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System Dynamics Perspective for Digital Maturity

Lekometsa Mokhesi

Prof. Nixon Ochara

A research report submitted to the Faculty of Commerce, Law and Management, University of the Witwatersrand, in partial fulfilment of the requirements for the degree of Master of Management in the field of Digital Business

Johannesburg, 2024

ABSTRACT

The advancement of the level of Digital maturity at a national level fosters a burgeoning digital economy for a country. Digital maturity is a critical determinant of economic growth and societal development in the modern era. However, South Africa, just like any developing country, faces significant challenges in advancing its digital maturity,

This explorative quantitative study applies Systems Dynamics (SD) modelling with the auspices of the DESI framework to assist policy/decision makers in understanding the dynamic and complex environment of digital maturity in South Africa's national context.

By utilising system dynamics archetypes, the study uncovered recurring patterns of behaviour that affect digital maturity development in South Africa. The development of the novel system dynamics models through stock and flow diagrams of each of the four dimensions of DESI was a pronounced and critical outcome of the study. The simulation of the models allowed an exploration of best-case and worst-case scenarios, highlighting how policy interventions impact digital maturity over time.

Based on the findings, it is recommended that policymakers and stakeholders prioritise sustained investment in digital infrastructure, particularly in broadband and 5G expansion, to ensure universal connectivity and affordability. The best-case scenario results demonstrate that high investment and low churn rates contribute to stable and accessible digital networks, fostering increased digital adoption. Additionally, boosting digital skills development through higher STEM enrollment, advanced digital training, and employment support for ICT professionals is crucial to building a digitally skilled workforce. This study highlights that reducing digital skills migration can further strengthen local expertise and innovation, reinforcing long-term digital transformation.

The application of system dynamics to the digital maturity index, such as the DESI framework, is novel in the study. This approach provides a holistic and structured approach to understanding the complexity involved in the digital maturity of a

country. Second, by modelling digital maturity using causal loop diagrams, the study contributes to the body of knowledge on how the components of digital maturity interact in a dynamic setting.

KEYWORDS

Digital Maturity, Systems Thinking, Systems Dynamics, Digital Economy, Complexity, ICT Competitiveness, Digital Economy Society Index

DECLARATION

I, _Lekometsa Mokhesi_____, declare that this research report is my own work except as indicated in the references and acknowledgements. It is submitted in partial fulfilment of the requirements for the degree of Master of Management in the field of Digital Business at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in this or any other university.

Name:Lekometsa Signature: L.Mokhesi

Signed at Midrand……

On the 05…….. day of December…… 2025…..

DEDICATION

To the departed, my father, Paul Motiki Mokhesi and my brother, Tota" Storsh" Mokhesi. May you continue to rest in eternal peace.
To my mother, 'Malipolelo Mokhesi.
To my sister, 'Lipolelo Mokhesi.
To my nieces, Mpho Mokhesi, Tumeliso Motsomi, and Palesa Motsomi.

ACKNOWLEDGEMENTS

To the Source of Life, the Primal Substance, for the awesome privilege of Life.
Thy Kingdom Come!
To My supervisor for his guidance and support throughout this research.
To My family, for their continual love and support.
To My friends for their encouragement.

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AI	Artificial Intelligence
AU	African Union
CLD	Causal Loop Diagram
DCDT	Department of Communications and Digital Technologies
DESI	Digital Economy and Society Index
DHET	Department of Higher Education and Training
EU	European Union
GDP	Gross Domestic Product
GITR	Global Information Technology Report
ICASA	Independent Communications Authority of South Africa
ICT	Information and Communications Technology
ILA	International Labour Organisation
ITA	International Trade Administration
ITU	International Telecommunication Union
NIE	National Information Ecology
OECD	Organisation for Economic Co-operation and Development
R&D	Research and Development
SADC	Southern African Development Community
SFD	Stock and Flow Diagram
SA-TIED	Southern Africa – Towards Inclusive Economic Development
SD	System Dynamics
SIM	Social Influence Model (of Technology Adoption)
TAM	Technology Acceptance Model
UNCTAD	United Nations Conference on Trade and Development
UTAUT	Unified Theory of Acceptance and Use of Technology

CHAPTER 1. INTRODUCTION

1.1 Statement of purpose

This quantitative study applies Systems Dynamics (SD) modelling to assist policy/decision makers in understanding the dynamic and complex environment of digital maturity in South Africa's national context. The advancement of the level of Digital maturity at a national level fosters a burgeoning digital economy for a country. However, it still presents a challenging phenomenon that necessitates the application of systems thinking approaches to understand its complexity.

1.2 Background of the study

Techtopia is an idealised design of a “Digitally Mature” country that balances digital innovation with human-centric values, sustainability, and inclusivity. It is a nation where digital services are seamlessly integrated into daily life, enabling economic growth, improving public services, and fostering a collaborative, informed, and empowered citizenry. Through this design, Techtopia not only leverages the power of digital technologies but also ensures that these innovations enhance the well-being of every citizen and protect the planet for future generations.

Unfortunately, the extant reality is far from this ideal for many countries, especially in Africa. In many developing countries, digital maturity levels remain low (Arbeláez-Rendón, 2023). Many developing countries often face significant challenges in advancing the level of their digital maturity due to factors such as limited infrastructure, low digital literacy, insufficient investment, and inadequate regulatory frameworks (World Bank Group, 2024). This results in limited economic growth, exacerbated social inequality, lower business productivity and limited access to public services by citizens.

Digital maturity has emerged as an important lynchpin for the digital economy. It has subsequently become ecumenically imperative to many leaders at different organisational establishments, i.e. departmental, corporate, country-level and

continental. The degree of digital maturity is a measure of the state (stage) of development of a company, the economy of a given country, or a group of countries in the implementation and use of digital technologies to achieve their objectives (Calabrese et al., 2020; Ghauri et al., 2021).

The level of a country's digital maturity significantly influences the growth and development of its digital economy. According to the World Bank Group (2024), the availability and use of digital technologies are strongly linked to economic growth, innovation, job creation, and inclusion at both the national and regional levels. A high level of digital maturity enables countries to capitalise on digital transformation, fostering innovation, improving productivity, and driving economic growth (World Bank Group, 2022). In contrast, countries with a low level of digital maturity face barriers that can slow down or inhibit the expansion of their digital economies (Adhikari & Tesfachew, 2024). The relationship between digital maturity and the digital economy is one of causality and reinforcement.

The development of the digital economy is important for driving economic growth (Dahlman et al, 2016), fostering innovation (Oloyede et al, 2023), promoting global connectivity (ITU & UNESCO, 2024), improving efficiency and productivity, creating jobs, advancing social inclusion and contributing to environmental sustainability (Oloyede et al, 2023). Embracing digitalisation can unlock new possibilities for individuals, businesses, and societies to thrive in the digital age.

The development of the digital economy presents burgeoning opportunities for the African continent. Due to its impending impacts on various sectors of the economy, such as agriculture, commerce, government, education, health, transportation, and many others (Dahlman et al, 2016). Following the omnipresent maxima that the digital economy is now seen as one of the important cardinals for the growth, development, and prosperity of countries, as it aids job creation, entrepreneurship, and innovations (Oloyede et al, 2023), the development of the digital economy is pertinent and forms part of many countries' and continents' mandates, economic policy agendas, and programmes with the African continent being no exception. For instance, the European Union (EU) has chartered what has been termed "The Digital Decade", which is a comprehensive and holistic approach to digital transformation, to position Europe as a global

leader in the digital economy by 2030 (European Commission, 2021). Correspondingly, the growth and development of the digital economy form part of the African Union's Digital transformation strategy for Africa (2020 – 2030) (African Union, 2020).

Several countries have significantly benefited from advancing the level of their digital maturity, an impetus to a thriving, innovative and modern digital economy, demonstrating various positive impacts across economic growth, employment, and overall societal advancement.

China: For several years, China has prioritised innovation-driven development and digital infrastructure construction. The importance of building digital infrastructure was recognised as early as 2006 with the release of the National Informatisation Development Strategy (2006–2020) (Borodyna, 2021). China's digital economy has grown tremendously, with e-commerce giants like Alibaba and JD.com driving significant online retail sales. China has invested heavily in digital infrastructure, including expanding high-speed internet access across urban and rural areas. The rollout of 5G networks has further enhanced connectivity and supported the growth of the Internet of Things (IoT). The Chinese government's "New Infrastructure" initiative focuses on developing 5G networks, data centres, artificial intelligence, and industrial internet to support future growth.

Singapore: Singapore was ranked second in the world according to national digital transformation evaluations conducted in 2018 using the Global Connectivity Index (GCI) (Huawei, 2018). Singapore has invested heavily in its Smart Nation initiative, focusing on harnessing technology to enhance urban living, government services, and business competitiveness. The city's advanced digital infrastructure and supportive regulatory environment have made it a global hub for tech startups and digital innovation (Putri et al., 2023).

In contrast, the level of digital maturity remains low in the African continent, particularly in Sub-Saharan Africa (World Bank Group, 2024). According to UNCTAD (2023a), only an average of 37% of Africa's population uses the Internet compared to 87% and 91% in America and Europe, respectively. Internet use

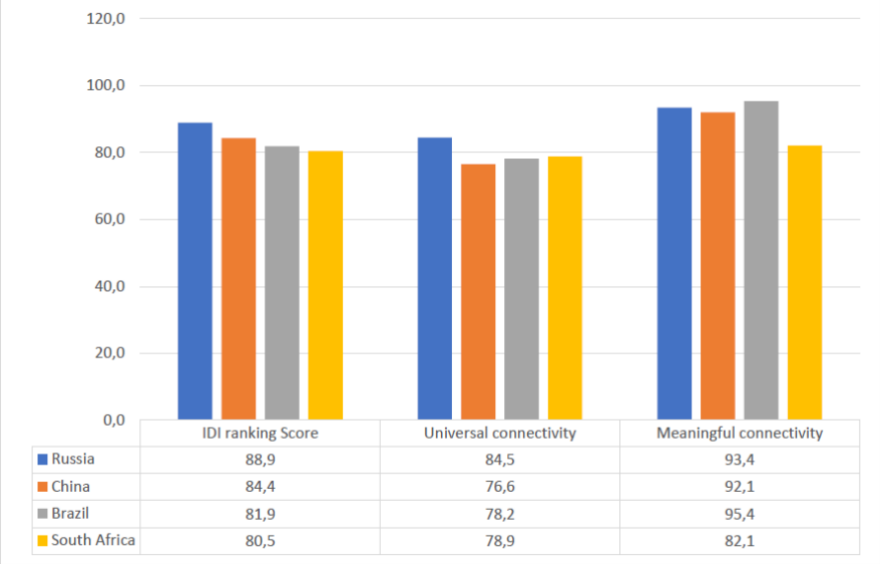
remains tightly linked to the level of a country's digital economy (ITU, 2023). In the 2023 Technology and Innovation report, only South Africa and Mauritius make it in the top 100 countries on the frontier technology readiness index, with South Africa ranking 56th, 71st on ICT infrastructure and 77th on ICT Skills. Mauritius ranks 73rd with 96th on ICT infrastructure and 57th on ICT Skills (UNCTAD, 2023a).

In this regard, the report also highlights a significant decline in the ranking of some African countries from 2021 to 2022. Namibia moved from 91st to 104th, while Kenya saw a 12-point decrease from 105 to 117. Other countries that also experienced a decline are Ghana, Rwanda, Zimbabwe, and Ethiopia. These rankings reflect the persistent challenges in developing the digital economy in Africa. Furthermore, no African country appears among the top exporters of frontier technologies (UNCTAD, 2023b). Bukht & Heeks (2017) advocate for further research to understand the barriers to and impacts of the digital economy in developing countries.

The 2023 IMD World Digital Competitiveness Ranking assessed the capacity of 64 economies to leverage digital technologies for economic and social transformation, based on three key factors: knowledge, technology, and future readiness (IMD, 2023). South Africa improved to 58th place in 2022 and maintained the same spot in 2023 after experiencing a significant decline to 60th place in 2020 from 48th place in 2019 (IMD, 2023). The country's knowledge rating declined from 54th in 2022 to 58th due to the decline in the attraction of foreign digital/technological skills and insufficient training and education in ICT (IMD, 2023). Adaptive attitudes remained constant in position 57, while business agility increased from 57th place to 54th place due to "an increased private sector response to opportunities and threats" IT integration saw a one-point decline from position 55 as the "Private-public partnership persisted in experiencing huddles (IMD, 2023).

In the G20 cluster, South Africa is penultimate in the ranking of the development of the digital economy, with the least developed being Argentina, according to the IMD World Digital Competitiveness Ranking 2023. Argentina ranks 61st, and South Africa, Brazil, India, Saudi Arabia, and China rank 58th, 57th, 49th, 30th and 19th, respectively (IMD, 2023). The ITU ICT Development Index 2023

corroborates similar rankings (ITU, 2023). In a similar vein, South Africa ranks the lowest amongst the BRICS countries, as depicted in Figure 1 below.



	IDI ranking Score	Universal connectivity	Meaningful connectivity
Russia	88,9	84,5	93,4
China	84,4	76,6	92,1
Brazil	81,9	78,2	95,4
South Africa	80,5	78,9	82,1

Figure 1: Source ITU - South Africa IDI ranking score compared to BRICS countries 2023.

Over the years, different theories have been applied to understand various facets or dimensions of the advancement of what is now referred to as “digital maturity” and the slow progress thereof, especially in developing countries. These include the Digital Divide Theory, the Unified Theory of Acceptance and Use of Technology and the Technology Acceptance Model (TAM), amongst others. Furthermore, studies in conjunction with several digital maturity indices have revealed that digital infrastructure, digital skills, technology integration and digital public services fundamentally and positively impact the advancement of the level of digital maturity (Shibambu, 2024; European Commission, 2016). These components have not been studied together in the context of the initiatives geared at increasing the level of digital maturity in a developing country such as South Africa. Each of these theories provides a different lens, although limited, through which to analyse the slow progress of digital maturity in developing countries, highlighting this issue's multifaceted, complex, and dynamic nature. Consequently, this provides an opportunity to study this complex phenomenon and produce new knowledge under the auspice of Systems Dynamics.

European Parliament (2015) describes the digital economy as a complex structure of several levels/layers connected by an almost endless and always-growing number of nodes. System Dynamics is a useful tool for understanding complex systems (Sterman, 2000). Using system dynamics, various factors, interactions, and feedback loops that influence the development of the digital economy in a dynamic setting can be modelled Using system dynamics, various factors, interactions, and feedback loops that influence the development of the digital economy in a dynamic setting can be modelled. This approach can allow the identification of leverage points for intervention, predict the impacts of various policies, and develop strategies to accelerate the advancement of a country's digital maturity (Mokgohloa et al., 2023; Liao et al., 2023; Armenia, S., et al., 2021). It can also help in visualising how improvements in one area (e.g., infrastructure) can have cascading positive effects on other areas (e.g., digital service adoption), ultimately leading to a more robust and inclusive digital economy (Mokgohloa et al., 2023).

1.2.1 *Context: South Africa's Rainbow Nation*

This study draws on Avgerou (2001), who argued that context is significant in understanding the development of information systems in organisations. Hence, the unit of analysis of the complexity embedded in the advancement of digital maturity of a country must characterise complexity. South Africa is the epitome of a complex country due to its *sui generis* mix of socio-economic, historical, and political factors. As a nation, it faces both the challenges of a developing country and the advanced economic infrastructure of a more developed one, leading to significant contrasts. Case in point, in the bigger cities as well as in the metropolitan areas, highly advanced technology and infrastructure can be found; however, access to even the most basic technologies is lacking in townships, smaller towns and rural regions (Venter & Daniels, 2020). The legacy of apartheid has left deep inequalities in wealth, education, and infrastructure, which continue to affect the country's development, including its digital and economic growth (Makgetla, 2020). This is corroborated by a report by Twinomurinzi et al. (2021) that highlights that in South Africa, people in urban areas are more in tune with the interconnected ethos of Industry 4.0 due to their significantly more engaged

digital behaviours. People in rural and township regions are at the digital usage stage, and those living in peri-urban areas are at the point of having access to digital technology but not utilising it. In peri-urban areas, access to digital technology remains a huge challenge (Twinomurinzi et al., 2021). Furthermore, the heterogeneity of South Africa's population, comprising a wide range of ethnic, linguistic, and cultural groups, presents significant challenges for the formulation of policies that equitably address the needs of all citizens (Mophosho et al, 2022).

Economically, South Africa has a strong industrial base and is a leader on the African continent, yet it also faces high levels of unemployment (StatsSA, 2024a), poverty (Amnesty International, 2020), and political instability (Tsagae, 2023) notwithstanding. The country's urban-rural divide complicates infrastructure development, particularly regarding access to digital technologies. South Africa still faces challenges in fully leveraging digital technologies for the development of its digital economy (Abrahams et al., 2022). Over the last 5 years, South Africa invested an average of 1,986 (US$b) in telecommunication spending (ICASA, 2024). With these significant investments, South Africa still ranks low in global digital economy development rankings (IMD, 2023; ITU, 2023).

South Africa's position in global trade, its strategic economic role in Africa, and its complex governance systems make it a compelling but challenging context for researchers to examine digital maturity.

1.3 Research problem

Digital maturity at the country level is a complex phenomenon due to the intricate interplay of infrastructure development, digital skills, regulatory frameworks, social factors, economic disparities, political will, technological innovation, and international dynamics (Němečková, 2021). This complexity results in a variety of short-term, long-term, and unintended effects. These include:

- The digital divide, not only between countries but also within countries (urban vs. rural, affluent vs. marginalised communities), further exacerbates inequalities in access to technology and opportunities (World Bank Group, 2016).

- A global and regional fragmentation of digital readiness, where leading countries push the boundaries of innovation while others struggle to catch up (UNCTAD, 2021).
- A growing economic divide between digitally mature economies and less advanced ones affects global trade patterns and the ability to compete in the digital marketplace (Dahlman et al., 2016).
- Social polarisation between digital adopters and laggards, with potential for both increased inclusion and exclusion depending on how well digital education and inclusion efforts are managed (World Bank Group, 2016).

Consequently, the understanding of how elements of digital maturity interact over time is imperative for policymakers to address both immediate needs and long-term goals. The understanding will foster coordinated efforts across multiple dimensions, long-term investment, and adaptive policies to ensure countries can fully participate in and benefit from the global digital economy. Therefore, having a nuanced understanding of the many factors that contribute to the slow advancement of South Africa's digital maturity is imperative.

This study, therefore, demonstrates the use of system dynamics to analyse and model the key factors contributing to the slow advancement of digital maturity in South Africa.

1.4 Research Questions

1. What are the systemic feedback structures and barriers that influence the development and utilisation of digital skills in South Africa?
2. Which dynamic factors contribute to the persistent lag in digital infrastructure development in South Africa, and how do they interact over time?
3. How do systemic factors inhibit the adoption of Industry 4.0 technologies (e.g., AI, blockchain, IoT) in South Africa's digital ecosystem?
4. How can system dynamics modelling support strategic decision-making and policy interventions to accelerate national digital maturity in South Africa?

1.5 Research Objectives

This explorative quantitative study aims to apply System Dynamics (SD) modelling to assist policymakers and decision-makers in understanding the dynamic and complex environment of digital maturity in South Africa's national context. The study seeks to identify and model the feedback loops, delays, and interdependencies that influence digital maturity at a national level.

To address the research questions, the following propositions are formulated and tested through causal loop diagrams and stock-and-flow models:

Proposition 1: Underinvestment in digital skills, coupled with low ICT graduate output and high levels of ICT skills migration, inhibits the effective development and utilisation of digital skills in South Africa.

Proposition 2: Low investment in ICT infrastructure, combined with affordability constraints and low adoption of digital services, slows the development of digital infrastructure.

Proposition 3: The adoption of Industry 4.0 technologies (e.g., AI, blockchain, IoT) is hindered by both underinvestment in technology and a shortage of relevant digital skills.

Proposition 4: Insufficient investment in digital technologies and skills hampers the digitalisation of public services and reduces citizen adoption of e-government services.

These propositions will be conceptually tested through modelling and simulation and empirically validated using simulation data. Furthermore, the models that include feedback structures (delays, reinforcements, etc.) will be explored in relation to these propositions.

1.6 Rationale

The advancement of a country’s digital maturity presents a plethora of challenges. The complexity presented by these challenges necessitates applying

and utilising tools native to studying complex interactions within systems in dynamic settings. System Dynamics is a best fit for understanding intricate interactions within complex dynamic systems.

Digital maturity can be defined as a complex system because it involves multiple interacting dimensions (technology, policy, education, society), is shaped by nonlinear feedback loops and time delays, and requires continuous adaptation and learning. It is also sensitive to initial conditions and external shocks, and it is embedded within a global network of digital actors and trends.

There is a paucity of research on how dynamic modelling approaches and techniques can be used to increase an understanding of the advancement of the digital maturity of a country. Understanding digital maturity through the lens of a complex dynamic system can provide valuable insights for policymakers, businesses, and other stakeholders in South Africa seeking to navigate its complexities, harness its potential, and address its challenges effectively.

The rationale for applying system dynamics to the development of digital maturity involves understanding and modelling the complex interrelationships among various factors that influence the growth and evolution of digital technologies, industries, and ecosystems. System dynamics provides a powerful framework for analysing feedback loops, time delays, and nonlinear relationships within the digital economy, allowing policymakers, businesses, and researchers to better understand the dynamics of technological innovation, adoption, and diffusion. The application of system dynamics involves recognising and understanding the intricate and interconnected elements that contribute to the advancement of a country's digital maturity.

Furthermore, the DESI index was chosen over other digital maturity indices because it provides a comprehensive and structured framework that evaluates multiple dimensions critical to a country's digital maturity. Unlike other indices that focus solely on connectivity or technological readiness, DESI integrates four key dimensions, namely digital skills, digital infrastructure, technology integration, and digital public services. These four dimensions offer a holistic assessment of digital maturity. Additionally, DESI is widely recognised within European policy

frameworks, making it a well-established and standardised measure that can be adapted for global comparisons. Its quantifiable indicators enable effective system dynamics modelling, allowing for the simulation of policy interventions and long-term digital development trends.

The DESI framework provides a comprehensive and policy-relevant framework, making it particularly suitable for System Dynamics modelling of digital economy development. Unlike other indices such as the Network Readiness Index (NRI), Global Connectivity Index (GCI), or ICT Development Index (IDI), DESI conceptualises digital transformation as a dynamic and interconnected system comprising four key dimensions—Digital Skills, Digital Infrastructure, integration of digital technology, and digital public services. These dimensions are interdependent and generate feedback loops that align naturally with System Dynamics principles.

