent with the studies' results. What the results mean is that an increased focus on capital directly influences an increase in economic growth. Capital that is directed towards physical construction, such as roads, bridges, railways, and buildings, as well as capital directed towards human capital such as education and training, has a direct impact towards the growth of the economy.

The investments such as the Kusile and Medupi power stations, which are directed towards increasing the country's electricity supply, are fundamental towards economic growth. Investments towards the Gautrain and Shosholoza Meyl Train to make transportation affordable, safe, and environmentally friendly, and increase travel experience, contribute towards economic growth.

The other important dimension forms human capital through the outcomes of investments in education and healthcare, which make a healthy and skilled workforce for innovation, productivity, and competitiveness in a developing economy like South Africa. Also, it is the optimal use of physical capital, such as advanced machinery and technology in different industrial sectors like manufacturing and mining, makes production more productive and massive. Access to entrepreneurship as well as innovations alongside business expansions is reliant on financial capital and proper financial markets. The entity

investments and credits would legitimize the sound economic output by allowing for growth in businesses and job creation. The development of financial markets and instruments has facilitated capital flow to various sectors, spurring growth. Positive capital flows impact economic growth in South Africa and demand strategic investment allocation that fosters synergies amidst financial, human, and physical capital towards sustainable inclusive development. Policies that encourage or strengthen capital increase result in an increase in the economy.

6.7. LABOUR

The coefficient variable of labour presents interesting yet contradictory results. The results show the presence of a positive relationship between labour and economic growth in the short and long run after adjusting the first lag; however, at level, the impact of labour on economic growth is negative. The negative impact of labour on economic growth means that labour initiatives yielded contrary results at level, which may be a result of several factors.

The introduction and adoption of new technologies in different industries like mining, with biotechnology gradually increasing, creates a misalignment of the jobs available not aligning with the skills required. The misalignment results in structural unemployment which shocks the economy negatively, as witnessed after the end of apartheid, when new technologies were introduced which were not aligned with the skills available in the employment pool, leading to the decline in employment in key sectors, and the decline in economic growth.

The labour environment in South Africa may not be encouraging the absorption of new employees in the employment pool, due to labour laws such as the minimum wage, which sets South Africa to be a low-income country, and the laws that discourage investment in certain sectors in the economy, which create stagnant work environments. The labour environment and laws contribute towards the high number of unemployed, especially the youth, in South Africa, which constrains the economy from growing due to a low level of productivity. Disruptions and labour strikes in key industries such as transport may have a negative impact on the country's productivity. Taxi strikes due to enquiries pertaining to

transport laws result in thousands of employees not being able to attend to their day-to-day work duties, which affects company performance and overall productivity. A poor education system may fall short in preparing the population for the required skills in industries, especially in sectors of the economy that are dominated by technological advancements, which further widens the skills gap, impeding economic growth. The results and discussions of the study are consistent with studies by Temitope (2013), Sodipe and Ogunrinola (2011), and Leibbrandt *et al.* (2010).

In contrast to the primary results, after adjusting the first-period lag, labour has a positive impact on economic growth in the short run and long run. The results are consistent with studies by Meyer (2017), Kaseeramm and Mahadea (2017), Bhorat, Cassim and Tseng (2016), Zulu and Banda (2015), and Mahadea and Simsons (2010). The results mean that continued support towards labour contributes towards economic growth. The results further highlight that a skilled and fit population is essential for sustained economic growth and the backbone of key industries such as health, financial services, manufacturing, mining, and education.

An employed population drives consumption, boosting domestic demand and economic acceleration. Investments made in the banking sector towards educating and training employees on data analytics to navigate the banking sector to be a more data-driven industry contribute towards a capable workforce that is skilled to meet industry demands and evolve their industries. Investments channelled into areas such as manufacturing, agriculture, and services, in the effort of raising a motivated and skilled workforce increase productivity and competitive advantage. The relationship between labour and economic growth is prominent in that shows an urgent need for well-thought-out policies meant to better skills, generate employment, and create a dynamic labour market. Moves like this are necessary to realise the full potential of the workforce of South Africa to keep up with the relentless economic progress.

6.8. CONCLUSION

Section 5 provided the results of the study, and this section aimed to provide a lucid understanding on what the results mean in application. Observing the IRTII and its

impact/link on economic growth, the results highlighted a positive relationship between the two variables, meaning that for an increase in the index, the presence of economic growth is eminent. By contrast, after adjusting for the first lag, the impact of the index become negative. The study attributed this negative relationship to the time it takes to adopt or adjust to the adaptation of new technologies in industries such as retail. The negative impact or link was also associated to some jobs lost due to the adoption of new technologies in optimising processes. The results are coherent both in the short-term and long term.

The discussions further elucidated other variables and the impact they have on economic growth. Technology transfers have a positive impact or link on economic growth, which the study attributed to the influx of technological products, services and expertise across the world, resulting in a positive relationship. R&D also highlighted a positive impact or link to economic growth, due to its ability to draw skillsets in the STEM fields, and its ability to draw collaborations between public and private institutions. Similar to R&D, HCD has a positive impact or link to economic growth, due to its ability to both attract trained labour and also train the labour force of the country, augmenting the efficiencies brought forth by new technologies.