Furthermore, DESI's annually updated, multidimensional data enable longitudinal analysis of policy impacts, while its structure allows for the simulation of causal relationships across subsystems, such as how improvements in digital skills influence technology adoption or public service delivery. Because DESI is grounded in EU policy frameworks, its indicators are both actionable and interpretable, facilitating effective policy experimentation and communication of model outcomes. Collectively, these characteristics make DESI a more robust and dynamic tool than other indices for analysing the systemic evolution of digital maturity and its socio-economic effects.

As one of the largest and most developed economies in Africa, South Africa serves as a regional economic hub with significant potential for digital transformation and serves as a blueprint or case for other developing African countries. However, despite its relatively advanced infrastructure and digital skills compared to many other African countries, South Africa still faces challenges in fully leveraging digital technologies for economic growth.

Government agencies and policymakers can use insights from the study to inform the design and implementation of policies, strategies, and regulations aimed at accelerating the development of their digital maturity, promoting digital inclusion,

and fostering economic growth. By understanding the barriers to progress and identifying opportunities for intervention, policymakers can develop targeted initiatives to address key challenges and unlock the potential of the digital economy.

The system dynamics models presented in this study provide a framework for designing, evaluating, and refining policy interventions. Policymakers can use models to simulate the effects of policy changes, such as investment strategies, on key performance indicators for the advancement of digital maturity.

System Dynamics has been applied in different areas, such as health care (George et al, 2023; Sansone et al, 2022), urban development (Wang et al, 2024), and supply chain (Khakdaman et al, 2024) amongst many, this research contributes to and extends the body of knowledge by demonstrating System Dynamics's applicability in a new discipline of digital maturity at a national level.

1.7 Delimitations of the study

This study focuses on the complexity embedded in digital maturity at a country level by applying system dynamics to understand the interplay between the different elements that constitute digital maturity in a dynamic setting. Firstly, the unit of analysis is South Africa, also referred to as “The Rainbow Nation” because of its diverse culture. Second, the model boundary chart below delineates the focus areas for assessing the digital maturity level through the DESI framework lens. The model explicates the Endogenous variables, which are Digital Skills, Digital Infrastructure, Technology integration and Digital Public Services. The Exogenous variables are the Rate of Technological change and Climate change, and offline activities are excluded from the model.

Table 1: Model Boundary Chart for Digital Maturity

ENDOGENOUS	EXOGENOUS	EXCLUDED
DIGITAL SKILLS	Rate of Technological Change	Climate Change
DIGITAL INFRASTRUCTURE		Offline Activities
TECHNOLOGY INTEGRATION		
DIGITAL PUBLIC SERVICES		

1.8 Definition of terms

TERM	DESCRIPTION	REFERENCE
DIGITAL MATURITY	A learned ability to respond to the environment appropriately, to become good at digital transformation	(Chanias & Hess, 2016; Armstrong & Lee, 2022)
DIGITAL ECONOMY	The use of Information and Communication Technologies (ICT) to offer digital products or services	(UNCTAD, 2019; Oloyede et al, 2023)

	and become an instrument for the social and economic development of countries.	
COMPLEXITY	Complexity in social systems refers to the intricate and interdependent relationships among individuals, groups, and institutions that give rise to emergent behaviour.	(Mesjasz, 2010)
SYSTEMS THINKING	Systems thinking is a way of analysing and understanding complex systems by examining their parts and their interrelationships, rather than focusing on individual elements in isolation. It involves seeing the big picture and recognising how different parts of a system are interconnected and interdependent.	(Von Bertalanffy, 1950; Beer, 1974)
SYSTEMS DYNAMICS	System dynamics is a theoretical framework and methodology that builds upon systems theory to model and analyse the behaviour of complex systems over time. It is based on the concept of feedback loops and the idea that changes in one part of a system can have cascading effects throughout the entire system.	(Forrester, 1971; Sterman, 2000)

1.9 Assumptions

This research assumes that digital maturity at a national level can be described as a complex system, with elements such as digital infrastructure, digital skills, technology integration, and digital public services that interact with each other in a dynamic setting to produce dynamic behaviour.

1.10 Organisation of the Research

The research is arranged into six chapters. Chapter 1 presents the background of the research, the context of the study, the research aim, the research questions and rationale, and the scope and limitations of the study.

Chapter 2 explores (i) the literature review relating to Digital Maturity, Digital Economy and the dimensions of the DESI framework, which are Digital Skills, Digital Infrastructure, Technology Integration, and Digital Public Services. (ii) The theoretical framework of Complexity using Systems Thinking and System Dynamics is introduced and discussed. (iii) Finally, the conceptual framework is discussed.

Chapter 3 explores the research methodology and its respective tenets. The chapter also introduces the System Dynamics modelling methodology used in the study as per the conceptual framework.

Chapter 4 articulates the model's development. This entails the system dynamics archetypes to explain the extant digital maturity in South Africa. Second, the chapter details in depth the causal and correlation relationship between the variables (dimensions, sub-dimensions, and indicators) that constitute the DESI framework. The chapter further provides a generic conceptual model overview that describes the interaction of the variables in a dynamic setting in the form of a subsystem diagram. Lastly, the model development is discussed with the qualitative models represented as causal loop diagrams and the quantitative models represented as stock and flow diagrams.

Chapter 5 discusses model verification and validation, and the policy design, followed by the simulation results.

Lastly, Chapter 6 articulates the conclusion, limitations of research, recommendations and contribution to the body of knowledge.

The structure of the research is depicted in Figure 2 below.

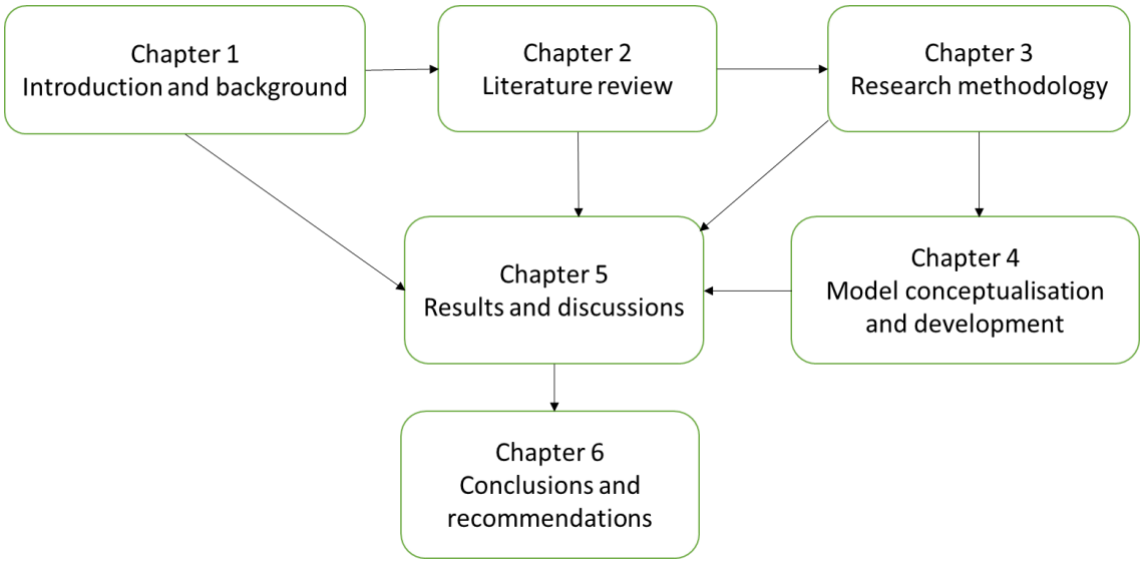


Figure 2: The research structure

CHAPTER 2. LITERATURE REVIEW AND THEORETICAL FRAMEWORK

2.1 Introduction

In this section, literature on Digital Maturity, Digital Economy, Complexity and Systems Thinking are explored, reviewed, and discussed to extract insights from previous research. The problem of understanding the factors that contribute to the slow progress of advancing a country's level of digital maturity is increasingly being discussed by researchers and thus also presented in this research. The conceptual framework that guides the research concludes the chapter.

2.2 Digital Maturity

2.2.1 *Definition*

Since the inception of the concept of digital maturity, there has been a haze of terminology (Vial, 2019; Kurmann & Arpe, 2019). What is digital maturity? There has been a debate in the literature as regards the definition of maturity in the context of "Digital Maturity". The dictionary definition of "Maturity" ranges from "the quality or state of being mature" to "a very advanced or developed form or state". These definitions imply that "Maturity" is an end state that can be reached. This is supported by Lahrmann et al. (2011), who define maturity as a state of being complete, perfect or ready. En passant, there's a second school of thought that considers "Maturity" from the field of psychology, which defines "Maturity" as the ability to respond to the environment in an appropriate manner (Wechsler, 1950). This is in concert with Armstrong & Lee (2022), who define Digital Maturity as "a learned ability to respond to the environment appropriately, to become good at digital transformation.

Regardless of the dichotomy of the definitions of maturity and the duality of continuous and complete, the consensus is that digital maturity refers to an organisation's effectiveness and efficiency in utilising digital technologies and

capabilities to achieve its business goals and adapt to a rapidly evolving digital landscape (Kane et al., 2017; Shahiduzzaman et al., 2017). It is a measure of an organisation's ability to leverage digital tools, processes, and strategies to drive innovation, improve customer experiences, optimise operations, and stay competitive in the digital age. Chanias & Hess (2016) define digital maturity as “the state of a company’s digital transformation” or "what a company has already achieved concerning transformation efforts".

In an increasingly digitalised environment, gaining digital maturity is synonymous with companies gaining and/or preserving competitiveness (Thordsen et al., 2022; Zaoui and Souissi, 2022). Chanias & Hess (2016) also purport that the digital “Digitaris”, which is the highest level of maturity, implies that a company has implemented the newest digital trends and coordinated them with a strong vision and digital culture, resulting in effective value creation. Consequently, they have a competitive advantage and outperform other companies in their industry. The terms digital maturity and digital transformation are sometimes erroneously used interchangeably.

Digital maturity is not a one-time achievement but rather a continuous journey as organisations strive to keep pace with technological advancements and evolving customer expectations. Organisations at higher levels of digital maturity are more likely to be agile, innovative, customer-centric, and capable of responding quickly to changes in the digital landscape (Thordsen et al, 2022; Zaoui & Souissi, 2022; Çallı & Çallı, 2021).

2.2.2 *Categories*

Digital maturity can be analysed at different granularities, including departmental (Thomas, 2020), organisational (Thordsen et al., 2022), country (Brodny & Tutak, 2023), and continent-wide (African Union, 2020; European Commission, 2016) scopes. Each level reflects the degree to which digital tools and processes are integrated and utilised for achieving operational, social, or economic benefits.

Departmental Level:

- At the most granular level, departments within organisations may have different levels of digital maturity. Some departments might excel in adopting digital tools, such as analytics, automation, or digital communication platforms (Thomas, 2020), while others might lag due to resource constraints or cultural resistance. The focus here is typically on efficiency, automation, and data-driven decision-making. Thomas (2020) examines the challenges that Human Resources (HR) departments in German Small and Medium-sized Enterprises (SMEs) face regarding digital transformation and how these departments struggle with digitalisation, underutilisation of data, and lack of integration with other IT systems within their organisations.

Organisational Level:

- A plethora of research from both academia and industry has been dedicated to measuring digital maturity at an organisational level (Westerman, 2014; Gill & VanBoskirk, 2016; Kane et al., 2017; Deloitte, 2018; Cogbet et al., 2019). At this level, digital maturity assesses how well an organisation incorporates digital transformation across its business model, operations, and culture. Companies with high digital maturity leverage data analytics, cloud computing, digital supply chains, and AI, creating more agile and responsive structures (Çallı & Çallı, 2021). Organisational maturity involves fostering a digital-first mindset, ensuring employees have the necessary skills, and aligning technology with strategic objectives.

Country Level:

- National digital maturity reflects how a country develops and integrates digital infrastructure, skills, governance, and innovation into its economy and public services. Countries with advanced levels of digital maturity benefit from robust broadband infrastructure, high digital literacy, advanced regulatory frameworks, and thriving digital industries (ITU, 2018).

2.2.3 *Measuring Digital Maturity*

How is digital maturity measured? At an organisational level, the usefulness of maturity models has been pondered upon by Zaoui and Souissi (2022). Within the past decade, a plethora of maturity models have emerged from the industry (VanBoskirk et al., 2017; Kane et al., 2017) and academia (Ifenthaler & Egloffstein, 2020; Salviotti et al., 2019). These models provide a framework to assess on a high level the digital maturity of organisations along a well-defined evolution path (Colli et al., 2018). Digital maturity assessment enables the identification of the level of digital maturity of the company, which is now considered a corporate key characteristic (Zaoui and Souissi, 2022). Aras & Büyüközkan (2023) define maturity assessment as a process of evaluating an organisation's level of digital maturity by assessing its capabilities, readiness, and progress in implementing digital technologies to transform its business operations and remain competitive in the digital age.

2.2.4 *Measuring Digital Maturity at a Country Level*

At a country level, the irrefutable importance of advancing the level of digital maturity for countries necessitates measuring its progress. The digital maturity models described above were designed for enterprises. Most of these models are complex and ill-suited to measure digital maturity at a country level and would require a collection of large data sets (Brodny & Tutak, 2023). Several indices offer valuable insights into the level of digital maturity's evolution, its impact on societies and economies, and the factors driving the digital economy. They serve as important tools for policymakers, businesses, researchers, and other stakeholders to monitor progress, benchmark performance, and inform evidence-based decision-making in the digital age. These indices include the Digital Economy and Society Index (DESI) (European Commission, 2016), Digital Adoption Index (DAI) (World Bank Group, 2016), and Networked Readiness Index (NRI) (Kirkman et al., 2002), amongst others.

2.3 The Digital Economy

As previously postulated, digital maturity has emerged as an important lynchpin for the digital economy. The conceptualisation of the term "digital economy" is attributed to Don Tapscott, who coined the term in his 1996 book, *The Digital Economy: Promise and Peril in the Age of Networked Intelligence*. Tapscott's work emphasised the transformative impact of digital technology on business, communication, and society. His insights highlighted how the integration of computers, the internet, and telecommunications was reshaping economic activities and the nature of work (Tapscott, 1996). In the late 1990s, various government and academic reports began to use the term "digital economy" to describe the economic shift resulting from digital technologies. These reports highlighted the transformative potential of the Internet and related technologies on economic activities (Unidos & Margherio, 1998).

In early 2000, electronic commerce (E-commerce hereafter) was added as a segment to fuel economic activities in the description of the digital economy. Mesenbourg (2001) similarly segments the digital economy into the production of ICT infrastructure and the use of ICTs for other economic processes. But in the latter category, he starts to look beyond the spotlighting of e-commerce to also add the use of ICTs to conduct other business processes. Previous concepts have been used in the past to describe what is today referred to as the digital economy. These include the “information economy” and the “network economy”.

The United Nations defines the digital economy as the “use of Information and Communication Technologies (ICT) to offer digital products or services and become an instrument for the social and economic development of countries” (UNCTAD, 2019).

2.4 Analysing the challenges of advancing the level of digital maturity in countries

System Dynamics applications that explicitly model a country’s digital economy remain relatively scarce: most published work uses system dynamics to analyse sectoral or policy subsystems (e.g., SMEs, public-sector digitalisation, energy or

environmental impacts) rather than constructing comprehensive, national-level digital-economy models (which require extensive, disaggregated time-series data and cross-sectoral calibration)(Jonsdottir et al, 2024; Fabolude et al, 2025). Moreover, while composite indices such as the DESI (European Commission, 2016), the GCI (Huawei, 2018), and the IDI (ITU, 2020) provide the kind of multidimensional, policy-relevant indicators that would readily map onto stocks, flows and feedbacks in system-dynamics models, few studies to date have systematically integrated these indices as core inputs for national SD simulations, researchers instead typically rely on bespoke, sectoral datasets or indicator subsets mentioned on the above indices. Digital, there is both a methodological opportunity and a data-driven need for research that couples established digital-economy indices with System Dynamics frameworks to simulate policy interventions and long-run dynamics at the country scale.

Oosthuizen & Manzini (2022) explore how systems thinking can help organisations, policymakers, and individuals navigate the complexities of the digital economy. It emphasises the interdependence between technology, people, and institutions, advocating for a holistic approach to digital transformation. Although, the research applies the broader concept of Systems Thinking, it does not employ System Dynamics on a maturity model.

2.5 Digital Economy and Society Index (DESI)

This research adopts the Digital Economy Society Index (DESI) as a framework to measure the advancement of digital maturity in South Africa. DESI is an index published by the European Commission that tracks the digital performance and progress of European Union (EU) member states (European Commission, 2016). The DESI framework provides a comprehensive assessment of how well EU countries are adapting to digital transformation and leveraging digital technologies for economic growth, innovation, and societal development (European Commission, 2016). The DESI dimensions are Digital Infrastructure, Digital skills, technology integration and digital public services. Each of these dimensions will be explored in detail in the succeeding section. It should be noted, however, that this research does not apply DESI to rank South Africa according

to the DESI ranking but rather applies System Dynamics to the DESI framework to suggest policy options per the System Dynamics models simulation.

The DESI framework does not come without limitations, especially when applied to a non-EU country such as South Africa. First, contextual misalignment occurs because DESI's indicators were developed to reflect EU policy priorities, regulatory environments, and infrastructural baselines that differ substantially from those of developing economies (European Commission, 2016). For example, the weighting of components such as digital public services and integration of digital technology assumes the existence of advanced e-government systems and widespread broadband access, which may not yet be comparable in emerging contexts. Second, as it would be discussed in the unit of analysis in Chapter 3 of the research methodology the data availability and standardisation present challenges: many of DESI's indicators rely on harmonised Eurostat datasets and survey instruments that have no direct equivalents in non-EU developing countries, leading to measurement inconsistencies and gaps. These limitations suggest that DESI's application outside the EU requires significant contextual adaptation and the inclusion of locally relevant indicators to ensure analytical validity and policy relevance.

2.6 Systemic Barriers to the Development of Digital Skills

The first component of the DESI framework is digital skills. The advancement of the level of digital maturity, particularly in developing countries, faces significant problems related to the lack of qualified people to be part of the ecosystem companies (OECD, 2016b; Němečková, 2021). The research study by Cogburn & Nyaki Adeya (2001) at the dawn of the 21st century already uncovered that South Africa's greatest challenge to harness the digital economy comes in the form of human capacity. There is a dire shortage of people with the skills necessary for growth in the economy and the ICT industry. Furthermore, the current South African post-school education model is unlikely to be able to expand to meet the backlogs in skills development, much less the additional skills pipeline required for an inclusive and competitive digital economy (Abrahams et al., 2022). Insufficient skills are often mentioned as an impediment to effective

ICT use (ITU, 2020). Digital skills are important because they underpin how we interact and how modern work is conducted. For many modern professions, digital skills are essential life skills. The digital skills required in the workplace are more advanced, and companies and institutions – both public and private - expect most of their employees to have them (European Commission, 2022). Additionally, digital literacy and skills training are essential to harness the potential of the digital economy. What are the systemic barriers and bottlenecks hindering the effective development and utilisation of digital skills in South Africa, and how can system dynamics modelling be used to identify leverage points and intervention strategies to overcome these challenges? The following sub-sections will discuss some of the key metrics that constitute barriers to digital skills development. These metrics will all be used construct causal loop and stock and flow diagrams in the modelling and simulation

2.6.1 *Investment in Digital Skills*

Investment in digital skills is a lynchpin to the development of digital skills. It impacts every aspect of education, from providing the necessary technology and training for teachers to developing a comprehensive curriculum and ensuring equitable access for all students (UNESCO, 2023). As digital skills become increasingly vital in the modern world, adequate and strategic investment in education is essential to prepare individuals for future challenges and opportunities.

2.6.2 *Digital Divide*

In regions with a significant digital divide, fewer professional development programs may focus on digital skills. Without reliable internet or up-to-date hardware and software, they cannot practice or learn digital skills (Chetty et al, 2018).

According to Marwala (2019), South Africa is a rapidly evolving society that is marked by extreme inequality and injustice; despite the enormous benefits

provided by digital technologies, the digital divide cannot be overlooked, which is similar to many other divisions in our country. According to ICASA (2023), in 2022, 21.4% of homes in South Africa had fixed-line access to the internet. Households in metro areas (at 21.4%) accounted for most of this connectivity, followed by the urban areas at 10.7%. Rural areas, however, only accounted for 1.6% of mobile broadband connectivity, demonstrating a geographic digital divide between metropolitan, urban, and rural areas.

2.6.3 *ICT Skills Migration*

When skilled professionals, especially those in the digital and technology fields, migrate to other countries, the origin country loses valuable expertise and experience. This can lead to a dire shortage of qualified individuals capable of training others, innovating, and driving digital advancements. Skills migration negatively affects a country's growth prospects since human capital formation is now viewed as a central engine of growth (Docquier & Rapoport, 2009).

2.6.4 *Foreign Skills Attraction*

The attraction of foreign skills can be a significant catalyst for the development of digital skills in the host country (Beerli, Indergand, & Kunz, 2023). It brings advanced knowledge, promotes innovation, and enhances global competitiveness. In 2019, there were 4.2 million immigrants and 824,000 South Africans residing elsewhere. Overall, it is a net recipient of migrants, but it loses more skilled workers than it receives (SA-TIED, 2021).

2.6.5 *ICT Graduates*

The rapid integration of digital technologies across various sectors has heightened the need for professionals with advanced transversal ICT competencies. Increasing the number of ICT graduates ensures that industries have access to the expertise required to innovate and maintain competitiveness (OECD, 2016a).

Given the role that investment in digital skills, skills migration and the production of ICT graduates play in developing and utilising digital skills, the following proposition can be formulated.

Proposition 1: Underinvestment in digital skills, coupled with low ICT graduate output and high levels of ICT skills migration, inhibits the effective development and utilisation of digital skills in South Africa.

2.7 Key factors in digital infrastructure development

The second dimension of the DESI framework is Digital Infrastructure. Without the appropriate digital infrastructure, it is impossible to implement the digital technology which underpins digital maturity (Dahlman et al., 2016). Digital infrastructure is the *sine qua non* of the digital economy (Cogburn & Nyaki Adeya, 2001). Digital Infrastructure is pivotal in the development of the digital economy. It encompasses the physical and virtual components necessary to support the transmission, processing, storage, and retrieval of digital information and services. Digital infrastructure, including broadband networks, optical fibre cables, and wireless communication systems, enables connectivity and access to the Internet. It provides the foundation for individuals, businesses, and governments to connect, communicate, and collaborate in the digital space (ITU, 2021).