The study further explained labour has a negative impact or link to economic growth at level, which the study attributed to being due to the jobs lost during the technology transition period. However, after adjusting the first lag, the impact becomes positive. Lastly, the development of the financial system in South Africa reflects the positive impact of capital.

CHAPTER SEVEN: SUMMARY, RECOMMENDATIONS AND CONCLUSION

7.1. INTRODUCTION

Technological innovations attributed to industrial revolutions over the years have been associated with the growth of economies and the spillover of an improved standard of living. However, despite the divergence of growth exuded by industrial revolutions, developing countries have come up short in experiencing the positive outcomes of the revolutions, and these developing countries have been lagging. The slow adoption and diffusion of technological innovation, especially in technologies of the 4th Industrial Revolution (4IR) has been attributed as one of the biggest culprits associated with the stagnant growth in developing countries. Because the 4th Industrial revolution has been characterised by the use of artificial intelligence, internet of things (IoT), robotics, etc., the existing measures of technology innovation have not been able to fully capture divergent facets of technological innovations in developing countries such as South Africa. Therefore, it has been difficult for developing countries to contextualise what technological innovation entails in their context, and where they should direct investment if they are to increase technological innovation. This is because traditional measures often focus on indicators rather than focusing and relying on direct achievements and adoption of technological innovation such as the success of technologies in informal sectors.

Moreover, the lack of digital roadmap strategies as well as continued challenges of inequality affect the implementation of technological initiatives, further reinforcing the slow adoption of industrial revolutions. Therefore, the fundamental objective of this study was to construct a multi-dimensionally measure of technological innovation in South Africa and assess its impact. In doing so, the study consulted a number of theoretical frameworks (See Chapter 2) and developed both theoretical and empirical objectives to achieve the main aim of the study. This chapter aims to provide summaries of the study's objectives, theoretical frameworks, theoretical and empirical findings, provide recommendations, and highlight the limitations of the study as well as provide areas for further investigations, and a conclusion.

7.2. SUMMARY OF STUDY

The study was directed towards remodelling the measure of technological innovation and its impact on economic growth in South Africa. To achieve this, the study carried out a number of investigations to tackle the primary objective, as well as both the theoretical and empirical objectives. Chapter one encapsulates the study's introduction and background, technological innovation in the landscape of South Africa (See Section 1.2), the study's problem statement, primary objective, theoretical and empirical objectives, contribution of the study and chapter classification. Chapter two presents existing theoretical and empirical literature on technological innovation, supported by case studies, as well as theoretical frameworks that frame the study. Chapter three elucidated theoretical objectives of the study by profiling technological innovation in terms of the trends and conditions of technology in South Africa. Chapter four and five examined the methodologies adopted by the study and also the primary empirical results. The chapters were then followed by chapter six, which discussed the primary empirical results and their implications. Lastly, chapter seven presents the study's summary, recommendations and conclusions.

7.2.1. Chapter Two: Summary of Theoretical and Empirical Literature

The theoretical and empirical literature of this study were highlighted and discussed in chapter two, with the intent of reviewing existing literature on the subject matter. The chapter firstly conceptualised different industrial revolutions to paint a picture and guide understanding how we arrived at the 4th Industrial Revolution and what the 4IR entails. The section details how each industrial revolution was phased out and how another revolution outlined the specific objectives that each industrial revolution aimed to achieve. The second section of chapter two elucidated the role of technological innovation towards economic growth. Section 2.3 conceptualised how economic theory explains how technological innovation impacts economic growth by highlighting the relationship that exists between the two, the transfer feedback loop spillovers spread by technology, and the synergic process of technological innovation, to lay a theoretical argument for attaining the objective of the study. Thirdly, chapter two conceptualised theoretical frameworks to establish foundational understanding of the study, accentuated by

theoretical assumptions that build a base of understanding. Four theories that assume a relationship between technological innovation and economic growth were contextualised for the study, namely, the Schumpeterian theory, Solow growth theory, endogenous growth theory, and the unified growth theory. The section highlighted each theory's primary assumptions and limitations to clarify the conditions and context in which each theory is applicable, and to underscore each theory's possible weakness and oversimplified elements of the theory.

The selected theories provide a foundational context for examining the relationship between technological innovation and economic growth. Schumpeterian theory, centred on the role of innovation and creative destruction, emphasised that economic growth is driven by entrepreneurial activities that introduce new products and processes, which overall transform industries and foster progress. The second theory, the Solow growth theory on the other hand, focused on capital accumulation, labour, and technological progress as key growth drivers of technological innovation, suggesting that long-term growth is achieved through exogenous technological advancements rather than endogenous economic factors. Thirdly, the endogenous growth theory challenged the Solow model, by positing that technological advancements and human capital development are fundamental components of growth. The theory further suggests that as fundamental components increase from endogenous factors in the economy due to investment in knowledge, innovation, and skills, economic growth arises. Finally, the Unified Growth Theory linked historical economic transitions to demographic and technological changes, examining how these factors interact to shape growth patterns over time.