The digital infrastructure supports e-commerce platforms, online marketplaces, and digital payment systems, enabling businesses to reach customers worldwide and engage in digital transactions. It expands market opportunities, reduces transaction costs, and enhances the efficiency of business operations (World Bank, 2020). Fernández-Portillo et al. (2020) used a causal loop model to validate that digital infrastructure directly influences the growth of a country's economy after analysing datasets from member countries of the Organisation for Economic Co-operation and Development (OECD). Ndubuisi et al. (2021) analysed 45 Sub-Saharan African countries for the period 1996–2017 on the impact of digital infrastructure on employment in the services sector. The findings reveal a positive correlation between digital infrastructure and employment in the services sector,

and digital infrastructure has the potential to promote inclusion and reduce inequality.

Digital infrastructure provides the essential backbone for innovation and technological advancement. It supports research and development activities, experimentation with emerging technologies, and the creation of digital products, services, and solutions that drive economic growth and competitiveness (European Commission, 2018). The following sub-sections will discuss some of the key metrics that constitute barriers to infrastructure development. These metrics will all be used construct causal loop and stock and flow diagrams in the modelling and simulation

2.7.1 *Investment in ICT*

The transition to the digital economy is challenging for developing countries because of the level of available infrastructure and financial resources needed for the transition (Oloyede et al., 2023). The lack of funding in digital infrastructure leads to an underdeveloped digital infrastructure. According to a 2024 World Bank report, regions such as Sub-Saharan Africa face critical challenges due to underdeveloped digital infrastructure and a lack of accessible, affordable connectivity. This results in large segments of the population being excluded from digital benefits, affecting overall economic development (World Bank Group, 2024). Well-developed infrastructure attracts knowledge-intensive international firms to localise their operations (Tranos & Mack, 2016). Developed digital infrastructure foments access and knowledge sharing between firms to benefit from online business networks (Tiwasin, 2021). Access to a well-developed digital infrastructure, therefore, supports firm growth, innovation, reputation, and competitive advantage (Webber et al., 2022; Vial, 2019).

Towards the end of the 20th century, investments in ICT infrastructure development in South Africa were reported to be the highest in Africa and amongst the highest in the developing world, lower than China, Brazil, Mexico, and India (Cogburn & Nyaki Adeya, 2001). Since then, South Africa has seen a decline in their ICT infrastructure investment. Over 5 years (2019 – 2023), ICT infrastructure investment decreased by 1.49% (ICASA, 2024).

2.7.2 *ICT Skills*

The lack of ICT skills creates significant barriers to the development and effective use of digital infrastructure. If the digital education attainment and skills of the next generation are to drive future development, then investments in ICT infrastructures and the facilitation of access so that marginalised groups can participate in the digital economy remain key for future prosperity (Webber et al., 2022).

2.7.3 *Adoption of Digital Services*

Given the role that the investment in digital infrastructure, the adoption rate of digital services and the level of ICT skills play in developing and utilising digital infrastructure, the following proposition can be formulated.

Proposition 2: Low investment in ICT infrastructure, combined with affordability constraints and low adoption of digital services, slows the development of digital infrastructure.

2.8 Systemic Barriers to Digital Technology Integration

The third DESI dimension measures the digitalisation of businesses and e-commerce, particularly the uptake of digital technologies by businesses from a very basic to an advanced level. These include electronic information sharing, social media use, and more advanced technologies such as big data analytics, cloud services, and artificial intelligence (AI) (European Commission, 2022). According to UNCTAD (2021), only South Africa in the African continent appears on the list of emerging digital leaders participating in the global data value chain activities. Participation in the data value chain has given developed countries such as the United States a competitive advantage in data generation and its use for productive purposes such as digital intelligence (UNCTAD, 2019). What are the systemic barriers hindering the widespread adoption of emerging technologies such as artificial intelligence (AI), blockchain, and the Internet of Things (IoT) in South Africa, and how do these barriers interact with socioeconomic factors? The following sub-sections will discuss some of the key

metrics that constitute barriers to technology integration. These metrics will all be used construct causal loop and stock and flow diagrams in the modelling and simulation.

2.8.1 *Technology Investment*

Investing in digital technology plays a pivotal role in driving the development of the digital economy and shaping the way societies operate, innovate, and interact. These investments serve as catalysts for transformation, unlocking opportunities for economic growth, social inclusion, and sustainable development (Daud & Trinugroho, 2024). By fostering the expansion of digital infrastructure, such as broadband networks, data centres, and digital platforms, countries can facilitate connectivity and access to information, empowering individuals and businesses to participate in the digital ecosystem (World Bank Group, 2023).

2.8.2 *Regulatory Framework*

Regulatory frameworks play a pivotal role in shaping the development of the digital economy by providing the necessary legal and institutional structures to govern digital activities, ensure market efficiency, protect consumer rights, and foster innovation. Well-designed regulatory frameworks help create a level playing field for businesses, facilitate market entry and competition, and promote trust and confidence among stakeholders (Thakoor, 2020). Key areas addressed by regulatory frameworks include data protection and privacy, cybersecurity, intellectual property rights, e-commerce, digital payments, and telecommunications.

2.8.3 *Digital Skills*

Investments in digital skills development and education enable individuals to navigate and leverage digital tools effectively, fostering a digitally literate workforce capable of driving innovation and entrepreneurship.

2.8.1 *New Technologies' Adoption*

The adoption of 4IR technologies has been significantly low in many South African companies and industries. Munoriyarwa, Chiumbu, & Motsaathebe (2023) reveal a varied uptake of AI technologies within mainstream South African newsrooms influenced by a mix of scepticism and optimism regarding AI's role in news production, with concerns revolving around potential job displacement and the ethical implications of AI-generated content.

Therefore, given the role that technology investment, the level of digital skills and the adoption of 4IR technologies play in a country in the adoption and utilisation of Industry 4.0 technologies, the following proposition can be formulated.

Proposition 3: The adoption of Industry 4.0 technologies (e.g., AI, blockchain, IoT) is hindered by both underinvestment in technology and a shortage of relevant digital skills.

2.9 System Dynamics in Digital Public Services

Digital technologies contribute to national and local development, facilitate the sharing of knowledge and guidance, and enable the provision of online services and solutions (ITU & UNESCO, 2024). Achieving the full potential of these technologies is a key challenge for governmental organisations. Effective e-government can provide a wide variety of benefits, including more efficiency and savings for both governments and businesses. It can also increase transparency and openness (European Commission, 2022). How can system dynamics modelling and simulation techniques be used to analyse the complex interactions and feedback loops within the digital economy ecosystem in South Africa, and how can they inform strategic decision-making and policy formulation? What are the systemic barriers to the adoption and integration of emerging technologies (e.g., AI, blockchain) in public services? The following sub-sections will discuss some of the key metrics that constitute barriers to the development of digital public services. These metrics will all be used construct causal loop and stock and flow diagrams in the modelling and simulation

2.9.1 *Online Service Availability*

The availability of online public services plays a pivotal role in the development of the digital economy, particularly in fostering inclusive growth and enhancing citizens' access to essential government services (Goloshchapova et al, 2023). By digitising administrative processes and making services accessible through online platforms, governments can streamline transactions, reduce bureaucratic barriers, and improve the efficiency of service delivery.

2.9.2 *ICT Infrastructure*

ICT infrastructure plays a pivotal role in driving the development of the digital economy by laying the foundation for the delivery of public digital services (Lu, 2022). A robust ICT infrastructure, including broadband networks, data centres, and digital platforms, serves as the backbone for enabling seamless and efficient interactions among governments, businesses, and citizens. By investing in ICT infrastructure, governments can expand access to essential public services such as education, healthcare, and governance, particularly in underserved and remote areas.

2.9.3 *Digital Skills*

The workforce's knowledge, skills, and competencies determine the quality, accessibility, and efficiency of these services (Lopes, Sargento, & Farto, 2023). Digital skills are one of the crucial components of eGovernment, enabling citizens to effectively utilise e-Government services and communicate with public administration (Stofkova et al., 2022). Investing in digital skills through education, training, and professional development is essential to harness the full potential of digital technologies in the public sector.

Given the role that technology investment and the level of digital skills in a country play in the development of digital public services, the following proposition can be formulated.

Proposition 4: Insufficient investment in digital technologies and skills hampers the digitalisation of public services and reduces citizen adoption of e-government services.

2.10 ANALYTICAL FRAMEWORK

2.10.1 *Theoretical Framework*

As previously postulated, digital maturity at a national level can be described as a complex system, with elements such as digital infrastructure, digital skills, technology integration, and digital public services that interact with each other in a dynamic setting to produce dynamic behaviour. Complexity in social systems refers to the intricate and interdependent relationships among individuals, groups, and institutions that give rise to emergent behaviour (Pourvand, 2024). Social systems are dynamic, non-linear, and adaptive, meaning that small changes in one part of the system can lead to disproportionately large and sometimes unpredictable outcomes (Mesjasz, 2010). These systems are characterised by multiple interacting components, feedback loops, and the constant evolution of relationships and norms. Unlike simple systems, social systems are often recalcitrant to formalisation and reductionism (Törnberg, 2017) because their behaviour cannot be fully understood by examining individual parts in isolation. Instead, the emergent properties arise from the interactions among the components.

Central to social systems that exhibit complex behaviour is their structure, following the axiom “Structure determines behaviour”. This section explores different complexity theories used to analyse complex systems.

2.10.2 *Complex Adaptive System (CAS) Theory*

Complex Adaptive Systems (CAS) Theory explores the behaviour of systems composed of multiple interconnected agents or components that interact dynamically and adapt to their environment (Holland, 1992). CAS focuses on how individual parts of a system evolve and how these local interactions give rise to

complex global patterns or emergent behaviour that cannot be predicted by simply analysing the parts in isolation. CAS emphasises that while structure plays a role, the emergent behaviour of the system is not strictly determined by structure. Small changes in agent behaviour or interactions can lead to disproportionate and unpredictable outcomes.

2.10.3 *Network Theory*

Network Theory is a branch of systems theory that studies how elements or nodes (such as individuals, organisations, or entities) are connected to form a network and how these connections impact the overall structure and behaviour of the system (Casti, 1995). The theory is used to analyse complex systems where relationships between elements play a crucial role in understanding the system's function and dynamics. While network structure is important, the behaviour of the system can be driven by random events, interactions, and non-structural factors such as network dynamics, random attacks, or targeted interventions.

2.10.4 *General Systems Theory (GST)*

Systems Theory, also referred to as General Systems Theory (GST), is a theoretical framework that views phenomena as complex systems composed of interconnected elements that interact with each other and their environment. Originally proposed by the biologist Von Bertalanffy (Von Bertalanffy, 1950), it provides a holistic perspective that emphasises the relationships and interactions within a system rather than focusing solely on the individual components. Systems theory applies to a wide range of disciplines, including biology, psychology, sociology, engineering, and management (Johnson et al., 1964).

At its core, systems theory recognises that a system is more than the sum of its parts, which are systematically placed for a defined purpose. It seeks to understand the emergent properties and behaviours that arise over time from the interactions among system elements, which are dynamic (Beer, 1974). These interactions can be characterised by feedback loops, where information or

outputs from one part of the system influence other parts, leading to dynamic and often nonlinear behaviour. In GST, the structure of a system (i.e. Components and their interconnections) determines how the system functions and responds to external stimuli. System behaviour emerges from the structure rather than being determined by individual components in isolation.

2.10.5 *System Dynamics*

System dynamics is a theoretical framework and methodology that builds upon systems theory to model and analyse the behaviour of complex systems over time. It was first developed by J. W. Forrester from MIT in the 1950s for industrial enterprises (Forrester, 1971). It focuses on understanding a system's dynamic relationships and feedback loops and how they give rise to system behaviour (Sterman, 2000).

Key principles and components of System Dynamics include:

- Causal Loop Diagrams: Causal loop diagrams are graphical representations used in System Dynamics to depict the relationships between variables and feedback loops within a system. These diagrams help to visualise the cause-and-effect relationships and identify the key feedback structures driving system behaviour. Causal loop diagrams are comprised of two types of feedback loops. Feedback loops can be either reinforcing (positive feedback) or balancing (negative feedback):
    - Reinforcing feedback loops amplify the effects and can lead to exponential growth or collapse.
    - Balancing feedback loops stabilise the system and maintain equilibrium.

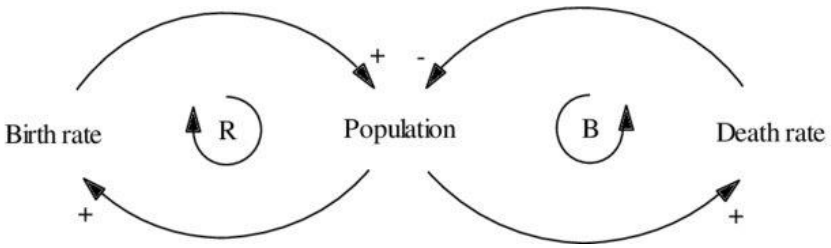


Figure 3: Example of both reinforcing and balancing feedback loops.

- Stocks and flows: System dynamics models represent the accumulation and flow of resources or entities within a system through stocks and flows. Stocks are accumulations of resources, such as inventory, population, or capital, while flows represent the rates at which resources move into, out of, or between stocks.

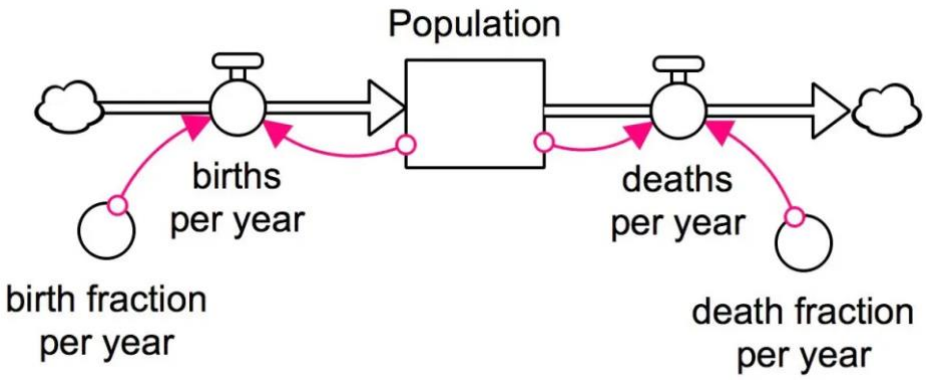


Figure 4: Example of a Stock and Flow Diagram

- Time Delays: System Dynamics recognises the presence of time delays in the system, where the effects of actions or events are not immediately felt. Time delays can give rise to oscillations, amplification, or dampening of system behaviour, and they need to be considered in understanding the dynamics of the system.
- Policy Analysis and Simulation: System Dynamics models provide a tool for policy analysis and decision-making. By simulating the models, stakeholders can explore the potential consequences of different policies or interventions on the behaviour of the system. This enables policymakers to test various strategies and evaluate their long-term effects before implementing them.
- Learning and Improvement: System Dynamics encourages learning and improvement through iterative modelling and analysis. As new data becomes available or the understanding of the system deepens, the models can be refined and updated to enhance their accuracy and usefulness for decision-making.

System Dynamics has been applied to various domains, including environmental sustainability, public health, organisational management, and public policy. It allows for a deeper understanding of the behaviour of complex systems,

facilitates the exploration of potential interventions and policies, and supports decision-making by considering the long-term implications and unintended consequences or side effects of actions. In system dynamics, the structure of stocks, flows, and feedback loops determines the behaviour of the system over time, including growth, decline, or oscillation. Understanding the structure allows predictions about system behaviour under different conditions. This research employs System Dynamics as it succinctly encapsulates the structure-behaviour relationship.

2.10.6 *Conceptual Framework*

Miles and Huberman (1994) describe a "Conceptual Framework" as a document that "explains, either graphically or in narrative form, the main things to be studied and the key factors, concepts, or variables; and the presumed relationships among them. It guides the researcher to visualise the main variables and concepts and provides the researcher with a general approach to their study (Imenda, 2014). The figure below provides a generalised and simplified process model adapted from Oosthuizen & Manzini (2022) that has guided the research.

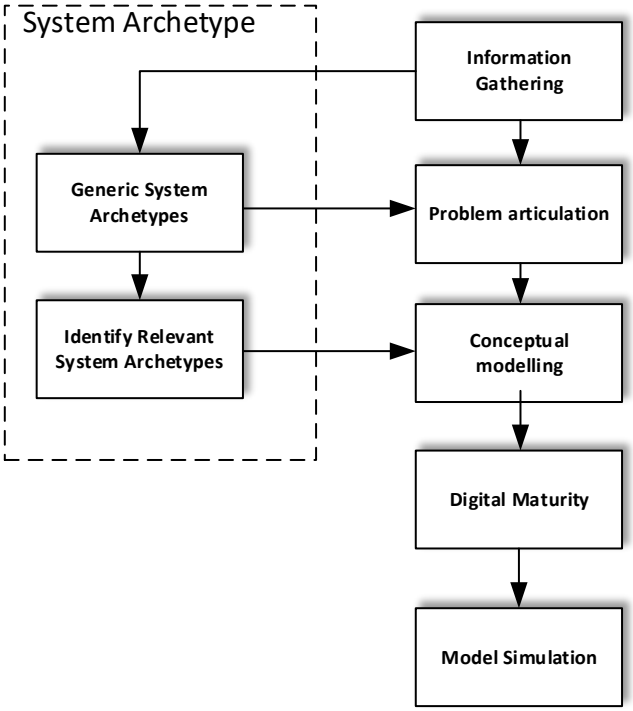


Figure 5: The conceptual model of the Systems Dynamics Approach to digital maturity.

The first step is to capture the symptomatic behaviour, which has been articulated in the research problem section of this study. The next step is archetype analysis, which assists in identifying the generic system archetypes. Archetype analysis is a methodological approach used to identify and understand recurrent patterns in variables and processes within complex systems. The generics System archetypes are expanded in the succeeding section. The problem articulation forms part of the dynamic hypothesis to describe the structure and behaviour of the system or a problem situation. The causes and effects among variables are linked in causal loop diagrams. Relevant System archetypes will be explicated in identifying common patterns that support insight into the underlying system structures. Lastly, A deeper analysis of system behaviour through system dynamics simulation (stock-and-flow diagrams) leads to recommendations about how to improve system performance. Solutions to these high-level complex system behaviours will include the design of policies.

2.10.7 *System Dynamics Archetypes*

Archetype analysis identifies recurring patterns at an intermediate abstraction level to develop multiple models explaining a phenomenon under specific conditions (Oberlack et al.). 2019). Therefore, system dynamics archetypes are patterns or structures commonly found in complex systems that produce characteristic and recurring behaviour (Meadows, 2008). Furthermore, they are also useful approaches to analysing the dynamics of possible scenarios of complex systems (Wolstenholme, 2004). These generic models are a central enabler to assist in understanding the underlying structures behind the challenges of the advancement of digital maturity in South Africa. The common system dynamics archetypes are “Limits to Growth,” “Shifting the Burden,” “Eroding the Goals”, and “Fixes that Fail.”. These archetypes are discussed below, and how they have been utilised in various literature to gain a deeper understanding of a complex phenomenon.

2.10.7.1 *"Limits to Growth" Archetype*

In the "Limits to Growth" archetype, a system experiences growth through continued efforts applied to the system. Over time, however, the system encounters a limit or constraint/s which slows down the growth or performance of the system, sometimes to the point of decline even if the efforts continue to rise. This archetype highlights growth challenges in one part of the system, leading to constraints that hinder further growth. The "limits to growth" archetype typically has one reinforcing loop and one balancing loop representing the growth of a system and the constraint on the system, respectively.

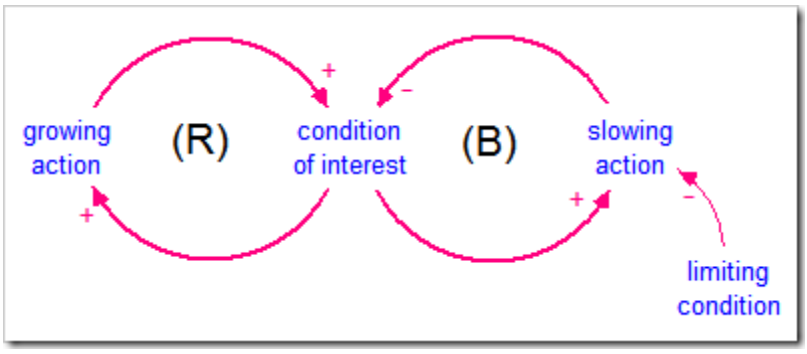


Figure 6: Limit to Growth Archetype Template

Mathis-Pertilla (2021) employs the "limits to growth" archetype as a diagnostic tool for understanding the complexities present within the business environment that affect strategy formulation and performance and how Female CEOs can identify bottlenecks (e.g., resource constraints) and balance growth with sustainable practices.

2.10.7.2 *"Shifting the burden" Archetype.*

The "Shifting the Burden" systems dynamics archetype describes a situation where a problem is addressed by applying symptomatic solutions that provide temporary relief rather than tackling the underlying root cause. Over time, reliance on symptomatic solutions can weaken the system's ability to address the root cause, often leading to a dependency on the short-term fix and exacerbating the problem. The "Shifting the Burden" systems dynamics archetype consists of two main feedback loops: a reinforcing loop (R) that represents the symptomatic

solution and a balancing loop (B) that represents the fundamental solution. Additionally, there is often a side effects loop (B2) that illustrates the negative consequences of relying on the symptomatic solution.

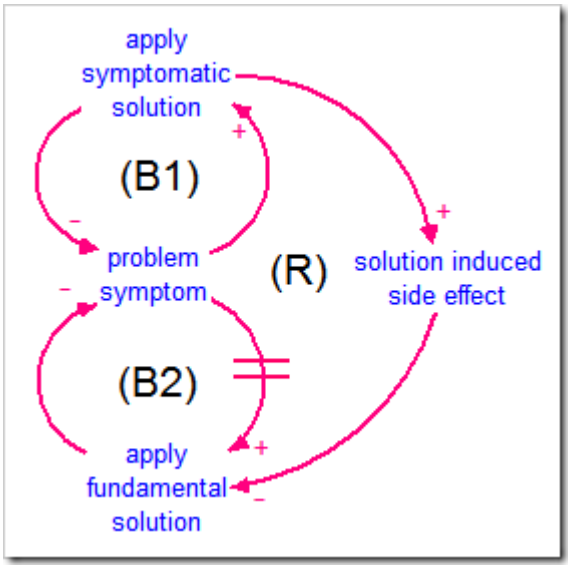


Figure 7: Shifting the Burden Archetype Template

Bano et al. (2022) use the “Shifting the Burden” archetype to explain the informal water system in Hyderabad and other cities in Pakistan. The study elucidates how reliance on informal water sources diverts attention from addressing underlying issues within the formal supply system, potentially leading to its further degradation over time.

2.10.7.3 *“Fixes that fail” Archetype.*

The "Fixes that Fail" systems dynamics archetype describes a situation where a quick fix to a problem initially appears to work but eventually leads to unintended consequences that cause the original problem to worsen over time. This archetype highlights the short-term effectiveness and long-term ineffectiveness of certain solutions, emphasising the need to address root causes rather than relying on superficial fixes. The archetype can be represented in a causal loop diagram with two main loops: an initial balancing loop (B1) that shows immediate improvement and a reinforcing loop (R) that shows long-term unintended consequences.

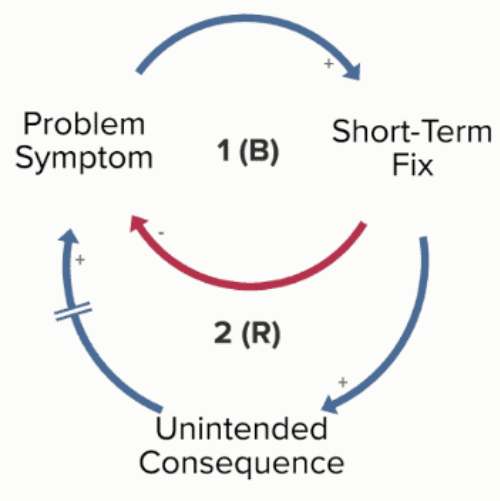


Figure 8: Fixes that Fail Archetype Template

Bano et al. (2022) use the “Fixes that fail” archetype to elucidate how short-term solutions, such as increasing informal water suppliers to meet immediate demand, lead to unintended long-term consequences, including resource depletion or system inefficiencies.

2.10.7.4 *“Eroding/Drifting” Goals Archetype*

The "Eroding Goals" systems dynamics archetype describes a situation where long-term goals are gradually lowered to match declining performance rather than addressing the root causes of the decline. This archetype is characterised by a feedback loop where a failure to meet targets leads to the adjustment of goals downward, resulting in a continuous cycle of goal erosion and underperformance.

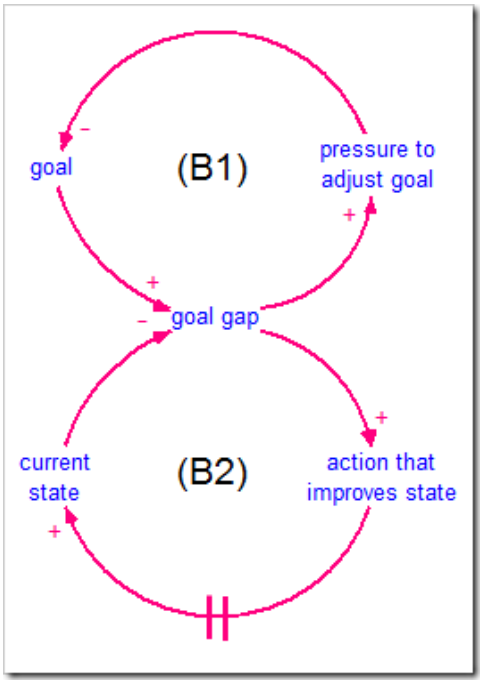


Figure 9: Eroding the Goals Archetype Template

2.11 Conclusion of Literature Review

The digital economy encompasses a broad range of economic activities that result from billions of daily online connections among people, businesses, devices, data, and processes. Central to this economy are digital technologies and infrastructures, which enable seamless communication, data exchange, and transactions. Key components include e-commerce, digital services, fintech, and digital platforms that drive innovation and efficiency across various sectors. The Digital Economy and Society Index (DESI) framework is a comprehensive tool developed by the European Commission to assess and monitor the digital performance of EU member states. DESI evaluates countries across four key dimensions: Digital skills, Digital infrastructure, Integration of Digital Technology, and Digital Public Services

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2.11.1 ***Proposition 1: Underinvestment in digital skills, coupled with low ICT graduate output and high levels of ICT skills migration, inhibits the effective development and utilisation of digital skills in South Africa.***

2.11.2 ***Proposition 2: Low investment in ICT infrastructure, combined with affordability constraints and low adoption of digital services, slows the development of digital infrastructure.***

2.11.3 ***Proposition 3: The adoption of Industry 4.0 technologies (e.g., AI, blockchain, IoT) is hindered by both underinvestment in technology and a shortage of relevant digital skills.***

2.11.4 ***Proposition 4: Insufficient investment in digital technologies and skills hampers the digitalisation of public services and reduces citizen adoption of e-government services. c***

CHAPTER 3. RESEARCH METHODOLOGY

This chapter articulates the research methodology adopted in the study. Research methodology refers to the systematic process used to conduct research. It outlines the approach in which the research troubles are solved thoroughly (Kothari, 2004). The chapter outlines the methodological choices underpinning the study, detailing the research design, data collection procedures, analytical approach, and modelling cycle. Given the complexity of digital maturity at a national level, System Dynamics was adopted as the primary methodological framework to explore causal relationships and simulate policy interventions.

Before proceeding with the remainder of this chapter, it is imperative to highlight the aim of the research. This exploratory research study applies Systems Dynamics modelling to assist policy/decision makers in understanding the dynamic and complex environment of digital maturity in South Africa's national context.

3.1 Research approach

This research is desk-based and exploratory, combining qualitative content analysis of secondary sources which was also used for formulation of causal loop diagrams with quantitative simulation using the stock-and-flow diagrams.

3.2 Research design

3.2.1 *System Dynamics Research Design*

This research follows the five steps from the System Dynamics modelling cycle depicted in Figure 10 below, and the corresponding explanation of each step is expanded in Table 2. The steps for system dynamics modelling were pioneered by Jay W. Forrester, a professor at the Massachusetts Institute of Technology (MIT). Forrester developed the foundational principles of system dynamics in

the 1950s and 1960s. His work laid the groundwork for applying this methodology to understand complex systems in various fields, including business, economics, environmental science, and public policy. These steps are problem articulation, formulation of a dynamic hypothesis, development of a model, test simulation model, and finally, policy design and evaluation.

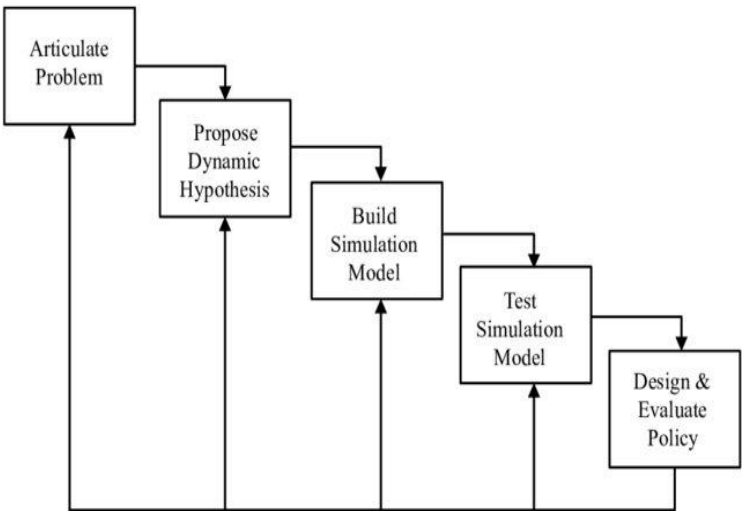


Figure 10: System Dynamics Modelling Cycle

Table 2: Steps of the modelling process (Sterman, 2000)

ELEMENT	PROCESS
PROBLEM ARTICULATION (BOUNDARY SELECTION)	**Theme selection**: What are the problems? Why are they a problem? **Key variables:** What significant variables and concepts must we contemplate? **Time horizon:** How far in the future should we contemplate? How far back in the past lie the origins of the problem? **Dynamic problem definition (reference modes):** What is the historical behaviour of the significant concepts and variables? What might their behaviour be in the future?
FORMULATION OF DYNAMIC HYPOTHESIS	**Initial hypothesis generation:** What are existing theories of challenging behaviour? **Endogenous focus:** Formulate a dynamic proposition that clarifies the dynamics as endogenous consequences of the feedback structure. **Mapping:** Develop maps of causal structure based on initial propositions, significant variables, reference modes, and other available data, using tools such as model boundary diagrams, Sub-system diagrams, Causal loop diagrams, Stock-and-flow maps, Policy structure diagrams, and other facilitation tools.
FORMULATION OF A SIMULATION MODEL	**Specification** of structure, and decision rules. **Estimation** of parameters, behavioural relationships, and initial conditions. **Tests** for consistency with the purpose and boundary
TESTING	**Comparison to reference modes:** Does the model replicate the problem sufficiently for your purpose? **Robustness under extreme conditions:** Does the model perform persuasively when stressed by extreme conditions. **Sensitivity:** How does the model perform given the ambiguity in parameters, initial conditions, model boundary, and aggregation?
POLICY DESIGN AND EVALUATION	**Scenario specification:** What conditions might arise? **Policy design:** What new decision guidelines, stratagems, and structures might be tried in the real-world? How can they be represented in the model? **'What if...'** analysis. What are the effects of the policies? **Sensitivity analysis:** How vigorous are the policy endorsements under different scenarios and given uncertainties? **Interactions of policies:** Do the policies intermingle? Are there synergies or compensatory responses?

Chapters 4 (Model Development) and 5 (Results and Discussion) articulate in detail how this process was applied in the current study.

3.3 Data collection methods – Exploratory study

The fundamental feature of qualitative research design culminates in the latitude to collect specific secondary data that provides insight to the researcher to comprehend the phenomenon under study (Heaton, 2004). Firstly, secondary data is often more cost-effective and time-efficient than primary data collection, as it leverages existing information that has already been gathered and processed (Bryman, 2016). This allows researchers to quickly access a wealth of data without the need for extensive fieldwork or resource allocation. Secondly, secondary data can provide a broader context and historical perspective, enabling researchers to identify trends, patterns, and relationships over time (Zhu & Thatcher, 2010). This is particularly valuable for comparative studies and longitudinal analyses. This is particularly useful in the context of the measurements of the digital economy that have been collected over a long period. The data collected for the exploratory (inductive logic) study and, therefore, the qualitative research design approach was secondary and comprised of in-depth literature on digital maturity and the digital maturity measurement indices for countries. Secondly, other secondary data was collected from industry reports such as the International Telecommunications Union, Independent Communications Authority of South Africa (ICASA), African Union (AU), United Nations Trade and Development (UNCTAD), Organisation for Economic Co-operation and Development (OECD), Institute of Management Development (IMD), and related literature. The table below summarises the data sources and the type of data used for each.

SOURCE	TYPE OF DATA USED	TIME PERIOD COLLECTED	PURPOSE
ITU	Trend report and indicators	2016 – 2024	Trend report and indicator value for input variable estimation
ICASA	Trend report and indicators	2016 – 2024	Trend report and indicator value for input variable estimation
UNCTAD			
AU	Policy document	2020 – 2024	Policy, Strategy and Roadmap
OECD	Trend report and indicators	2016 – 2024	Trend report and indicator value for input variable estimation
IMD	Trend report and indicators	2016 – 2024	Trend report and indicator value for input variable estimation

Chapter 4 on Model Development expands on how i) the input data was used to estimate model parameters. ii) Data calibration and validation were performed, and the tool was used in the study.

3.4 Population and sample

3.4.1 *Population*

The entire population considered for this study consisted of a single country, South Africa, which was also utilised as the sample. The paucity of research data from other African countries, which was discussed in the limitations of the DESI framework, contributed to the limitations of the study.

3.4.2 *Sample*

This study did not use sampling, as the research solely focused on South Africa.

3.5 The research instrument

This study employed secondary research, also called “Desk-based research”.

3.6 Procedure for data collection

The following steps were followed in collecting the data:

- Identification of Data Sources - Determination of the appropriate sources of information that align with the research theme, considering both online and offline resources. These data were collected from literature, industry and academic reports. These data focused on the definitions, conceptualisation, measurements, and indices (and their indicators) of digital maturity, such as Digital skills, Digital Infrastructure, Technology Integration and Digital Public Services, as outlined in Table 3 as per the DESI Framework. These definitions, conceptualisations, measurements, and indices were discussed in-depth in the literature review in Chapter 2.
- Collection of Data
- Evaluation of Data Quality

- Systematically gather data from identified sources, ensuring the source and context of each piece of information are noted for accurate referencing.
- Assessment of the credibility, accuracy, and reliability of the data sources. Consider the reputation of the source, the methodology used to gather the data, and the date of publication.
- Organisation of Data.
- Compilation and organisation of the collected data in a structured format, such as spreadsheets or databases, to facilitate analysis.

Table 3: DESI Dimensions, Sub-Dimensions, and Indicators

DIMENSION	SUB-DIMENSION	INDICATOR
1 DIGITAL SKILLS	1a. Internet user skills	1a1 At least basic digital skills 1a2 Above basic digital skills. 1a3 At least basic digital content creation skills.
	1b. Advanced skills and development	1b1 ICT specialists 1b2 Enterprises providing ICT training 1b3 ICT graduates
2 DIGITAL INFRASTRUCTURE	2a Fixed broadband take-up.	2a1 Overall fixed broadband take-up 2a2 At least 100 Mbps fixed broadband take-up 2a3 At least 1 Gbps take-up.
	2b Fixed broadband coverage.	2b1 Fast broadband (NGA) coverage 2b2 Fixed Very High-Capacity Network (VHCN) coverage.
	2c Mobile broadband	2c1 4G coverage. 2c2 5G readiness 2c3 5G coverage 2c4 Mobile broadband take-up

	2d Broadband prices	2d1 Broadband price index
3 INTEGRATIONS OF TECHNOLOGY	3a Digital technologies for businesses	3a1 Electronic information sharing 3a2 Social media 3a3 Big data 3a4 Cloud 3a5 AI 3a6 e-Invoices
	3b e-Commerce	3b1 SMEs selling online 3b2 e-Commerce turnover 3b3 Selling online cross-border
4 DIGITAL PUBLIC SERVICES	4a e-Government	4a1 e-Government users 4a2 pre-filled forms 4a3 Digital public services for citizens 4a4 Digital public services for businesses 4a5 Open data

3.7 Data analysis strategies and interpretation

The input simulation data is crucial for model accuracy and reliability. The analysis and interpretation of input data involve ensuring the validity of the model's assumptions, assessing parameter sensitivity, and understanding how input variations influence system behaviour.

3.8 Possible limitations and challenges of the study

The study only focused on South Africa as a case study. This constitutes a limitation in the generalisability of the System Dynamics model. However, given the time constraints of the research and the paucity of the measurement data of digital maturity that is not readily available from and about other African countries, this research suffers a limitation.

3.9 Quality Assurance

3.9.1 *Transferability*

Transferability is the extent to which the results of a qualitative study can be transferred into different contexts with different samples (Creswell & Creswell, 2017). This study utilised secondary data. Secondary data can enhance the validity and reliability of research findings by offering a larger sample size and a diverse range of data sources. It allows for triangulation, where findings from multiple sources are compared and corroborated, strengthening the study's overall conclusions.

3.9.2 *Credibility*

Credibility is the certainty of the research outcomes (Corbin & Strauss, 2015). The study gathered data from reputable and authoritative sources, such as government agencies, academic institutions, and industry reports, ensuring a high level of credibility and accuracy.

3.9.3 *Dependability*

The study follows Sterman’s five-step process that was discussed in Section 3.2.1. The development of the model is based on the normative DESI framework, which has been widely adopted in many European countries. Lastly, the model will be subjected to the validation and verification procedures, which will be discussed in Section 3.11.4.

3.10 Ethical considerations

The research produces multiple outputs, including the System Dynamics models, simulation results and policy options derived from simulation results. Policy simulation, particularly when using methods such as System Dynamics, raises several important ethical considerations. First, model transparency and validity are crucial; hence, the data sources and model structures have been documented as thoroughly as possible to prevent misleading interpretations. Second, data ethics was observed by utilising secondary data obtained from reputable sources that publicly publish their research data and findings with permission. Furthermore, all ethical standards were observed in conducting this research project.

3.11 System Dynamics Approach

3.11.1 *Problem Articulation*

Problem articulation in system dynamics is the process of defining and understanding a problem within a system by identifying its key variables, relationships, and underlying structures (Sterman, 2000; Schoenenberger, 2021). It is a crucial first step in developing effective models to address complex issues.

According to Sterman (2000), effective problem articulation requires distinguishing symptoms from underlying systemic causes and recognising feedback loops that drive system behaviour. Richardson (2011) highlights the importance of engaging stakeholders early in the process to align perspectives and ensure that the problem definition accurately reflects real-world dynamics. A well-articulated problem statement serves as the foundation for model development, guiding the selection of relevant variables and interactions that shape system behaviour. Without a clear articulation, subsequent modelling efforts risk addressing superficial issues rather than systemic root causes, reducing the effectiveness of policy recommendations (Meadows, 2008). Thus, problem articulation is essential for ensuring that system dynamics modelling leads to meaningful insights and actionable solutions.

3.11.2 *Dynamic Hypothesis*

The dynamic hypothesis is a preliminary explanation or theory about the underlying structure and feedback mechanisms driving the behaviour of a system over time (Schoenenberger, 2021). It serves as a foundation for building and testing simulation models, helping to identify key variables, causal relationships, and feedback loops that explain observed patterns. A dynamic hypothesis is typically represented as a causal loop diagram or stock-and-flow model, capturing the interdependencies and delays in the system. Focusing on dynamic complexity rather than static details enables modellers to explore how policies or interventions might impact system behaviour. This iterative process refines the hypothesis through simulation and validation against real-world data, offering insights into system performance and decision-making.

3.11.3 *Model Development and Design*

The model structure will be constructed to represent the interaction of dimensions, subdimensions, and indicators at play in advancing the level of digital maturity. Modelling and simulation do for organisational systems what engineering prototypes do for product design (White & Alfeld, 1998). These variables are connected and presented in the Causal Loop Diagrams (CLDs) and Stock and Flow Diagrams (SFDs), which were introduced and discussed in Chapter 2.

3.11.4 *Model Testing and Validation*

Model testing and validation are about “the process of establishing confidence in the soundness and usefulness of a model” (Senge & Forrester, 1980). These steps are crucial in the system dynamics modelling process to ensure that the model accurately represents the real-world system and can reliably predict its behaviour. These steps help build confidence in the model's structure and results, making it a valuable tool for decision-making and policy analysis. Sterman (2000) outlines a list of main tests in System Dynamics to assist modellers in uncovering

flaws and improving models. The summary of the tests is provided in the table below.

Table 4: Tests for assessment of dynamic models

TEST	PURPOSE OF TEST	TOOLS AND PROCEDURES
BOUNDARY ADEQUACY TEST	Are the significant notions for addressing the problem endogenous to the model captured? Does the behaviour of the model vary significantly when boundary assumptions are relaxed?	Use model boundary charts, subsystem diagrams, causal diagrams, stock and flow maps, and direct inspection of model equations
STRUCTURE ASSESSMENT	Is the model structure in line with the relevant descriptive acquaintance of the system? Is the level of aggregation appropriate? Does the model obey basic physical laws such as conservation laws? Do the decision guidelines capture the behaviour of the actors in the system?	Use model boundary charts, subsystem diagrams, causal diagrams, stock and flow maps, and direct inspection of model equations
DIMENSIONAL CONSISTENCY	Is each equation dimensionally reliable without the use of parameters having no real-world meaning?	Use dimensional analysis software. Inspect mode equations for suspect parameters.

PARAMETER ASSESSMENT	Are the parameter values consistent with relevant descriptive and mathematical knowledge of the system? Does the model reply conceivably when exposed to extreme policies, shocks, and parameters?	Use statistical methods to estimate parameters (wide range of methods available), Use partial model tests to calibrate subsystems
EXTREME CONDITIONS	Is each equation sensible even when its inputs take on extreme values? Does the model reply conceivably when exposed to extreme policies, shocks, and parameters?	Inspect each equation. Test response to extreme values of each Input, alone and in combination. Subject model to large shocks and extreme conditions. Implement tests that examine conformance to basic physical laws
BEHAVIOUR ANOMALY TEST	Do uncharacteristic behaviours result when assumptions of the model are changed or deleted?	Compute statistical measures of Correspondence between model and data
SENSITIVITY ANALYSIS TEST	Numerical sensitivity: Do the mathematical values alter significantly when assumptions about parameters, boundary, and aggregation are varied over the conceivable range of uncertainty? Behavioural sensitivity: Do the modes of behaviour generated by the model	Perform univariate and multivariate sensitivity analysis. Use analytic methods (linearisation, local and global stability analysis, etc.).

	change meaningfully when assumptions about parameters, boundary, and aggregation are varied over the probable range of uncertainty? Policy sensitivity: Do the policy implications vary meaningfully when assumptions about parameters, boundaries, and aggregation are varied over the plausible range of uncertainty?

3.12 Chapter Summary

This chapter articulated the research methodology adopted in the study, which discussed the research approach, strategy, research methodological choice, and data collection procedures and tools. The System Dynamics research approach was introduced with its corresponding modelling cycle principles. Furthermore, the modelling cycle process steps of problem articulation, dynamic hypothesis, model construction, testing and validation were discussed. It is imperative to underscore that the advancement of digital maturity at a national level constitutes a critical driver of a country's digital economy, offering vast opportunities for innovation, competitiveness, and inclusive growth. Nevertheless, this progression remains a multifaceted and dynamic phenomenon that demands rigorous analytical approaches such as System Dynamics to unravel its inherent complexity. Through simulation, System Dynamics enables the exploration and evaluation of alternative policy pathways, thereby providing an invaluable foundation for evidence-based policymaking and strategic national development.