Lastly, section 2.5 presented empirical findings related to the study to corroborate the empirical literature that exists between technological innovation and economic growth. Section 2.5 was divided into three sections (2.5.1 to 2.5.3) that categorised empirical case studies into developed and developing countries, and the comparison between the empirical cases. The empirical literature cases were selected based on criteria of shared characteristics with South Africa. The chapter noted cases, and highlighted that there are empirical studies in the literature that share positive relationships between technological

innovation and economic growth; on the other hand there are other cases that share a negative relationship. The empirical literature aligned the study objectives with cases that may be utilised as references.

In developing economies such as Egypt, Nigeria, Russia, China, and Brazil, technological advancement is primarily driven by foreign direct investment (FDI), human capital development, and digital technology adoption. For example, the Nigerian research emphasises the importance of human capital in driving economic growth through digital integration in productive areas. Similarly, the Egyptian situation emphasises the importance of FDI and technical innovation as development drivers, as well as the influence of technology transfer. In Brazil and Russia, social capital and creativity have a positive impact on R&D and economic performance, but structural changes in China have facilitated technical growth, placing the country as a competitive emerging market. These studies show how emerging economies use financial inflows, technological transfers, and digital adoption to drive innovation and economic development.

By contrast, developed countries such as Finland, Qatar, Lebanon, and Argentina use a more sophisticated strategy to promoting technical innovation, emphasising the transition to knowledge-based economies inside powerful innovation ecosystems. These countries prioritise endogenous innovation initiatives that are supported by governmental policies, educational programmes, and technology platforms. Finland is notable for its use of open technical advances that encourage cross-sector collaboration within a knowledge-based framework. The Argentine scenario emphasises government assistance as critical for increasing technical competitiveness, reflecting policies targeted at national economic progress. Similarly, Qatar and Lebanon deploy intellectual human resources, digital infrastructure, and targeted R&D to foster a knowledge-based economy. Overall, highly developed economies prioritise internal innovation capabilities through well-aligned policies and worldwide collaborations over relying largely on foreign resources.

7.2.2. Chapter Three: Summary of Profiling Technological Innovation in South Africa

Theoretical assumptions discussed in chapter two indicated that government institutions play a pivotal role in creating a conducive environment for technological innovation to thrive. Factoring in this, chapter three examined the theoretical objectives of the study highlighted in Section 1.4.2. The section profiled the role of different institutions in curating a conducive environment that drives the implementation and adoption of technological innovation initiative. In doing so, chapter three firstly assessed different institutional policies and regulations that delineate the technological innovation conditions in South Africa. Moreover, the chapter elucidated and investigated emerging technologies that are shaping the landscape of South Africa's technological environment, to aid the understanding of what technological trends are arising from institutional efforts. In addition to the theoretical objectives, chapter three examined the role of educational and research institutions (See Section 3.2.5) in augmenting a conducive environment for technological initiatives as well as assessing the role the institutions play in the global and South African context. Lastly, chapter three underscored the challenges associated with the adoption of technological innovation (See Section 3.3.2) in South Africa to scrutinise and call out areas of focus that may be channelled towards easing the adoption of technological innovation.

7.2.3. Chapter Four: Summary of Methodology and Data

Chapter four examined and reviewed the methods and data adopted by the study in evaluating the relationship between IRTII and economic growth in South Africa. The section argued and justified the used of methods and data utilised to attain the primary and empirical objectives. To attain the outcome of the section, the section alluded to the research design that was to be carried out, and encompassed how patterns, trends and relationships of variables were to be identified. Secondly, the chapter denoted the theoretical framework on which macroeconomic theoretical principles (neoclassical and endogenous growth theories) the study is grounded. As the primary objective of constructing the IRTII, chapter four highlights that the PCA method was selected due to its ability to reduce data dimensionality while retaining essential information about the

underlying variables. Three variables were chosen to construct the IRTII, namely mobile cellular phones, telephone lines, and internet access, which were collected from the World Bank as annual secondary data from 1992 to 2022. The period was chosen as it provides a substantial timeframe to capture long-term trends, cycles, and structural changes within South Africa's economy.

Mobile cellular phones, telephone lines, and internet access serve as crucial indications for assessing digital adoption, since they represent the population's degree of connectivity, access to technical breakthroughs, and the strength of communication infrastructure. These characteristics indicate the extent to which individuals and organisations can interact with digital platforms, access online information, and participate in digital economies. Furthermore, they shed light on digital inclusion, technical integration, and socioeconomic growth, making them critical for measuring a country's digital preparedness and the overall influence of digital technologies on economic and social advancement.

After the methodising of the PCA model, the study elucidated the steps in attaining the second empirical objective (See Section 1.4.3). For the study to achieve the aforementioned objective, it adopted a model that seeks to establish the relationship between the IRTII and economic growth in South Africa. In doing so, the study adopted the ARDL model to capture how GDP responds to IRTII changes and variables outside of the traditional metrics. The ARDL model was applied to analyse the impact of IRTII on economic growth, due to its optimal ability in investigating both short-term and long-term connections within variables with diverse integration orders. This model is stable in small sample sizes, offering dynamic insight into complex relationships and lagged effects that are important for understanding economic growth factors.