CHAPTER 4. Model Development

4.1 Introduction

This chapter operationalises the first three stages of Sterman's five-step modelling process which are problem articulation, dynamic hypothesis formulation, model development, as outlined in Section 3.11. It commences with the problem articulation stage, which delineates the key challenges confronting South Africa in advancing its level of digital maturity. The dynamic hypothesis is discussed with the augmentation of the System Dynamics archetypes to explain the extant digital maturity in South Africa. The generic System Dynamics Archetypes were initially introduced in Section 2.10.7 as a framework for understanding and addressing recurring behaviour patterns within complex systems. The chapter then explicates the archetypes that the research deemed relevant to the slow progress of digital maturity in South Africa.

An overview of the generic conceptual model that describes the interaction of the variables in a dynamic setting in the form of a sub-system diagram ensues. Four main subsystems complete the whole system of digital maturity. These are Digital Skills, Digital Infrastructure, Technology integration and Digital Public Services.

The model development phase then commences first with the qualitative models represented as causal loop diagrams that detail in depth the causal and correlation relationship between the variables (dimensions, sub-dimensions, and indicators) that constitute the DESI framework and structure outlined in Table Two of Chapter Three. Lastly, the quantitative models represented as stock and flow diagrams that are derived from the conceptual model and causal loop diagrams are presented and discussed. These models constitute the simulation artefacts of the research.

4.2 System Dynamics Approach to the Advancement of the Level of Digital Maturity

4.2.1 *Problem Articulation*

The painstakingly slow progress in advancing the level of digital maturity in South Africa has rendered it ineffective in servicing its citizens, widened the digital divide, and stifled its international competitiveness. The official unemployment rate was 32,9% in the first quarter of 2024 (StatsSA, 2024a), making it the only country in the G20 countries with an unemployment rate of more than 15%. Figure 11 below shows that South Africa's overall digital competitiveness has been declining from 2019 to 2023, according to IMD (2023). The rankings are based on the following factors: Knowledge, Technology and Future Readiness. Knowledge is comprised of Talent, Training & Education, and Scientific concentration. Technology is measured on the Regulatory framework, Capital, and Technological framework. Lastly, future readiness is made up of Adaptive attitudes, Business agility, and IT integration.

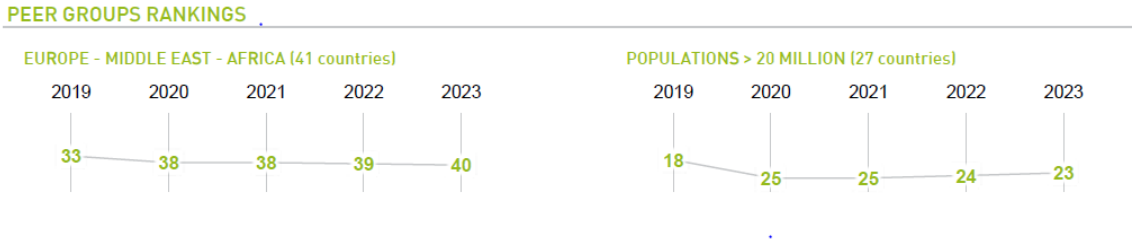


Figure 11: South Africa's Digital Competitiveness 5 years. (Source: IMD World Competitiveness 2023)

4.2.2 *Dynamic Hypothesis*

A dynamic hypothesis explains the behaviour of a system according to the underlying feedback and interactions between its components (Sterman, 2000). According to the DESI framework, the digital maturity at a national level is made up of four components framework (Digital Skills, Digital Infrastructure, Integration of Technologies, and Digital Public Services).

To better understand the underlying structures behind the challenges in advancing the level of digital maturity in South Africa, suitable archetypes are identified for each component of the DESI framework for digital maturity. These archetypes help elucidate how these structures influence the system's behaviour. The following archetypes were identified for each DESI element, as shown in Table 5 below.

Table 5: System Dynamics Archetype for Digital Maturity Mapped to Each DESI Dimension

	DESI DIMENSIONS			
	Digital Skills	Digital Infrastructure	Integration of Technology	Digital Public Services
SYSTEM DYNAMICS ARCHETYPE	Limits to growth	Limits to growth	Shifting the burden	Shifting the burden

- “Limits to Growth” and “Eroding Goals” archetypes for digital skills development.
- "Limits to Growth” archetype for digital infrastructure development.
- "Shifting the Burden" archetype for integration of technology.
- “Shifting the Burden” archetype for digital public services.

The details of these archetypes are explained in the succeeding sections.

4.2.3 *“Limit to Growth” archetype for Digital Skills Development.*

In Figure 12 below, the growth factor and investments in digital skills bolster the digital skills development efforts. The digital skills development efforts (initiatives, projects, programmes, etc) positively affect the increase in digital skills development. The increase in digital skills development also positively affects the digital skills development efforts, creating a reinforcing loop R. The increase in the development of digital skills is constrained by a balancing loop B, with constraints such as lack of funding, skills migration, low rate of skills attraction, etc.

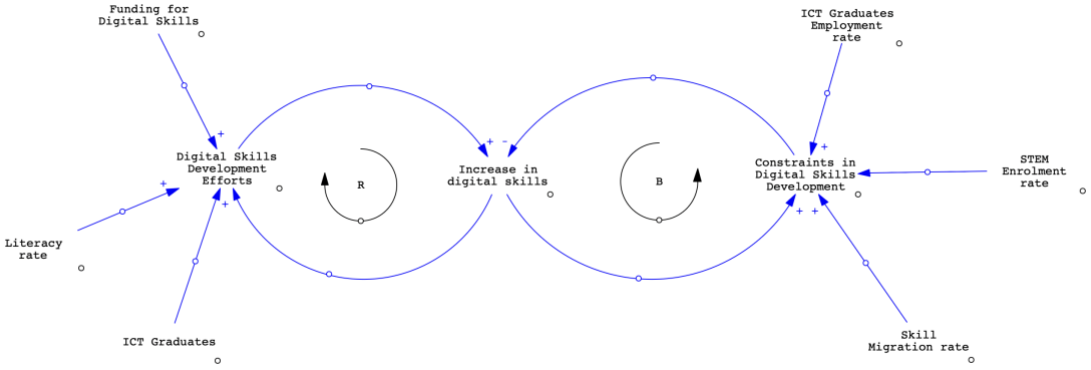


Figure 12: Limits to Growth for Digital Skills Development

Initial growth:

Every economy makes a concerted effort to increase its digital skills. South Africa's total public expenditure on education is higher than most developed countries. The National Skills Fund (NSF) is a public entity established by the government in 1999. The entity provides funding for skills development initiatives identified by the National Skills Development Plan 2030 as national priorities. The NSF recognised an expenditure of R1,2 billion for skills development funding in the 2022/23 financial year (DHET, 2023).

Growth Efforts:

This Digital and Future Skills Strategy, prepared by DCDT (2024b), sets out a structured series of initiatives intended to contribute to the capacities of South Africans to meet the challenges arising from the increasing deployment and adoption of digital technologies in the economy and society, understanding that the digital revolution.

Second, producing more ICT graduates each year ensures that a country has the talent necessary to support its digital economy, address skill shortages, foster innovation, and enhance overall digital readiness. From 2014 to 2017, the number of students who graduated with undergraduate degrees in Computer and

Information Science at public higher education institutions increased from 2670 to 2843 (Businesstech, 2019).

Growth Constraints:

South Africa has experienced rising numbers of skilled workers emigrating, losing more skilled workers than it receives (SA-TIED, 2021). South Africa's Brain Drain report published by Playroll in 2023 suggested that out of 121,000 developers in SA, 40% worked remotely for foreign companies, a typical case of virtual emigration. In the telecommunications industry in 2023, there were approximately 21,832 skilled employees, 5,002 semi-skilled employees, 510 unskilled employees, and an estimated 436 employees living with disabilities. The data shows a 6.4% decline in the employment of skilled labour over 5 years (ICASA, 2024).

The other constraint that some researchers have noted is the employment rate of ICT graduates. According to the 2022 IITPSA ICT Skills Survey, only half of ICT graduates can find employment immediately after graduating, with around 25% taking six months to a year to find work (IITPSA, 2022). The employment rate of ICT graduates significantly impacts the effective use and growth of digital skills in a country. A low employment rate is a barrier to applying, retaining, and disseminating skills across the economy, creating a negative cycle of digital development and innovation.

Furthermore, enrolment into STEM disciplines has also decreased in South Africa (IITPSA, 2024), as shown in Figures 13 and 14 below. STEM education and increasing enrolment in these disciplines are essential for a country's economic growth, technological advancement, and societal well-being. By building a strong STEM workforce, countries position themselves to address global challenges, improve quality of life, and remain competitive in an increasingly technology-driven world.

STEM Discipline	Enrolment in 2022	Enrolment in 2023	Change in Enrolment
Agricultural Sciences	128 180	118 320	-8%
Life Sciences	407 919	386 830	-5%
Mathematical Literacy	460 708	432 057	-6%
Mathematics	276 241	268 100	-3%
Physical Sciences	213 554	210 897	-1%
Source: DBE: 2023 NSC Examination Outcome			

Figure 13: (Source: Department of Basic Education): National Senior Certificate Enrolment 2022 – 2023

Exhibit 2.7 Enrolment in the Ministerial-approved Programmes at TVET Colleges 2022 - 2023			
	Enrolment in 2022	Enrolment in 2023	Difference in Enrolment
Number of Students	508 000	497 032	-2%
Source: Engineering News			

Figure 14: Enrolment in the Ministerial-approved Programmes at TVET Colleges 2022 – 2023

4.2.3.1 *Undesired Reference Modes for Digital Skills*

There are several undesired reference modes for digital skills in a country. The figure below illustrates the undesired reference modes for digital skills for a

country.

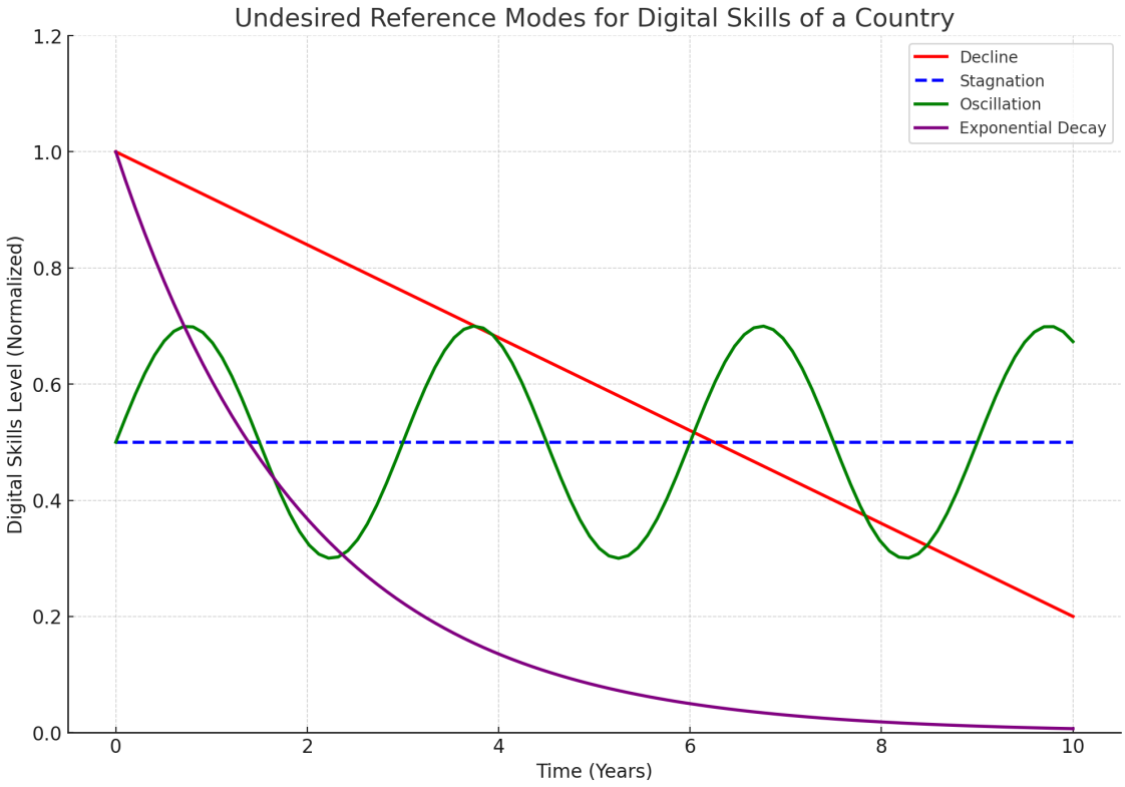


Figure 15: Undesired Reference Modes for Digital Skills Development

These are:

- **Stagnation**, where digital skills remain low due to a lack of access to quality education, inadequate training programs, or poor internet connectivity. This stagnation often results in a "skills gap," where the demand for advanced skills in emerging technologies (like AI, IoT, and blockchain) outpaces supply.
- **Decline**, where previously acquired skills become obsolete due to rapid technological advancements or shifts in industry demands, especially if there is no continuous learning or upskilling strategy.
- **Oscillatory** behaviour is also common, where short-term interventions (like government-funded training programs) result in temporary improvements, but once funding or incentives end, skill levels revert to their original state.

- **Delayed growth** is another concern, where digital skills development is slow due to long implementation times for educational reforms, curriculum updates, or changes in national policy.

4.2.4 *"Limits to Growth" archetype for Digital Infrastructure Development*

In Figure 16 below, the growth factor, which is infrastructure funding, bolsters the infrastructure development efforts. Infrastructure development efforts (initiatives, projects, programmes, etc.) positively affect the increase in infrastructure development. The rise in infrastructure development also positively affects the infrastructure development efforts, creating a reinforcing loop R. The rise in infrastructure development is constrained by the balancing loop B, with constraints such as lack of funding, skills shortage, affordability index, etc.

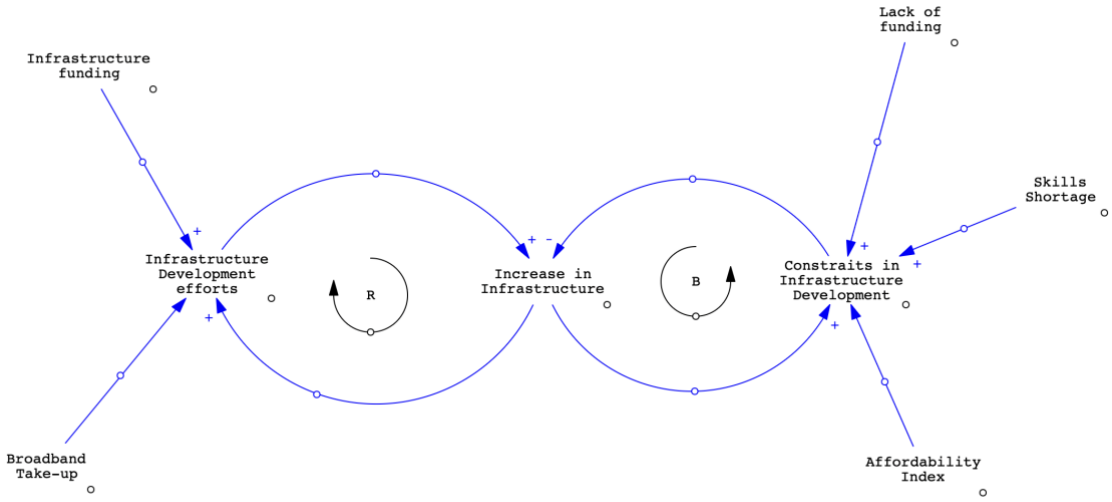
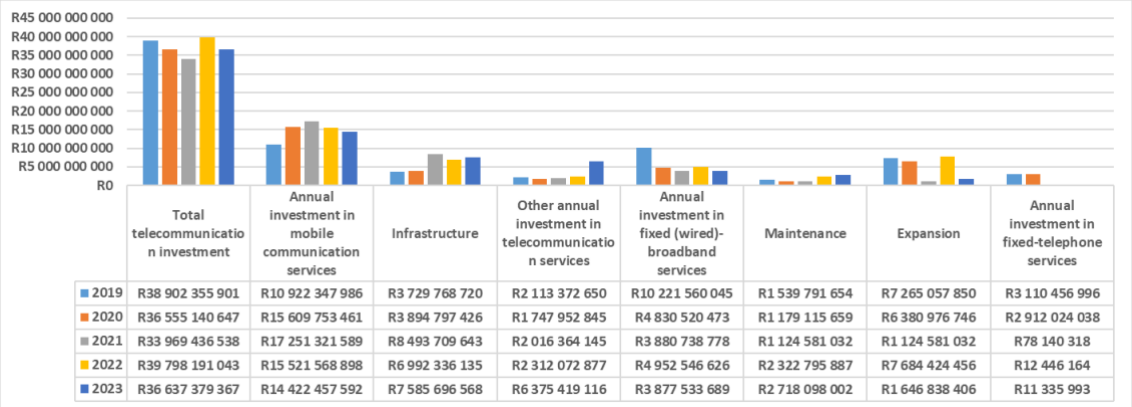


Figure 16: Limits to Growth for Digital Infrastructure Development

Initial growth: The initial growth of digital infrastructure development can be fuelled by digital infrastructure funding. Digital infrastructure funding positively affects digital infrastructure efforts, which positively affect digital infrastructure development. The growth of digital infrastructure development positively affects digital infrastructure efforts, creating a reinforcing loop B. Figure 16 below from ICASA shows the growth factor (digital infrastructure funding) for the 12 months

from 2019 to 2023. Over 5 years, the annual investments in mobile communication services and infrastructure increased by 7.20% and 19.42%, respectively (ICASA, 2024).



	Total telecommunication investment	Annual investment in mobile communication services	Infrastructure	Other annual investment in telecommunication services	Annual investment in fixed (wired)-broadband services	Maintenance	Expansion	Annual investment in fixed-telephone services
2019	R38 902 355 901	R10 922 347 986	R3 729 768 720	R2 113 372 650	R10 221 560 045	R1 539 791 654	R7 265 057 850	R3 110 456 996
2020	R36 555 140 647	R15 609 753 461	R3 894 797 426	R1 747 952 845	R4 830 520 473	R1 179 115 659	R6 380 976 746	R2 912 024 038
2021	R33 969 436 538	R17 251 321 589	R8 493 709 643	R2 016 364 145	R3 880 738 778	R1 124 581 032	R1 124 581 032	R78 140 318
2022	R39 798 191 043	R15 521 568 898	R6 992 336 135	R2 312 072 877	R4 952 546 626	R2 322 795 887	R7 684 424 456	R12 446 164
2023	R36 637 379 367	R14 422 457 592	R7 585 696 568	R6 375 419 116	R3 877 533 689	R2 718 098 002	R1 646 838 406	R11 335 993

Figure 17: (Source: The State of the ICT Sector Report of South Africa March 2024): Telecommunication investment breakdown for the 12 months from 2019 to 2023.

Growth Efforts: Digital Infrastructure Development efforts (initiatives, projects, programmes, etc) positively affect the increase in infrastructure development. The public-private partnerships in South Africa have contributed significantly to developing digital infrastructure. A growing commitment by the South African state to public-private partnerships is also demonstrated in establishing the Infrastructure Fund (IF). This has been structured through the Development Bank of Southern Africa (DBSA), which aims to use billions of public funding over the next 10 years to crowd in private sector investment through blended finance models (Infrastructure South Africa, 2023).

The 5G/broadband take-up rate positively affects digital infrastructure efforts. As more of the population takes up digital services, there is more incentive to bolster digital infrastructure efforts. Furthermore, investments in mobile broadband coverage positively affect mobile broadband take-up. In 2022, 5G coverage stood at 20%; however, by 2023, it surged to 38.42%, marking a substantial increase within a year (ICASA, 2024).

Growth Constraints: After considerable growth in the development of digital infrastructure, the system begins to experience some constraints. The digital infrastructure constraints negatively affect the development of digital

infrastructure, consequently creating a balancing loop B. The digital infrastructure constraints are environmental and financial. Environmental factors, such as climate change, ecological degradation, and natural disasters can constrain infrastructure development. The 2022 Durban floods in South Africa were the most catastrophic in the recent history of KwaZulu Natal. The heavy rains caused serious damage to the telecommunication infrastructure of the main telecommunication operators in the region (Techcentral, 2022).

The financial constraints, such as the affordability index of digital services, contribute significantly to the slow take-up of digital infrastructure. South Africa ranks as one of the top countries in Africa with expensive data prices (GGA, 2024). Some constraints are institutional (governance issues, regulatory frameworks, political instability, Corruption, bureaucratic inefficiencies, and lack of transparency).

4.2.4.1 *Undesired Reference Modes for Digital Infrastructure Development*

Undesired reference modes for a country's digital infrastructure development reflect patterns of change that policymakers and stakeholders aim to avoid. The figure below illustrates the undesired reference modes for digital infrastructure development.

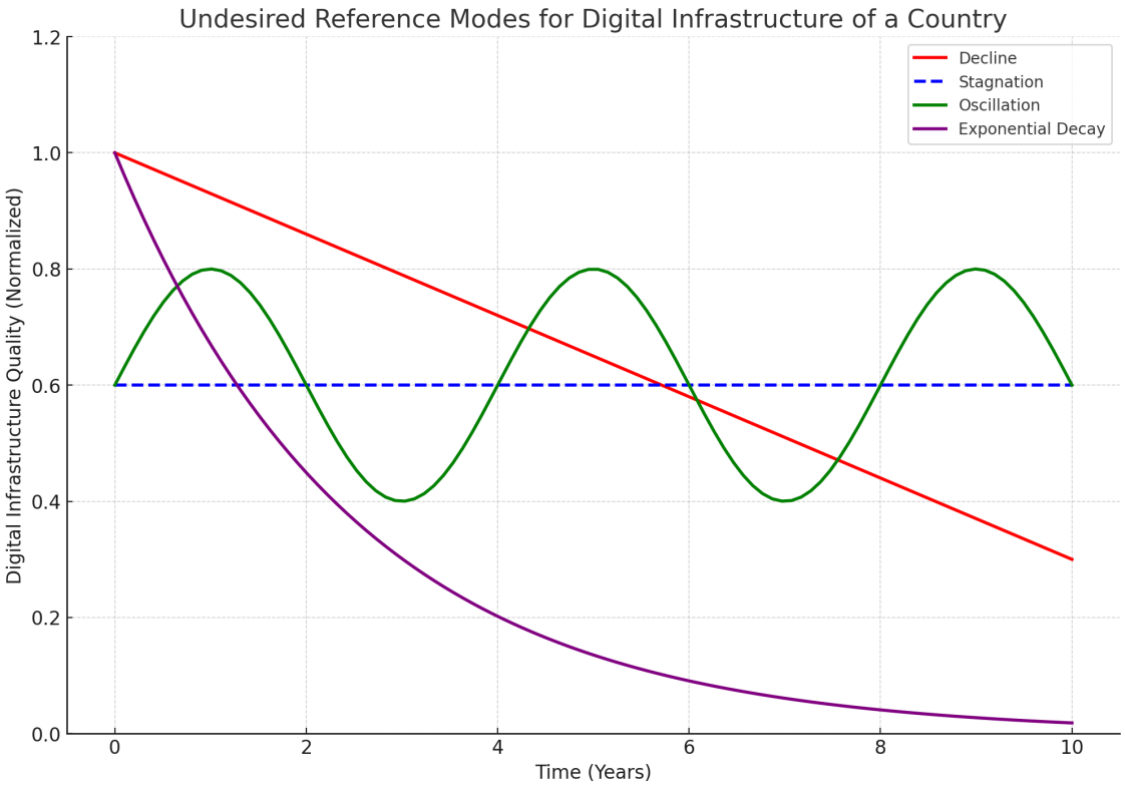


Figure 18: Undesired Reference Modes for Digital Infrastructure Development

These modes include stagnation, boom-and-bust cycles, plateauing, delays in adoption, and erosion or decline.