Following econometric techniques (ADF and PP Stationarity Tests), the section further continued to methodise the ARDL model for short run and long run estimations. While modelling the ARDL model, the section outlined that the study would apply a linear equation including target variables, namely: Real GDP (GDP) (economic growth), Capital (CAP), Labour (LAB), technological innovation (IRTII); Research and Development (R&D); Human Capital Development (HCD); and Technology Transfer (TT). The targeted

variables selected were collected as secondary annual data from the World Bank covering the period from 1992 to 2022; the variables were prompted by the availability of secondary data. Lastly, the section shows the assessment of the study's results to ascertain the reliability and validity of the empirical findings.

7.2.4. Chapter Five: Summary of Empirical and Results

Chapter five dispensed and interpreted the empirical findings obtained through the application of econometric techniques in assessing the impact of technological innovation on economic growth, as highlighted in chapter four. Chapter four highlighted that the econometric methods applied by the study include PCA analysis, pre-diagnostic tests that include summary statistics and stationarity tests, long-run estimates, long-run bound test, ECM, and post-estimation results. The PCA results produced three PCA eigenvectors from which one was selected and justified to create the index. The summary statistics denotes that three of the seven variables exude a positive upward trend in ten defined timeframes; three of the other variables exude a sideways trend pattern, and the last variable highlighted both an upward and downward trend pattern. The variable results of the stationarity test indicated a combination of orders of integration, $I(0)$ and $I(1)$, reinforcing the use of the ARDL model. Assessing the two key variables (GDP and IRTII), the correlation analysis showed a strong positive correlation. All other variables reflected a strong and moderate positive correlation; however, TT and Capital, IRTII and Capital, and TT and R&D reflected a negative correlation relationship.

As highlighted by the results in Section 5.3.2, the ARDL model was adopted to conduct the long-run estimation tests in which the results highlighted that there exists a positive relationship or impact between the index (IRTII) and economic growth in the long-run. Interestingly, after adjusting the one period lag, the relationship between the index and economic growth is negative. To ascertain the ARDL results, the long-run bound test results highlighted a long-run relationship between the independent and dependent variables. Additionally, the section explained the ECM results to assess the short-run relationship between the index and economic growth. The results reflected a positive relationship between IRTII and economic growth in the short run. The ECM results also reflected a magnitude of 0.26, highlighting a slow speed of adjustment.

The last section of chapter five depicts the post-estimation tests of the results to validate and ascertain the study's results. The chapter reflects that the Breusch- Pagan-Godfrey tests show that the data series is homoscedastic. This is followed by the IRTII impulse response, in which the chapter reflects and reports that a shock in GDP (economic growth) has a positive direction towards the index, and the continued unit shock of GDP drives technological initiatives. Similarly, the GDP impulse response results reflect that the index shock has a positive direction towards economic growth, further confirming the primary results that there exists a positive relationship between the index (IRTII) and economic growth. Lastly, the study reports the variance decomposition results in which the results ascertain that technological innovation (index) has the highest explanation of economic growth (GDP) variations in both the short-term and long-term.

7.2.5. Chapter Six: Summary of Result Discussion

Chapter six consists of the primary empirical results discussion of the key variables IRTII and GDP as well as other variables of interest. In the discussion of the results, the chapter argues that the study exudes similar results to previously published studies, and the study also presented contrary results. The chapter further explains the meaning of the results and what the results mean in the context of the study objectives and South Africa. The key results on all variables are also further summarised in the chapter to align the objectives of the study and the results.

7.3. REALISATION OF THE STUDY OBJECTIVES

This section details the approach carried out by the study in attaining the objectives this investigation stipulated in Section 1.4; the objectives were classified into three key sections, namely, primary objective, theoretical objectives, and empirical objectives. Understanding the objectives, this section revises the manner and approach in which the objectives have been achieved. Figure 18 summarises the study's objectives.

Figure 18: Summary of Objectives

	OBJECTIVES
Primary Objective	The primary objective of this study is to construct the 4th Industrial Revolution adjusted Technological Innovation Index (IRTII) for measuring technological innovation and to measure its impact on economic growth
Theoretical Objectives	• To identify technological innovation conditions in South Africa. • To identify technological innovation trends in South Africa. • Review and synthesise theories surrounding economic growth and technological innovation
Empirical Objectives	• To construct the 4th Industrial Revolution Adjusted Technological Innovation Index (IRTII). • To evaluate and examine the relationship between IRTII and economic growth in South Africa.

Source: Author’s computation (2024)

7.3.1. Primary Objective

The primary objective of the study was to construct the 4th Industrial Revolution adjusted Technological Innovation Index (IRTII) for measuring technological innovation within the 4th industrial revolution and assess the link/relationship that exists between the index and economic growth in South Africa. The overarching research question is to investigate whether there is a link or relationship between the index and economic growth.

7.3.2. Theoretical Objectives

Chapter one Section 1.4.2 stated two theoretical objectives of the study, in which all of the objectives were achieved in chapter three. Chapter three Section 3.2 achieves the first theoretical objective of identifying the technological innovation conditions in South

Africa. The section achieved the objective by firstly investigating the government policies and regulations that provide regulatory support in driving technological initiatives. Secondly, section 3.2.2 assessed institutions established in South Africa to play a crucial role towards advancing the science, innovation, technology and knowledge of a country. This was then followed by the intellectual property rights in South Africa (See Section 3.2.4) and how the property rights are benchmarked and ranked in comparison to global economies. To further assess the conditions of technological innovation in South Africa, section 3.2.5.2 of chapter 3 examined the role of educational and research institutions in creating a conducive environment for technological innovation in South Africa.

In examining the second theoretical objective highlighted in section 1.4.2 of chapter one, chapter three section 3.3 achieves the objective by elucidating the emerging technological trends in South Africa. The section illustrated South Africa digital adoption trends. The following subsection, section 3.3.1 highlighted South Africa's current and emerging technologies, in which digital commerce revenue growth was deciphered. Trends such as the Hydrogen Society Roadmap, Artificial Intelligence (AI) and Machine learning, Internet of Things, Square Kilometre Array, and Fintech and Insurtech were noted and discussed. The challenges associated with the adoption of digital technologies and the adoption of new technologies were discussed to ascertain how the technological innovation trends are challenged in terms of implementation.

Lastly, the third theoretical objective highlighted in Section 1.4.2 was realised in chapter 2. Lastly, the third theoretical objective highlighted in Section 1.4.2 was realised in chapter two. The objective of reviewing and synthesising thoughts on economic development and technological innovation has been achieved by an in-depth examination of the Schumpeterian theory, Solow growth theory, endogenous growth theory, and unified growth theory. Schumpeterian thought emphasises the transformational effect of technical innovation in promoting creative destruction and economic dynamism. According to the Solow growth hypothesis, technical advancement is an external element that contributes to long-term economic growth, notably by increasing productivity and compensating for declining capital returns. Endogenous growth theory broadens this notion by defining technological innovation as an internally driven force impacted by

investments in human capital, R&D, and knowledge spillovers. Finally, the unified growth theory combines both perspectives by linking advances in technology to historical economic shifts, implying a critical role in the transition from stagnation to sustainable development. Collectively, these theories give a complete framework for understanding the complex link between technical innovation and economic growth, which is consistent with the study's goal of contextualising this interaction.

7.3.3. Empirical Objectives

Chapter one Section 1.4.3 highlighted two empirical objectives which all link to the primary objective, which were all covered in chapter five. Econometric techniques were adopted as discussed in chapter four to achieve both empirical objectives. The empirical results that answer the empirical goals are expressed in Section 5.2 and 5.4 of chapter five. The first empirical objective of creating the IRTII was achieved in Section 5.2, in which three variables (cellular phones, telephone lines, and internet access) were utilised to create the index. The correlation of the three variables validates the use of PCA to construct a single index that measures technological innovation. Three PCA Eigenvectors loadings were conveyed, and the section justified the criteria utilised in selecting the PCA loading aligned to the study.

To attain the second empirical objective, chapter five section 5.4.1 and 5.4.3 established the results that explain the attainment of the objective. The sections aimed to understand if there is a link between the IRTII and economic growth. The study adopted the ARDL model to establish the long run link or impact between the index and economic growth, and the ECM to diagnose the short-term relationship. The models were also adopted to assess the relationship between GDP, index, and other variables (Cap, Lab, TT, R&D, and HCD). The evidence from the long-run estimates denotes that there exists a positive link or impact between the constructed index and economic growth. The short-term results highlight similar results, of a positive relationship between the two primary results. The last section of chapter 5, section 5.4 ascertains and validates the long-run and short-run estimates of the primary variables, as well other variables.

7.4. KEY FINDINGS OF THE STUDY

The empirical findings of this study are highlighted as follows: looking at the primary objective and the primary research question of the study, the key findings suggest that the constructed IRTII demonstrates a positive statistically significant relationship with economic growth in both the short-run and long-run; interestingly, after adjusting the one period lag, the impact/relationship of the IRTII towards economic growth is negative in both the short and long run periods. The results are consistent with the theoretical argument by Saba *et al.* (2023), that there is a long-term positive relationship between the index variables and economic growth, meaning an increase in the index increases economic growth through increased productivity and optimisation of efficiencies. The implication of the results suggests that promoting innovation may boost productivity, increase competitiveness, and contribute to long-term economic development, so boosting national wealth.

The Technological Transfer (TT) variable, which was added as one of the non-traditional variables in assessing the impact of technological innovation, demonstrated a positive and statistically significant impact on economic growth in the short and long term. The results align with Asongu and Odhiambo's (2020) argument, that increased technological transfers induce a positive inflow of economic activity. The implications of the results suggest that absorbing innovative technology from global sources can boost local productivity, innovation, and competitiveness, promoting long-term economic growth. Similarly, Human Capital Development (HCD), another non-traditional variable added in the study, denoted a statistically significant positive relationship with economic growth in both the short-run and long-run. The results align with Sulaiman *et al.* (2015) and imply that investing in education, skills, and workforce development can enhance productivity, innovation, and competitiveness, leading to sustainable economic growth, reduced inequality, and improved social well-being.