- **Stagnation** occurs when investments in digital infrastructure fail to keep pace with technological change, leading to flat or negligible growth in broadband penetration or 5G rollout.
- **Boom-and-bust cycles** are seen when sudden surges in infrastructure investment are followed by periods of disinvestment, creating oscillations in digital growth.
- **Plateauing** occurs when the growth of infrastructure reaches a saturation point, often due to market saturation, geographic limitations (like rural areas), or the limits of existing technology.
- **Delays in adoption** arise when infrastructure is available, but adoption is slow due to affordability issues, lack of awareness, or regulatory hurdles, creating a lag between technological availability and societal usage.

- Lastly, **erosion or decline** occurs when existing infrastructure deteriorates due to poor maintenance or technological obsolescence, decreasing the quality or availability of digital services.

4.2.5 *"Shifting the Burden" archetype for Technology Integration*

In Figure 19 below, the "Shifting the Burden" system dynamics archetype can be used to explain the lack of technology adoption in South Africa. This archetype describes a situation where a problem persists because short-term solutions are prioritised over addressing systemic issues.

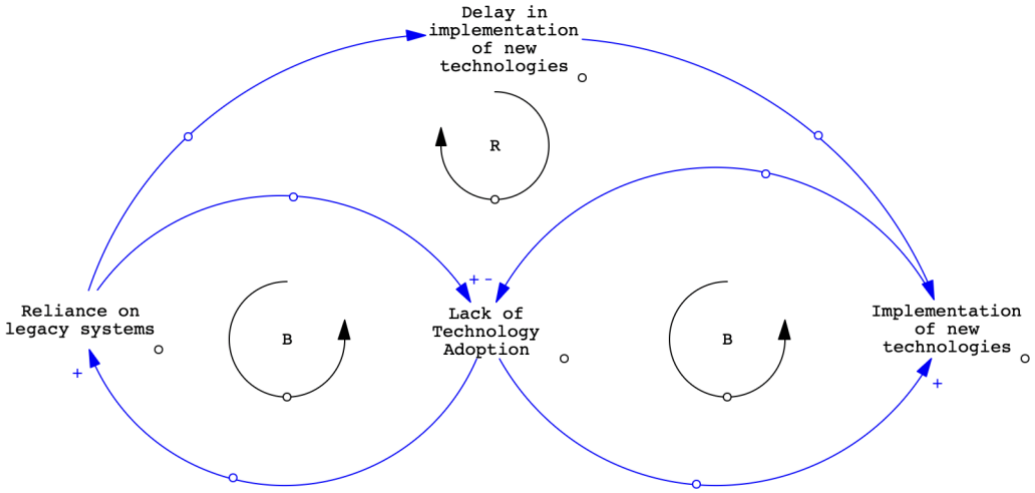


Figure 19: "Shifting the Burden" Archetype for Technology Integration

Symptom: Lack of adoption of new technologies:

Adopting new technologies in South Africa has been slow and/or even declining, as evidenced by reports from several indices such as IMD and The Global Innovation Index (GII). The GII report of 2024 ranks South Africa 69th among the 133 economies featured in the GII 2024 (GII, 2024). A significant ten-point decline from 2023. On the converse, South Africa has improved slightly in ranking as per the IMD Digital Competitiveness Report 2024. The technology factor of IMD

Digital Competitiveness examines the overall context that enables the development of digital technologies. South Africa's ranking improved to 54th in 2024 from 59th in 2023, primarily due to advancements in the technological framework subfactor, which rose from 61st to 55th.

Despite these gains, the regulatory framework subfactor declined from 56th to 62nd, with specific weaknesses in starting businesses (ranked 61st) and immigration laws (ranked 65th). On a positive note, the country ranks 7th in IT and media stock capitalisation and 12th in investment in telecommunications (IMD, 2024).

Short-Term Solutions:

Some short-term solutions employed by South Africa to address slow technology adoption:

- Outsourcing Technical Expertise – The 2022 IITPSA report indicates that the number of SA employers reporting they are recruiting ICT skills overseas has increased dramatically in the past year – up from 38% to over 50% (IITPSA, 2022).
- Overreliance and investment in legacy systems - South African financial institutions have long relied on legacy systems that present significant challenges in the rapidly evolving digital landscape. These systems often lack the agility required to integrate with modern technologies, leading to inefficiencies and increased operational risks (Mantyi, 2020; ITA, 2024).

Symptomatic Relief:

Short-term solutions may provide temporary relief by addressing immediate challenges; however, a more strategic approach is necessary to tackle the growing digital skills gap in the country (IITPSA, 2024). However, these interventions often fail to create sustainable and widespread technology adoption across South Africa, and the underlying barriers to adoption persist.

4.2.5.1 *Undesired Reference Modes for Technology Integration*

Undesired reference modes in this dimension reflect scenarios where technology adoption and integration fail to achieve desired outcomes. The figure below illustrates the undesired reference modes for technology integration for a country

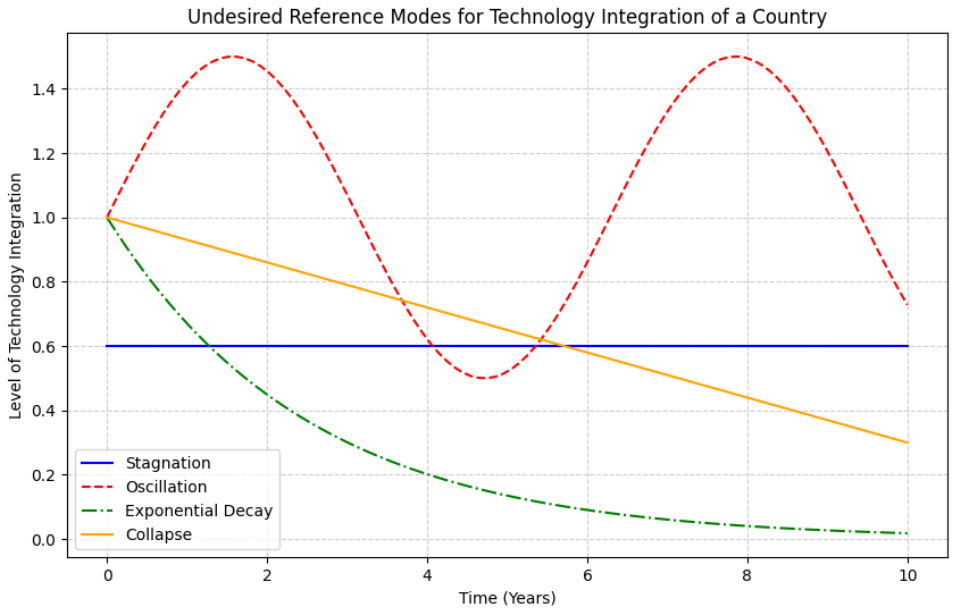


Figure 20: Undesired Reference Mode for Technology Integration

- A decline in technology integration could occur if a country's digital infrastructure, investment, or skills development stagnates, causing it to fall behind in the global digital economy.
- Stagnation may happen when digital transformation efforts plateau, despite government policies and initiatives, resulting in slow or no progress in fields like e-commerce, digital public services, and cloud adoption.
- Oscillation is characterized by periodic fluctuations in technology integration, driven by inconsistent government policies, shifting business priorities, or technological disruptions, leading to a lack of long-term stability.

- Lastly, exponential decay in technology integration could result from rapid technological obsolescence, lack of innovation, or severe underinvestment, causing a steep decline in digital capabilities and exacerbating the digital divide. These reference modes highlight the difficulties countries have in maintaining sustainable, inclusive, and adaptable technology integration.

4.2.6 *"Shifting the Burden" archetype for digital public services.*

In Figure 21 below, the "Shifting the Burden" system dynamics archetype can be used to explain the challenges in the digitalisation of public services in South Africa. Governments recognise the need to modernise public services and address gaps in service delivery gaps through digital technologies. As a result, they implement various initiatives to digitise public services, such as developing online portals, mobile applications, and e-government platforms. Little over a decade ago, the government of South Africa, through the National Development Plan (NDP) (NPC, 2012, p. 190), envisaged that by 2030 "a seamless information infrastructure will be universally available and accessible and will meet the needs of citizens, business and the public sector, providing access to the creation and consumption of a wide range of converged services required for effective economic and social participation – at a cost and quality at least equal to South Africa's main peers and competitors".

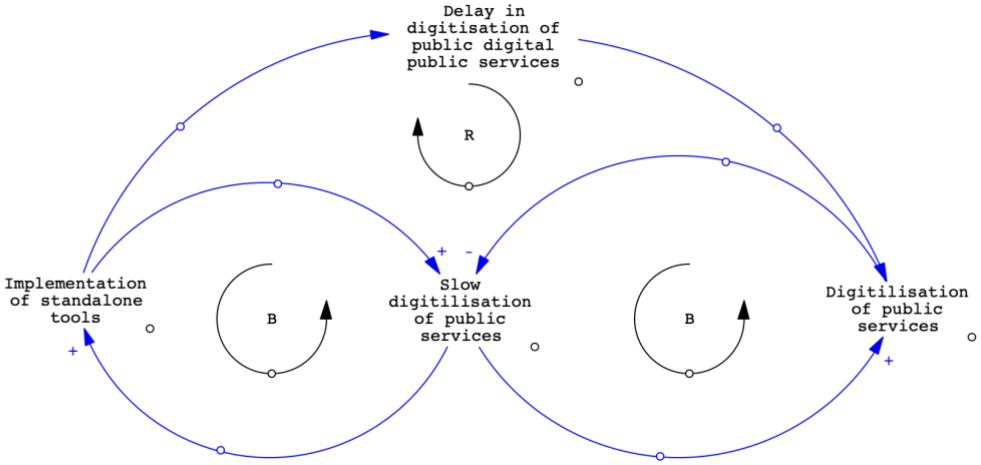


Figure 21: "Shifting the Burden" Archetype for Digital Public Services

Symptom: Slow digitalisation of public services in South Africa

- Many government services, such as Home Affairs (for IDs, passports, and birth certificates), rely heavily on manual processes.
- There is a low number of IT workers in government departments. Brederode (2023) notes that there are around 0.4% of IT staff in the total government workforce of South Africa, with some departments having only 3 IT personnel.
- Long queues, extensive paperwork, and inefficiencies are common.
- Fragmented Digital Initiatives:
    - Some digital tools and platforms exist, such as the e-Filing system for taxes and some Home Affairs online services, but they are often siloed and not part of a broader integrated system.
    - Many online platforms are not user-friendly or are inaccessible to citizens without digital literacy or reliable internet access.
- Citizen Frustration:
    - The slow pace of digitisation results in public dissatisfaction due to delays and service delivery failures.

Short-Term Solutions:

- Temporary Staff and Resources:

- The government often hires additional temporary staff or extends operating hours to manage backlogs (e.g., at Home Affairs or Social Development offices).

- Standalone Digital Tools:
  - Initiatives like the Department of Home Affairs' online booking system or SARS' e-Filing platform address specific issues but are not integrated into a broader, seamless ecosystem of digital public services.

4.2.6.1 *Undesired Reference Modes for Digital Public Services*

Undesired reference modes for digital public services in a country represent performance patterns or trends hindering progress and accessibility. The figure below illustrates the undesired reference modes for digital public services for a country.

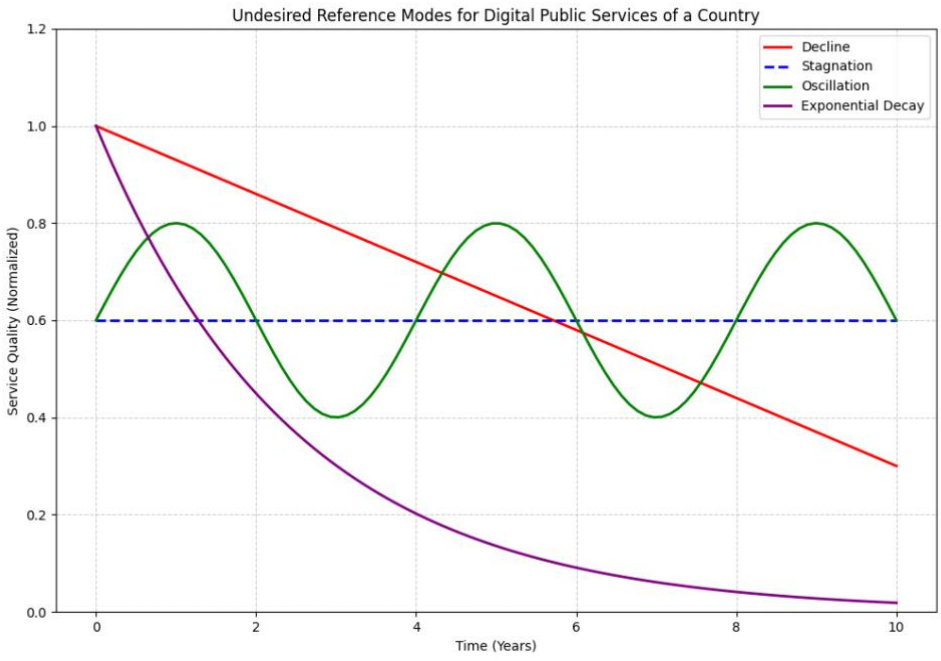


Figure 22: Undesired Reference Mode for Digital Public Services

- **Decline** refers to a steady deterioration in the quality or availability of digital services, often caused by underinvestment, technological obsolescence, or poor infrastructure maintenance.
- **Stagnation** occurs when digital public services fail to evolve or improve. This results in outdated systems that cannot meet citizens' growing needs, leading to frustration and inefficiencies.
- **Oscillation** is characterised by inconsistent fluctuations in service quality or availability, where periods of improvement are followed by declines, often due to erratic government policies, funding issues, or temporary fixes.
- **Exponential decay** represents a rapid and severe decline in digital services, usually resulting from a sudden loss of infrastructure, major technological shifts, or severe mismanagement. This drastically impacts citizens' access to essential services. These undesired trends highlight the importance of proactive, consistent, and forward-thinking policies to ensure that digital public services remain reliable, scalable, and effective.

4.3 Sub-system Diagram for Digital Maturity

The dynamic interaction between digital skills, digital infrastructure, technology integration, and digital public services is crucial, as these elements are interdependent and collectively contribute to the digital maturity of a country. Figure 23 below shows the conceptual model of these interactions developed by the research.

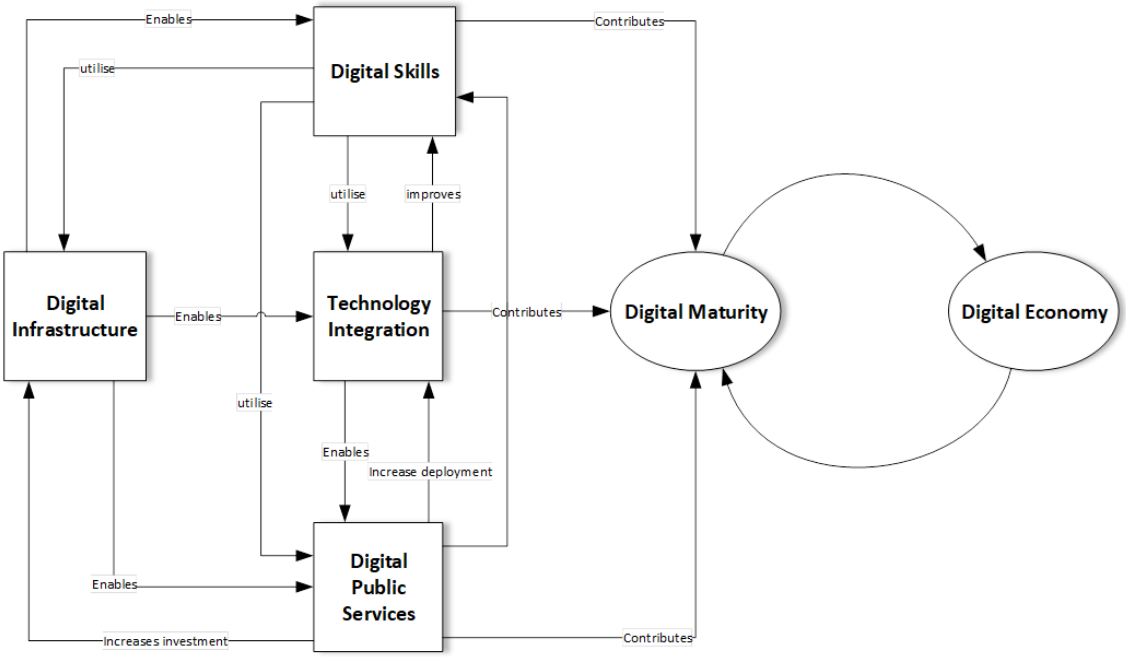


Figure 23: Subsystem diagram showing feedback relationships between the four DESI dimensions as part of the digital maturity model in South Africa.

The synergistic relationship of each component relative to the others is as follows:

4.3.1 *Digital Infrastructure and Digital Skills*

Robust digital infrastructure, such as high-speed internet and widespread connectivity, provides the foundational platform for accessing digital tools and resources. This accessibility enables individuals and organisations to develop and enhance digital skills through online learning platforms, digital training programs, and access to information. As digital skills improve, Individuals and organisations with improved and strong digital skills are better equipped to utilise digital infrastructure efficiently. They can maximise the benefits of available technologies, leading to improved productivity and innovation.

Furthermore, as digital skills improve, there is a growing demand for more sophisticated and reliable digital infrastructure. Skilled users require high-speed internet, secure networks, and advanced technological tools to perform complex tasks, thereby driving investment and development in digital infrastructure.

4.3.2 *Digital Infrastructure and Technology Integration*

Robust digital Infrastructure is fundamental for both individuals and businesses to engage in digital activities. High-quality digital infrastructure supports deploying and using advanced technologies (e.g., cloud computing, IoT, AI). Better connectivity facilitates the adoption of digital tools and technologies by businesses. Increased technology integration leads to increased demand for robust and reliable digital infrastructure. The increased demand and economic benefits derived from technology integration drive further investments in digital infrastructure.

4.3.3 *Digital Skills and Technology Integration*

Investments in digital skills enhance the workforce's capability to adopt and utilise digital technologies, supporting business growth and economic development. Employees with strong digital skills can leverage tools like cloud computing, big data analytics, and e-commerce platforms to enhance productivity and innovation. This growth leads to further investment in skills development, creating a continuous improvement loop. Furthermore, as businesses integrate more digital technologies, there is an increased demand for employees with the necessary skills to manage and operate these technologies. This creates a positive feedback loop where technology adoption drives the need for continuous skill development.

4.3.4 *Digital Infrastructure and Digital Public Services*

Robust digital infrastructure provides the essential foundation for digital public services. Digital public services cannot be effectively delivered or accessed without reliable and widespread broadband connectivity. High-speed networks and cloud services enable the scalability of digital public services, allowing governments to serve a larger population efficiently and effectively. Advanced infrastructure supports the deployment of innovative public services, such as AI-driven applications, big data analytics for public health, and IoT-based smart city solutions.

As more public services go digital, the demand for reliable and high-speed internet increases. This encourages investment in upgrading and expanding digital infrastructure. The success and increased usage of digital public services can create a positive feedback loop, where the demand for better infrastructure drives further investment, which in turn enhances the capacity and quality of public services.

4.3.5 *Digital Skills and Digital Public Service*

High levels of digital skills among the workforce enable the development and implementation of advanced digital public services. Skilled individuals can design, develop, and maintain digital platforms that provide public services, ensuring these services are efficient, user-friendly, and secure. When citizens possess digital skills, they are more likely to use digital public services. This includes accessing e-government platforms, utilizing online health services, and participating in digital education programs. High user engagement can lead to better outcomes and higher satisfaction with public services.

Digital public services often include educational resources and training programs that help citizens enhance their digital skills. For example, online courses, digital literacy programs, and e-learning platforms provided by the government can improve the population's overall digital competence.

As public services become more digitalised and accessible, more people engage with digital tools and platforms. This interaction inherently improves their digital skills through practical use and experience, creating a more digitally literate society.

As digital public services expand and improve, there is a higher demand for a workforce with advanced digital skills to manage and enhance these services. This can lead to increased investment in education and training programs, further boosting the digital skill level of the population.

Enhanced digital skills contribute to innovation within public services, leading to more effective and efficient service delivery. This, in turn, can drive economic

growth by improving productivity, reducing costs, and fostering a more innovative public sector.

4.4 Causal Loop Diagrams for Digital Maturity

Causal loop diagrams (CLDs), which were first introduced in Section 2.10.5, can be employed to map the interrelationships between the various dimensions, sub-dimensions, and indicators of the DESI (Digital Economy and Society Index). In such a diagram, each dimension would be represented as a variable influencing corresponding sub-dimensions, which, in turn, affect specific indicators. Feedback loops would emerge from the interaction between these elements, where changes in one dimension could either amplify or dampen effects in another, creating reinforcing or balancing feedback mechanisms. The relationships could be depicted through arrows indicating cause-and-effect dynamics, with positive or negative feedback indicating the nature of the influence. By capturing these interactions, CLDs help in understanding how shifts in one area of the DESI framework can trigger cascading effects throughout the broader system, highlighting the interconnectedness and potential leverage points within the digital economy and society. All CLDs in this section were developed by the researcher based on the DESI framework and contextualised to the South African case.