The results of the Research and Development (R&D) highlight a positive and statistically significant impact on economic growth in both timeframes. By contrast, after adjusting for the first and second period lag, the impact of R&D on economic growth remains positive; however, the impact is statistically insignificant in the same timeframes. The theoretical

and empirical results coincide with those made by Bujari and Martinez (2016), arguing that an increase in expenditure on R&D will equally increase economic growth. The results of the study imply that increased investment in research and development can drive innovation, improve technological capabilities, enhance productivity, and foster economic competitiveness, contributing to long-term growth, industrial development, and improved global economic positioning.

Capital investments similarly depict a positive link or impact that is statistically significant with economic growth in the short-run and long-run. However, the first period lag adjustment reveals a negative yet statistically insignificant impact with economic growth in both timeframes. Chirwa and Odhiambo's (2018) theoretical argument reinforces the study's results, that an increased focus on capital directly influences an increase in economic growth in the long run. The results imply that increased investment in infrastructure, machinery, and technology fosters productivity and economic development. However, in the long run, diminishing returns to capital, inefficient allocation, and resource constraints may lead to a negative impact on growth. The variable labour exerts a positive and statistically significant link with economic growth at the first period lag adjustment; however, at level, labour has a negative and statistically significant impact on economic growth in the short- and long-run period. Meyer (2017), and Sodipe and Ogunrinola's (2011) theoretical and empirical arguments supported the study's results, arguing that a negative relationship between labour and economic growth in South Africa suggests inefficiencies in the labour market, such as unemployment or underemployment. However, in the long run, improvements in education, skills development, and labour market policies can enhance productivity, leading to a positive relationship between labour and economic growth.

The assessment of the theoretical objectives highlights a key finding, that South Africa's technological innovation landscape is multifaceted yet supported by policies and regulations that aim to foster an environmentally conducive scenario for technological initiatives. Significantly, the 2019 White Paper on Science and Technology and the subsequent IPR Phase Two policy framework, which addresses 11 critical issues, were reinforced in the policy frameworks. However, despite the continued regulatory and

institutional efforts, policy implementations have been lagging and have not kept pace with the adoption of technological initiatives. The lag has been evidenced by the decline in South Africa's IPR ranking and IPRI score in 2023. Despite South Africa's complex technological innovation environment, the trend indicates a positive and proactive adoption of innovations, particularly in sectors such as the financial services. Consequently, South Africa exhibits an active inclination towards embracing technological advancements and digital adoption.

7.5. CONTRIBUTIONS TO THE FIELD OF STUDY

South Africa's economy continues to face significant challenges in achieving critical macroeconomic goals such as boosting economic growth, managing inflation, and lowering unemployment. Furthermore, chronic concerns such as poverty and underdeveloped healthcare systems have exacerbated South Africa's slow growth, with the Covid-19 outbreak exposing systemic economic flaws. South Africa, like many other countries, confronts the difficult problem of building policy frameworks that can manage these economic challenges while also promoting national growth and development.

A comprehensive measure of technological innovation, incorporating the factors related to digital divide (IRTII), HCD and TT, enhances economic analysis in South Africa. Traditional metrics often overlook disparities in digital access and human capital, which shape innovation's impact on growth. Integrating these factors provides deeper insights into productivity, employment, and sectoral shifts. Addressing digital inequality ensures inclusive development, while human capital fosters innovation adoption and creation. This refined approach aids policymakers in bridging technological gaps and enhancing workforce capabilities, promoting sustainable economic growth.

7.6. POLICY RECOMMENDATIONS

7.6.1. INDUSTRIAL REVOLUTION ADJUSTED TECHNOLOGICAL INNOVATION INDEX (IRTII)

The Small Business Institute (2021) postulates that South Africa's policy and regulations are not keeping pace with the current and constant cycles in technological innovations,

especially in the 4th Industrial Revolution that is data-driven, and the study highlighted a positive relationship between the index and economic growth. Therefore, the study echoes an extended focus on policies and regulations that are in sync with the current technological innovations, and clearer government frameworks that ensure a safe and secure environment for consumers and businesses to transact in the digital space, as the robustness checks of the study highlight that continued shocks towards digitisation and technological innovation have a long and conclusive positive impact towards economic growth.

The study further recommends placing emphasis and priority on substantial investments towards digital education and skills development, which will cater for students, employees in need of training, and educators guiding these employees and students, simultaneously, placing emphasis on establishing accessible and necessary digital infrastructure for economic progress and inclusivity, with encouragement for the involvement of the private sector. Public-private partnerships are sought after, especially concerning solutions for e-governance, innovative institutional approaches, and the execution of digitalisation strategies. Scrutiny on the access of technological products across different income parities and geographical locations should be prioritised to ensure holistic reach and utilisation of technological products, services, and initiatives. The study further suggests that cheaper and alternative methods to increase access to technology need to be prioritised. Additionally, urgent priority towards the approvals for large-scale renewable energy projects is crucial for the energy sector in South Africa.