The causal loop diagram in Figure 24 below illustrates a mutually reinforcing digital transformation system comprising four core elements: digital skills, digital infrastructure, technology integration, and digital public services. An increase in digital skills enhances the public sector's capacity to adopt and integrate new technologies, which in turn expands the scope and quality of digital public services. The growth of digital public services stimulates further development of digital skills among both public officials and citizens as engagement with digital platforms becomes routine. Digital infrastructure underpins and strengthens all components in the system by enabling effective technology deployment, facilitating skills development, and supporting the delivery of digital services. Simultaneously, advances in digital services and technology integration create heightened demand for improved infrastructure, reinforcing investment and

expansion in this domain. Collectively, these positive feedback loops depict a virtuous cycle in which improvements in one dimension of the digital ecosystem amplify progress across the others, accelerating the overall digitalisation of public services.

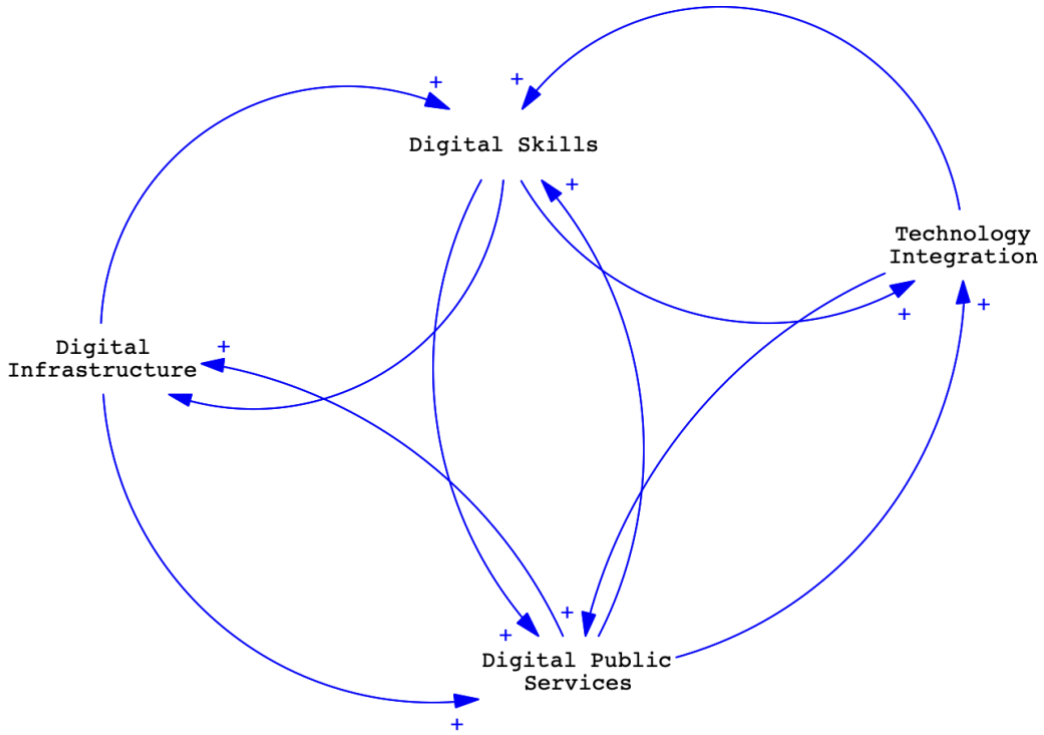


Figure 24: CLD for Digital Maturity.

Table 6 below explains in more detail the causal loops from Figure 24 above.

Table 6: Description of country-level digital maturity loops

LOOP	EXPLANATION
R1: THE DIGITAL SKILLS - DIGITAL INFRASTRUCTURE LOOP	Better Digital Infrastructure provides people access to online learning platforms, digital education resources, and remote work opportunities. As digital skills increase, there is a higher demand for better, faster digital infrastructure.

R2: THE DIGITAL TRANSFORMATION INVESTMENT LOOP	Better digital infrastructure enables businesses to adopt advanced digital technologies (like cloud, IoT, or AI). As companies integrate more digital technology, it drives demand for better digital infrastructure to support these tools, prompting further investment in digital infrastructure.
R3: THE E-GOVERNMENT ACCESS LOOP	Improved digital infrastructure increases access to online public services. When citizens and businesses use these services, it motivates governments to further develop and improve these platforms, requiring enhanced digital infrastructure.
R4: THE SKILLS FOR DIGITAL TRANSFORMATION LOOP	As the workforce becomes more skilled in digital technologies, businesses are more likely to adopt and integrate new digital tools. As companies use more technology, they require a more skilled workforce, encouraging more people to upskill.
R5: THE E-CITIZEN SKILLS LOOP	As citizens acquire digital skills, they become more capable of using digital public services. Greater usage of these services prompts the government to create better, more user-friendly systems, which motivates people to develop their digital skills further.
R6: THE PUBLIC-PRIVATE DIGITAL COLLABORATION LOOP	Digital public services rely on businesses to develop apps, infrastructure, and software. As more public services go digital, the private sector sees more opportunities to integrate technologies (e.g., cloud services), leading to further innovation in digital services.

4.4.1 *Digital Skills*

4.4.1.1 *Digital Skills CLD*

The digital skills causal loop diagram is depicted in Figure 25 below: illustrates the interconnected dynamics that underpin the development of digital skills within an evolving digital ecosystem. At the core of the system is digital literacy, which is reinforced through multiple skill pathways. As internet user skills increase, they stimulate higher internet usage, which in turn enhances content creation skills. Improved content creation skills elevate overall digital literacy, which then feeds back positively into internet user skills, forming a reinforcing loop.The model also differentiates between levels of digital capability. Basic skills support the acquisition of above-basic skills, which subsequently enable the development of advanced skills. These advanced skills strengthen digital literacy, illustrating a developmental progression where each layer of skills builds upon the previous one.

The diagram further incorporates the professional pipeline of the digital sector. Growth in ICT training enterprises produces more ICT graduates, who enter the workforce as ICT specialists. An increase in ICT specialists contributes to higher levels of advanced digital skills and development, reinforcing both the skills ecosystem and the broader digital literacy base. Overall, the model depicts a system dominated by reinforcing feedback loops, showing how improvements in foundational skills, professional capacity, and digital participation amplify one another. This creates a cumulative effect that supports long-term digital capability growth at individual and systemic levels.

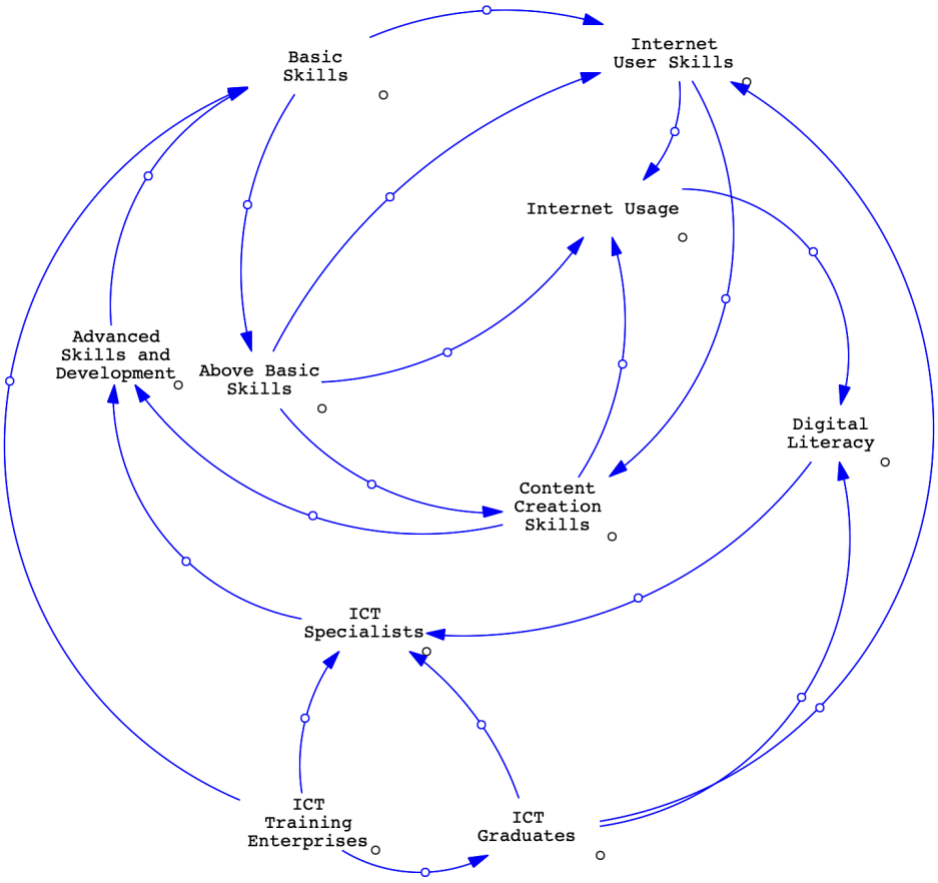


Figure 25: Digital Skills CLD

Table 7 below explains in detail the causal loops in Figure 25 above.

Table 7: Description of digital skills causal loops

LOOP	EXPLANATION
R1: SKILLS GROWTH CYCLE	Population with basic digital skills form a pipeline to learn advanced skills, ultimately becoming ICT specialists. This Increases workforce productivity which further demand for further digital literacy.
B1: INTERNET ACCESS CONSTRAINT	Lack of internet access hinders basic digital skill development which then limits advanced

	skill pipeline ultimately leading to restricted ICT specialist growth.
B2: STEM GRADUATE SHORTFALL	insufficient STEM graduates limits ICT recruitment pipeline into the workforce skill ultimately leading to restricted ICT specialist growth.

4.4.1.2 *Desired Reference Mode for Digital Skills*

The desired reference mode for a country's digital skills reflects the goal of achieving sustained, exponential growth followed by stabilisation. This typically follows an S-shaped growth curve, which reflects a gradual but accelerating improvement in both basic and advanced skills across the population. Initially, progress is slow due to limited access to education, training, and awareness of the importance of digital skills, as illustrated by the "Limits to Growth" archetype in section 4.2.3. However, with more focus and funding into training programs, the pace of digital skills development accelerates. Ideally, the growth should stabilise at a high level, where a large proportion of the population possesses basic to advanced digital competencies. Key influencing factors include the availability of ICT training programs, the integration of digital skills into formal education, and ongoing reskilling and upskilling opportunities for the workforce. Figure 26 below depicts the desired reference modes for the digital skills for a country.

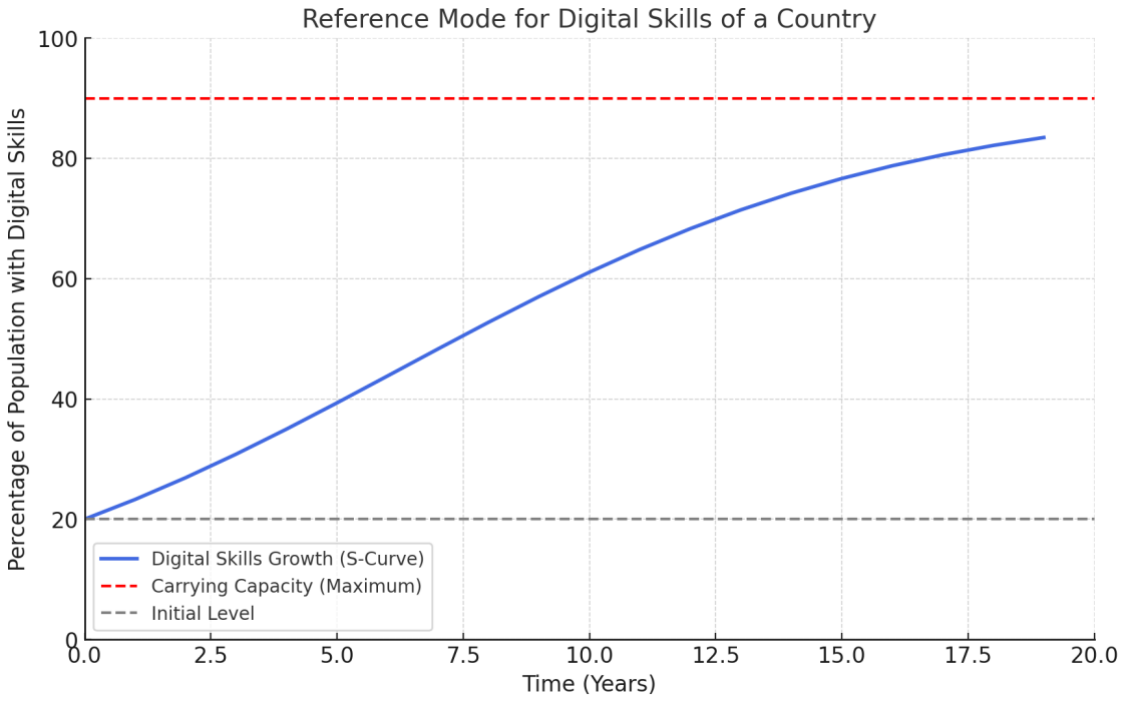


Figure 26: Desired Reference Mode for Digital Skills for a Country

4.4.2 *Digital Infrastructure*

4.4.2.1 *Digital Infrastructure CLD*

The Digital Infrastructure causal loop diagram is depicted in Figure 27 below, illustrates the interconnected dynamics of broadband infrastructure deployment and market adoption. The system is primarily driven by two strong, coupled reinforcing mechanisms where the Utilisation of Digital Services fuels Demand for Improved Infrastructure, which secures Infrastructure funding to further enhance both fixed and mobile network coverage and, subsequently, adoption. Critically, this growth-driving process is counterbalanced by a negative feedback loop centred on affordability: high utilisation is modelled as driving Broadband prices upward, thereby negatively impacting Broadband Affordability and imposing a natural constraint on the rate of Mobile broadband take-up. Consequently, the system exhibits dynamics of self-reinforcing growth tempered by a critical price-elasticity ceiling, suggesting that sustainable expansion

necessitates intervention to decouple rising demand from escalating consumer costs.

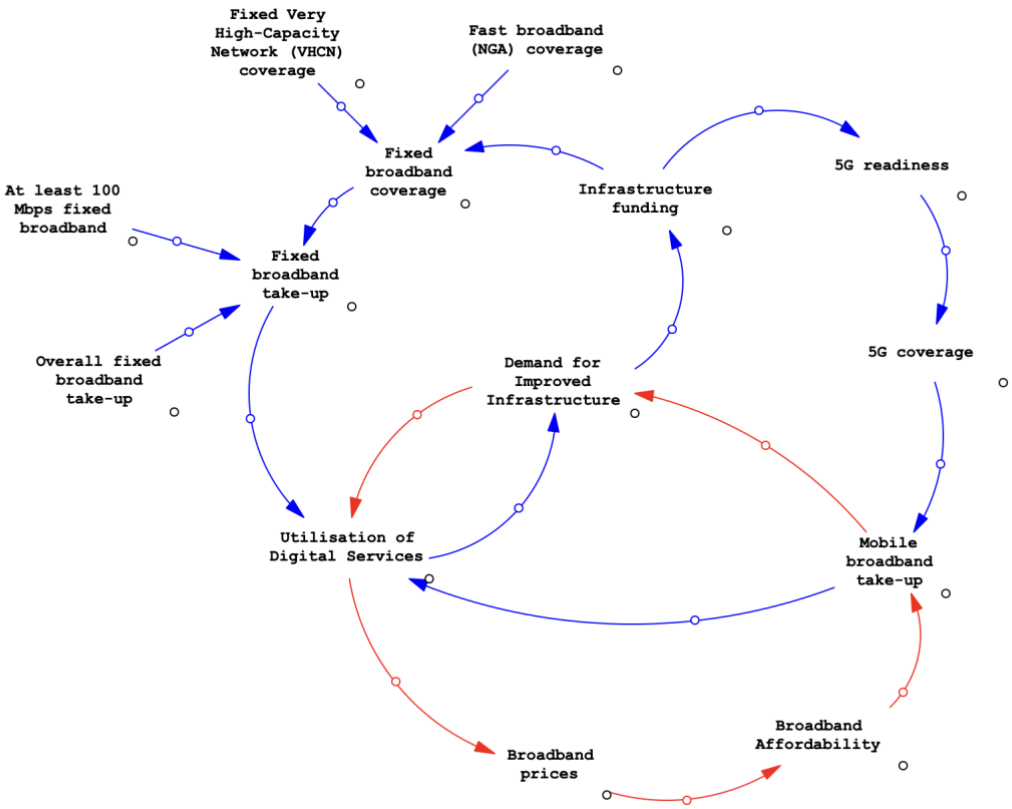


Figure 27: Digital Infrastructure CLD

Table 8 below explains the causal loops from Figure 27 above in detail.

Table 8: Description of digital infrastructure causal loops

LOOP	EXPLANATION
R1: BROADBAND DEMAND AND COVERAGE	Increased broadband take-up leads to a higher demand for fast and ultra-fast broadband. This demand Incentivises investment in infrastructure. More coverage leads to more broadband availability which attracts further increases in service take-up.

R2: MOBILE CONNECTIVITY AND DIGITAL UPTAKE	Wider 5G coverage attracts an Increase in 5G subscriptions. This boosts mobile internet usage which leads to a demand for better mobile infrastructure ultimately incentivising further 5G rollout.
B1: AFFORDABILITY AND DEMAND	High broadband prices limit take-up among low-income groups which reduces demand ultimately leading to low investment in coverage and quality.
B2: CAPACITY AND OVERUSE	Increased internet traffic per user strains network capacity which leads to bad user experience ultimately slowing growth in broadband

4.4.2.2 *Desired Reference Modes for Digital Infrastructure*

The desired reference mode for a country's digital infrastructure reflects the goal of achieving sustained, exponential growth followed by stabilisation at a high-performance level. Initially, the infrastructure (e.g., broadband coverage, 5G networks, fibre-optic connections) should experience accelerated growth as investment surges and connectivity expands to underserved areas. This growth typically follows an S-shaped curve, where initial adoption of digital services is slow due to limited coverage and the high cost of digital services. This was illuminated by the “Limits to Growth” archetype in section 4.2.4. This is then followed by rapid expansion as investments in infrastructure increase. Finally, growth slows as infrastructure nears saturation (full coverage and capacity). Figure 28 below depicts the reference mode for desired desired digital infrastructure.

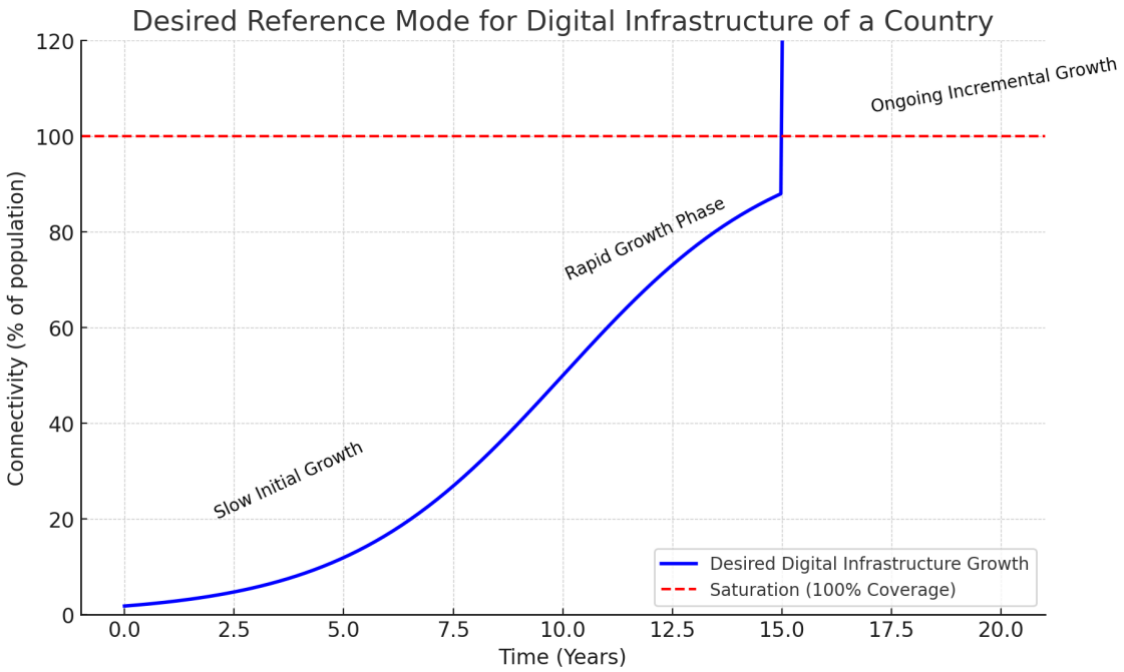


Figure 28: Desired Reference Mode for Digital Infrastructure

4.4.3 *Technology Integration*

4.4.3.1 *Technology Integration CLD*

The Technology integration causal loop diagram is depicted in Figure 29 below illustrates the systemic relationship between digital infrastructure adoption and economic efficiency, primarily focusing on small and medium enterprises (SMEs) and e-commerce. The core dynamic is a dominant reinforcing cycle wherein Cost Reduction/Efficiency positively fuels the adoption of sophisticated digital tools: it stimulates Demand for Cloud Services, accelerates Cloud Computing Adoption, enhances Big Data capabilities, and fosters AI development, all of which contribute to further efficiency gains. This virtuous cycle is externally accelerated by the growth of e-Commerce turnover and SMEs selling online. However, this mechanism is critically moderated by a balancing loop: increasing Cloud Computing Adoption leads to rising Cloud Computing Costs, which directly opposes and limits the overall Cost Reduction/Efficiency achieved. Consequently, the model suggests that while technological integration generates significant organisational value, the full realisation of economic efficiency is

dynamically constrained by the accumulating cost structure of the underlying digital infrastructure.