7.6.2. TECHNOLOGY TRANSFERS (TT)

The research noted a prominent positive relationship between technology transfers and economic growth in South Africa, which indicates an increased focus towards technology transfers, and the study makes the following recommendations towards technology transfers. The South African Technology Transfer Offices (TTOs) have been noted to face restricted invention disclosures as a result of academic overload and resource limitations, which is one of the identified difficulties. Therefore, there is an emphasised priority to improve technology transfer focus on identifying and overcoming these barriers through collaboration as a critical method for bridging the innovation gap by encouraging

collaborations, collaborative research, and technological licencing agreements between universities, research institutes, and the public and private sectors.

Second, incentivising university lecturers and students with financial benefits from licensing agreements and industrial collaborations can serve as a driver for improving technology transfer. Furthermore, measures such as the Intellectual Property Rights from Publicly Funded Research and Development Act can be utilised to strive for an accelerated technological innovation environment in South Africa, introducing new opportunities for universities and research institutions, which will foster capacity development initiatives that include training, seminars, and mentoring programmes that have proven to be beneficial in providing necessary abilities to analyse, understand, and effectively transmit technology.

7.6.3. RESEARCH AND DEVELOPMENT (R&D)

Similar to technology transfers, R&D plays a pivotal role in the growth of an economy, and extending a focus towards R&D further increases the growth of South Africa's economy. The study's results permit the research to suggest that R&D frameworks should be drafted to align with key industries that are crucial for economic growth, such as SMMEs, and areas that ensure optimal utilisation of resources which yield positive results. To foster such optimal R&D initiatives, the study submits that the policies directed towards R&D provide benefits such as tax break incentives, subsidies, and a basic fixed grant across all initiatives, and grants that are specific to certain fields such as health and science, to institutions and individuals participating in such activities.

Additionally, the study submits that policies towards R&D encourage extensive public and private collaborations which will not only see an easing of the financial burden but create a bridge into and alignment between academic objectives and industry's needs. Collaborations may also be extended globally for extended sharing of knowledge. The collaboration may further contribute towards the development and improvement of research facilities and technology infrastructures that support R&D. The policies may further move towards easing the regulation hurdles that pose a challenge towards R&D

activities, and streamline regulations that protect intellectual property, which will safeguard, enhance, and provide assurance towards innovations.

7.6.4. HUMAN CAPITAL DEVELOPMENT (HCD)

The result from the study highlights that focus should further be directed towards human capital development due to its salient impact on economic growth, and policies directed towards human capital should look towards ensuring equal access towards education especially in previously marginalised areas, and addressing educational disparities between public and private providers, and urban and rural areas. In addressing disparities, the policies may be drawn towards continued training developments in activities that address 4th Industrial Revolution needs for both educators and recipients of training or education. The programmes will promote technical training and exercises to aid in bridging the gap in the skills needed in industries as well as providing opportunities for entrepreneurial drive and having a well-skilled population. Policies may also be directed toward encouraging collaborations with private industries to bridge the skills gap on what is required in the industry and what the population is being trained on. Such initiatives will drive investments towards infrastructure that integrates technology within the teaching and learning experience, preparing the workforce for a data-driven economy, and encouraging the participation of the population towards STEM fields. The study further submits increased financial injection towards human capital, which may be directed towards incentivising teachers, and obtaining adequate resources that are crucial for development, and will assist in addressing disparities.

7.6.5. CAPITAL

Increasing capital investments and initiatives have positive short-term and long-run impacts on economic growth, as the study's results highlight. The study recommends a further and more focused reform to ensure the effective use of capital to drive the economy. The study submits that capital should be heavily directed toward infrastructure development in areas related to telecommunications, transport, and energy, which drive economic activity. Well-built infrastructure facilities attract investments and pioneer job opportunities, and improve industry efficiencies and support. The study further submits that scrutiny be directed towards policy reforms to promote a more conducive

environment in the financial services sectors, to make it easy to obtain and use credit, and minimise bureaucracy to encourage investments to be directed towards machines and advancements in technology. Additionally, policies may be framed to align with sustainable development goals such as green growth initiatives, and renewable and environmentally friendly projects.

Policies should further be directed towards the country being an export-led economy which encourages investments to be channelled towards local production facilities to meet international demand. The policy may also advocate for extended regional economic integration through regional agreements, which will increase South Africa's market footprint, making it more competitive globally. As in the other recommendations, private-public collaborations are essential for driving investments as well as ensuring aligned developments are narrowed between both public and private. The implementation of these recommendations can play a pivotal role in increasing the capital margin in South Africa, which is essential for the growth of the economy.

7.6.6. LABOUR

The variable labour provided interesting yet contrary results. The study firstly recommends the development of policies that will set frameworks that promote training and education initiatives that are aligned with industries' needs, especially in a data-driven economy for the 4th Industrial Revolution. Such initiatives aid in bridging the gap between industry needs and skills available, and will ensure that the workforce is readily available and prepared for the continued developments in the technology world. Small Medium and Micro Enterprises play a key role in the creation of labour, therefore, support towards SMMEs through financial aid and easy regulatory requirements will aid in exposing the workforce to employment, which has a positive impact on economic growth. Policies should not solely focus on employee creation initiatives but also look towards employee retention solutions for people within the employment pool.

The blueprint set by banks in terms of employee retention may be adopted as a blueprint, to ensure that employed individuals continue being employed, and if they are employed for a sustainable timeframe, consumption will be encouraged. South Africa is one of the

countries with the highest number of unemployed youth, therefore, having noted the impact of labour on the economy, the study submits a stringent focus towards youth empowerment initiatives, policies developed during the Thabo Mbeki tenure, may be utilised as a base in developing and adopting such initiatives. Collaboration conducted by the Youth Employment Services (YES) needs to be expanded to reach more youth and get more private companies involved in the employment of the youth. In addition, the focus may also be directed towards the development of rural areas in agricultural projects that will encourage entrepreneurship, boost employment, and reduce migration to urban areas. Promoting such initiatives may increase the labour landscape in South Africa which will not only encourage employment but also ensure the labour is ready and available for advancements made in technology and can bridge the gap of skills needed in industries.

7.7. LIMITATIONS OF THE STUDY

The scope of the study is constrained by its use of proxy metrics for technological innovation, specifically the IRTII index. While the index is built with PCA, which captures essential aspects of technological innovation socially in the 4th Industrial Revolution, the study may not fully reflect the dynamic and varied nature of technological breakthroughs. The limitations of this study, particularly the use of the IRTII index as a proxy for technological innovation, may influence the study's outcomes by not fully capturing the dynamic and multifaceted nature of technological advancements in the 4th Industrial Revolution. While PCA ensures that essential aspects of technological innovation are considered, the reliance on a single index may introduce potential biases stemming from data selection or the exclusion of critical dimensions of innovation. These limitations could result in a narrower interpretation of the relationship between technological innovation and economic growth. To mitigate such constraints in future research, adopting a multi-index approach or integrating qualitative assessments alongside quantitative measures could offer a more comprehensive understanding of technological progress. Furthermore, expanding the dataset to include broader or more diverse metrics and ensuring robust cross-validation of indices would enhance the reliability and applicability of the findings, contributing to a more nuanced analysis of technological innovation's impact on economic development.

Secondly, while the study's emphasis on South Africa's economy is contextually important, the focus however restricts the findings' applicability to other economies with distinct structural and policy contexts. Comparative examinations of both established and emerging economies may provide insights into how certain contextual factors impact the effectiveness of technological innovation in supporting economic growth. Furthermore, future studies may further assess the roles of complementary factors including institutional quality, regulatory settings, and infrastructural capacity, which are expected to moderate the link between technological innovation and economic results.

Finally, while the study's analytical approach is robust, the study may benefit from alternative econometric models that account for nonlinear linkages and potential endogeneity difficulties, notably those linking technological innovation, human capital development, technology transfers and economic growth. Expanding the analytical methodology may provide a better understanding of how the factors interact dynamically over time, giving crucial insights for policymakers looking to optimise technological innovation plans for long-term growth.

Expanding the analytical methodology could significantly enhance the understanding of how various factors influencing technological innovation interact dynamically over time. A more robust methodological approach, such as integrating advanced econometric techniques like time-varying parameter models or panel data analysis, could reveal nuanced relationships and the evolving significance of key drivers such as human capital, R&D, and technology transfers. This would allow for a more granular examination of temporal and contextual shifts in how these factors contribute to economic growth, especially in response to policy interventions or external shocks. For policymakers, such insights would be invaluable in designing and fine-tuning innovation strategies, ensuring that resources are allocated effectively to areas that yield the highest long-term benefits. Additionally, expanding the methodological scope could help identify lagging variables or emerging trends, enabling proactive adjustments to innovation policies that support sustainable and inclusive economic growth in a rapidly evolving global landscape.

7.8. CHAPTER CONCLUSION

This dissertation set out to investigate the impact of technological innovation and its impact on economic growth in South Africa, particularly during the 4th Industrial Revolution. The primary objective was to construct a comprehensive model that integrates the 4th Industrial Revolution adjusted Technological Innovation Index (IRTII). The reconstructed model served to measure the impact of technological innovation in South Africa, with the primary aim of answering the research question: What is the link between technological innovation and economic growth during the industrial revolution in South Africa? The focus was on the role that digital adoption, education and technology transfers play in measuring the impact of technological innovation and economic growth in South Africa.

The key empirical findings from this research demonstrate that the IRTII has a positive long-run and short-run significant impact on economic growth. The key finding indicates a link between technological innovation and economic growth in South Africa. The results denote that the increase and promotion of the index coefficient have a considerable impact on the growth and level of economic growth in South Africa. However, after adjusting for one lag, technological innovation has a negative impact towards economic growth. The study assessed existing literature and assessed South Africa's current technological environment, in which the primary results denoted that South Africa has a complex technological innovation environment. Seven institutions have been established by the DSI to facilitate and execute different regulatory frameworks to ensure a friendly and flexible environment of technological innovation activities; however, the policy frameworks have not yielded positive results. Despite the limitations, the study makes the key recommendations for a more streamlined policy approach, that augments an ease in data-driven initiatives, and more active adoption of policies that pioneer the adoption and invention of digital approaches. The study further recommends an extended focus towards educational initiatives related to data-driven initiatives to ensure that the population is ready for any technological innovations.

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ANNEXURE A: LETTER FROM LANGUAGE EDITOR

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This is to certify that the dissertation entitled

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