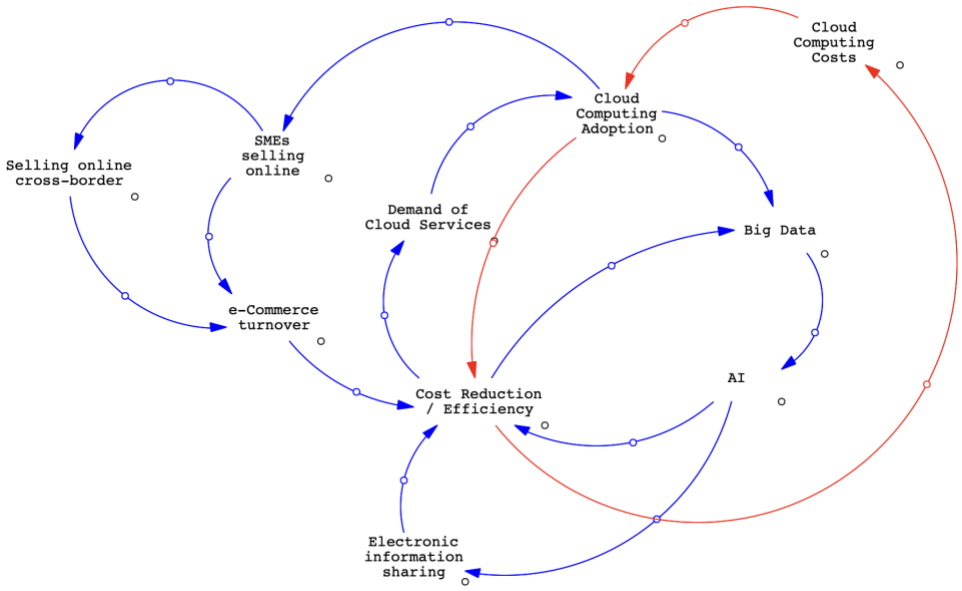


Figure 29: Technology Integration CLD

Table 9 below explains the causal loops in Figure 29 in more detail.

Table 9: Description of technology integration causal loops

4.4.3.2 *Desired Reference Modes for Technology Integration*

The desired reference mode for technology integration within a country's DESI (Digital Economy and Society Index) framework is an "S-shaped growth curve" representing a steady and continuous improvement over time. Initially, the adoption of technology starts slowly as users, businesses, and governments navigate through learning curves, resistance to change, and limited infrastructure. Over time, with increased investments in digital infrastructure, regulatory reforms, and capacity-building efforts, the rate of technology integration accelerates. This acceleration is often driven by network effects, increased digital literacy, and the availability of advanced technological solutions,

resulting in exponential growth during the mid-phase. Once technology becomes widespread, the growth rate begins to level off as the country approaches saturation, and further gains are incremental rather than exponential.

In this context, the ideal scenario for a country's DESI performance would show steady progress in technology adoption, integration into business processes, public service digitisation, and citizen participation in digital platforms. Such a trajectory would demonstrate successful alignment with global best practices, increased competitiveness, and improved socio-economic outcomes. Ensuring sustained growth in technology integration requires continuous investment in education, infrastructure, and policy support to avoid stagnation or regression. The desired reference mode for technology integration for a country is depicted in picture 30 below.

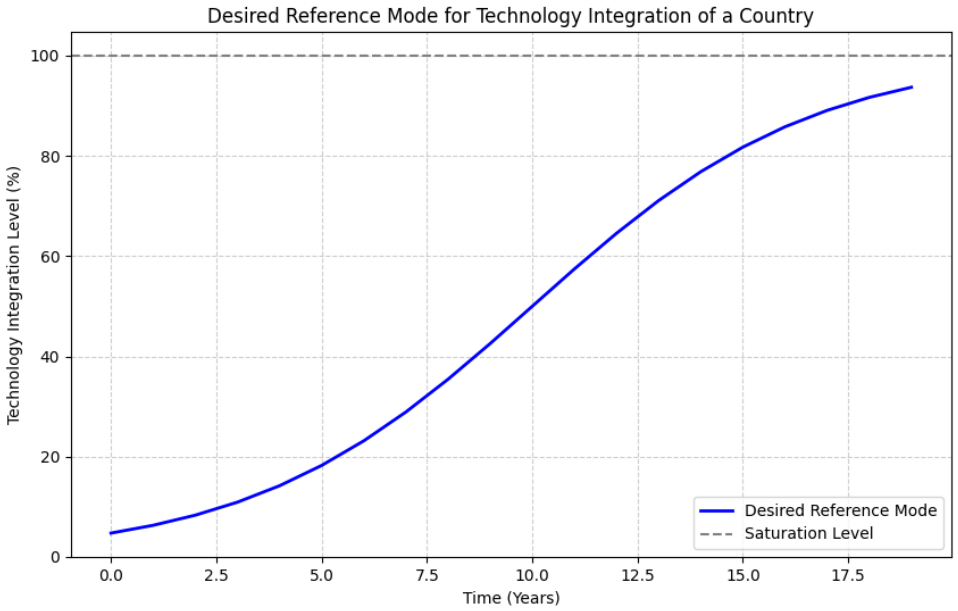


Figure 30: Desired Reference Mode for Technology Integration

4.4.4 *Digital Public Services*

4.4.4.1 *Digital Public Services CLD*

The digital Public Services causal loop diagram is depicted in Figure 31 below, illustrates the systemic influences governing the adoption and impact of e-Government services, primarily through the interaction of efficiency and access. The model establishes a powerful reinforcing cycle where Efficiency/Cost saving drives the development of Digital public services for citizens and businesses, encouraging their Adoption of Digital Services, which, in turn, amplifies the system's overall efficiency. A key element accelerating this is the provision of user-friendly features like Pre-filled forms. Conversely, the system is fundamentally constrained by a significant balancing loop related to equality: increases in e-Government users and the adoption of Digital Services reinforce the Digital Divide, diminishing Internet Access and ultimately limiting the growth of the user base. This dynamic suggests that while efficiency gains promote service development, the inherent disparities in Internet Access pose a persistent barrier that actively limits the penetration and universal success of e-Government initiatives.

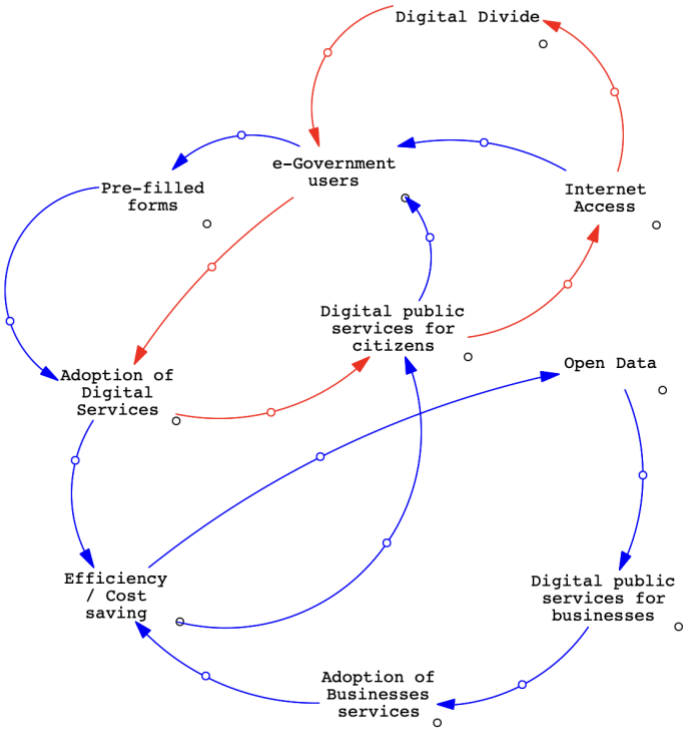


Figure 31: Digital Public Services CLD

Table 10 below provides a detailed explanation of the causal loops in Figure 31.

Table 10: Description of digital public services causal loops

Loop	Explanation
R1: Digital Service Utilization Loop	Increased availability of pre-filled forms and online service completion simplifies administrative processes. This encourages more citizens to use digital public services. Increased utilisation leads to service improvement.
R2: Citizen Engagement Loop	Higher digital public service accessibility boosts citizen engagement with government platforms. This then encourages investment in digital public services which increases service adoption and satisfaction.

B1: Digital Divide Loop	Lack of access to the internet or digital literacy limits usage of eGovernment services which slows growth in service adoption.
B2: Resource Constraints Loop	Limited government budgets → Constrain investments in digital infrastructure → Slows the rollout of new digital public services.

The matrix below gives a summary of the loops described above

SUBSYTEM	REINFORCING LOOP	BALANCING LOOP
ENTIRE DIGITAL MATURITY OF A COUNTRY	R1, R2, R3, R4, R5, R6	
DIGITAL SKILLS	R1	B1, B2
DIGITAL INFRASTRUCTURE	R1, R2	B1, B2
TECHNOLOGY INTEGRATION	R1, R2, R3	B1, B2, B3
DIGITAL PUBLIC SERVICES	R1, R2	B1, B2

4.4.4.2 *Desired Reference Modes for Digital Public Services*

The desired reference mode for a country's digital public services is one of continuous growth and improvement. Ideally, digital public services should evolve to meet the changing needs of citizens, ensuring accessibility, efficiency, and inclusivity. This growth should be marked by steady progress in expanding coverage, enhancing service quality, and integrating new technologies. The reference mode would reflect an upward trajectory, with increasing digital adoption, greater user satisfaction, and integration of emerging technologies like AI, machine learning, and blockchain to streamline government processes. Over time, these services should become more responsive and adaptable, improving public engagement, reducing administrative burdens, and providing a seamless digital experience for all citizens. The aim is to create a dynamic, forward-looking system that addresses societal challenges, fosters economic development, and promotes social equity. The desired reference mode for digital public services for a country is depicted in picture 32 below.

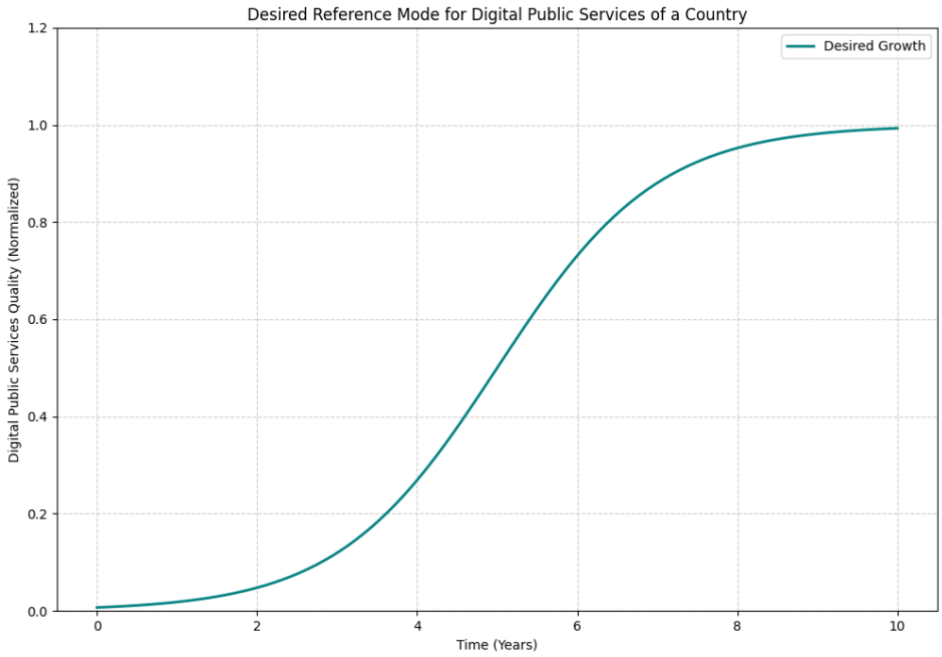


Figure 32: Desired Reference Mode for Digital Public Services

4.5 Stock and Flow Diagrams for Digital Maturity

4.5.1 *Introduction*

The four DESI dimensions, sub-dimensions, and indicators outlined in Table Two of Chapter Three were used to construct stock-and-flow diagrams of digital maturity in the context of South Africa. The Stock and Flow diagrams were introduced and discussed in detail in Chapter 2, Section 2.10.5. The Vensim PLE software was used to develop the structure of the models. The four dimensions, Digital Skills, Digital Infrastructure, Technology Integration, and Digital Public Services, and their Stocks and Flow diagrams are discussed below. It is important to note that the models do not contain all the indicators as outlined by the DESI framework, but rather the important indicators, else the models would be complicated, cumbersome and unwieldy. For example, in the 2024 version of DESI, additional networks such as Fixed Very High Capacity Networks and Fibre to home are excluded as they represent a different version of fixed networks, As Sterman (2000) cautions, “A model is a representation of a system…For a model to be useful, it must address a specific problem and must simplify rather than attempt to mirror an entire system in detail”.

4.5.2 *Digital Skills*

4.5.2.1 *The Model Structure*

The first SD model presented in Figure 33 below has been developed to represent the structural and behavioural complexity underpinning the evolution of digital skills within South Africa’s digital economy. Grounded in the methodological principles outlined by Sterman (2000), the model conceptualises the causal relationships and feedback loops among critical variables, including population growth, education pathways, training investments, and workforce integration. It delineates the progression from basic skills acquisition through advanced training and ICT specialisation, culminating in the formation of ICT and STEM graduates who contribute to the national labour force. Key feedback structures, such as the reinforcing effects of training investment on skill

accumulation and the balancing impacts of migration and dropout rates, capture the dynamic interactions that influence digital skills formation over time. This model serves as a foundational step for simulation and policy experimentation, enabling the exploration of alternative strategies aimed at enhancing digital maturity and addressing skill shortages in South Africa's ICT sector.

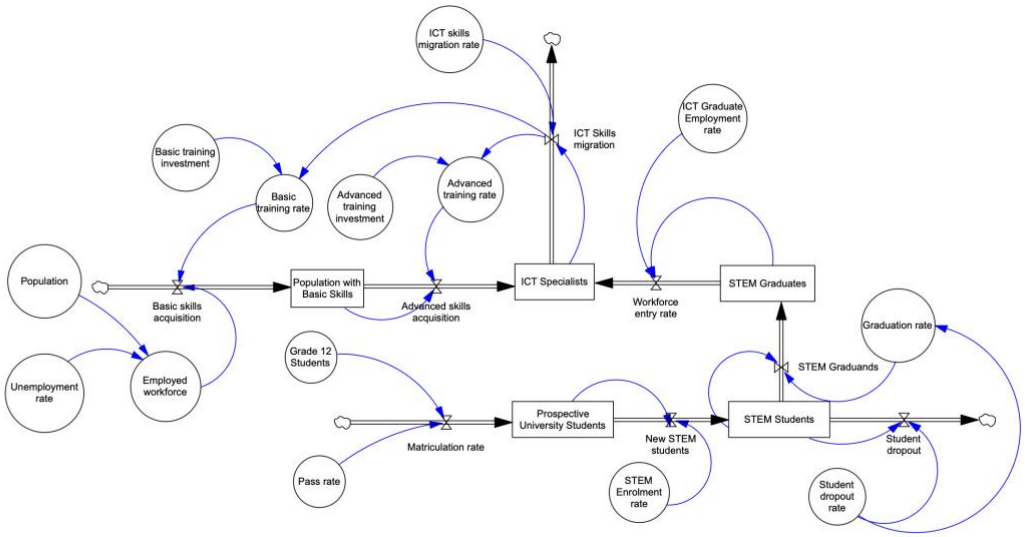


Figure 33: Digital Skills Stock and Flow Diagram formulated in Vensim PLE

The first dimension of the DESI framework, which is Digital Skills, encompasses the ability of individuals to effectively utilise digital technologies, segmented into sub-dimensions like basic digital skills, STEM graduates and advanced skills (i.e. ICT specialists). Stocks in this dimension represent accumulations such as the population with basic digital skills, STEM graduates, and ICT specialists in the workforce. Flows are the rates at which these stocks change, driven by factors like training programs, enrolment in education systems, self-learning adoption, and workforce attrition. For self-learning adoption, according to IITPSA (2024), a growing number of practitioners are either interested in or have taken a short course or certification to complement their tertiary qualification on platforms such as Coursera, Skillshare, and Udemy, with some pursuing professional certifications and vendor certifications. For instance, the inflow to the stock of individuals with basic digital skills may include school-based training, community initiatives, and government-sponsored digital literacy campaigns. As these are qualitative, the model defines a qualitative composite attribute, basic training rate,

to represent them (refer to Figure 33). The outflow could consist of skill degradation over time or shifts to advanced skill categories. Similarly, the development of ICT specialists is influenced by flows such as higher education enrolments in ICT fields, upskilling through certifications, and career advancements, with attrition caused by ICT Skills migration.

4.5.2.2 *Digital Skills Stocks*

The first stock, Population with basic skills, can be described as the value of Population with basic skills at time t, plus an increase in Population with basic skills (Basic skills acquisition) at time t, minus any persons who acquire advanced skills at time t. This can be described mathematically as in equation 1 below.

$$Population\ with\ basic\ skills\ (t) = Population\ with\ basic\ skills\ (t-1) + Basic\ skills\ acquisition - Advanced\ skills\ (t) \qquad EQ1$$

The second stock, People with advanced skills (i.e. ICT specialists), can be described as the value of ICT Specialists at any time t, plus an increase in People with advanced skills at time t minus any persons that migrate (ICT Skills migration) at time t. This can be described mathematically as in equation 2 below.

$$ICT\ Specialists\ (t) = ICT\ Specialists\ (t-1) + ICT\ Specialists - ICT\ Skill\ migration\ (t) \qquad EQ2$$

The third stock, STEM Students, can be described as the value of STEM Students at any time t, plus an increase in new students who enrol into STEM at time t, minus any students who have completed their STEM studies (STEM graduands) at time t. This can be described mathematically as in equation 3 below.

$$STEM\ Students\ (t) = STEM\ Students\ (t-1) + STEM\ Students - STEM\ Graduands\ (t) \qquad EQ3$$

The fourth stock, STEM Graduates, can be described as the value of STEM Graduates at time t plus an increase in STEM Graduates at time t minus any students that enter the workforce (workforce entry rate) at time t. This can be described mathematically as in equation 4 below.

$$STEM\ Graduates\ (t) = STEM\ Graduates\ (t-1) + STEM\ Graduates\ -\ ICT\ workforce\ entry\ rate\ (t) \quad EQ4$$

4.5.2.3 *Digital Skills Flows*

The first flow, basic skills acquisition, can be described as a function of the employed workforce and basic skill training rate. This can be expressed mathematically as in equation 5 below.

$$Basic\ skills\ acquisition\ (t) = Employed\ workforce * Basic\ training\ rate \quad EQ5$$

The second flow, advanced skills acquisition, can be described as a function of the employed workforce and basic skill training rate. This can be expressed mathematically as in equation 5 below.

$$Advanced\ skills\ acquisition\ (t) = Population\ with\ Basic\ Skills * Advanced\ training\ rate \quad EQ6$$

The third flow, matriculation rate, can be described as a function of students doing their final year in high school (grade 12) and the pass rate. This can be expressed mathematically as in equation 7 below. The “Pass rate” is defined as a constant variable.

$$Matriculation\ rate\ (t) = Grade\ 12\ Students * Pass\ rate \quad EQ7$$

The fourth flow, New STEM Students, can be described as a function of prospective tertiary students and the STEM enrolment rate. This can be expressed mathematically as in equation 8 below.

$$New\ STEM\ Students\ (t) = Prospective\ University\ Students\ (t) * STEM\ Enrolment\ rate \quad EQ8$$

The fifth flow, Student dropout rate, can be described as a function of currently enrolled STEM students and the student dropout rate. This can be expressed mathematically as in equation 9 below.

$$Student\ dropout\ (t) = STEM\ Students\ (t) * Student\ dropout\ rate \quad EQ9$$

The sixth flow, STEM Graduands, can be described as a function of currently enrolled STEM students and the graduation rate. This can be expressed mathematically as in equation 10 below.

$$New\ STEM\ Graduands\ (t) = STEM\ Students\ (t) * Graduation\ rate \quad EQ10$$

The seventh flow, Graduate workforce entry, can be described as a function of current STEM graduates and the graduate employment rate. This can be expressed mathematically as in equation 11 below.

$$Graduate\ Workforce\ entry\ (t) = STEM\ Graduates\ (t) * ICT\ Graduate\ Employment\ rate \quad EQ11$$

The eighth flow, ICT Skills migration, can be described as a function of current ICT specialists and the ICT skills migration rate. This can be expressed mathematically as in equation 11 below.

$$ICT\ skills\ migration\ (t) = ICT\ Specialists(t) * ICT\ skills\ migration\ rate \quad EQ12$$

4.5.2.4 *Digital Skills Auxiliary Variables*

The digital skill stock and flow model also includes auxiliary variables: employed workforce, basic training rate, and advanced training rate. These can be expressed mathematically as in equations 13, 14 and 15 below. Basic training investment can be classified as an investment in basic computer literacy courses. While advanced training investment can include advanced training such as data science courses,

$$Employed\ workforce\ (t) = population - (population * unemployment\ rate) \quad EQ13$$

$$Basic\ training\ rate = 1/(ICT\ Skills\ migration * Basic\ training\ investment) \quad EQ14$$

$$Employed\ workforce\ (t) = 1/ICT\ Skills\ migration * Advanced\ training\ investment \quad EQ15$$

4.5.2.5 *Digital Skills Constant Variables*

The table below outlines the constant variables used in the model.

Table 11: Digital Skills factors' values

Variable	Minimum	Maximum	Baseline	Source
Population	0	100 million	63.21 million	(StatsSA, 2024b)
Grade 12 Students	0	1 million	705 291	(South African Government, 2025)
Matric pass rate (Bachelor)	0	1	0.478	(South African Government, 2025)
STEM Enrolment rate	0	1	0.105	(IITPSA, 2024)
Student dropout rate	0	1	0.88	Estimate. (SMESouthAfrica, 2016)
STEM Graduation rate	0	1	0.12	Calculated
ICT Graduate Employment rate	0	1	0.5	Estimate (IITPSA, 2022)
Basic training rate	0	1	0.8	Estimate (DCDT, 2024)
Advanced training rate	0	1	0.03	Estimate - (ILA, 2023)

ICT skills migration rate	0	1	0.01	Estimate - (Statista, 2024)
Unemployment rate	0	1	0.329	(StatsSA, 2024a)

4.5.3 *Digital Infrastructure*

4.5.3.1 *The Model Structure*

The second SD model presented in Figure 34 below represents the second dimension of the DESI framework is Digital Infrastructure. Digital infrastructure evaluates the development, availability, and adoption of digital infrastructure, encompassing sub-dimensions, including broadband coverage and penetration, 5G coverage and penetration. Stocks in this dimension represent accumulations, such as the extent of broadband network coverage, the number of 5G base stations, households with broadband access, and 5G penetration. Flows are the rates of change in these stocks, influenced by factors including broadband take-up rate, investment in infrastructure, and un-affordability index.

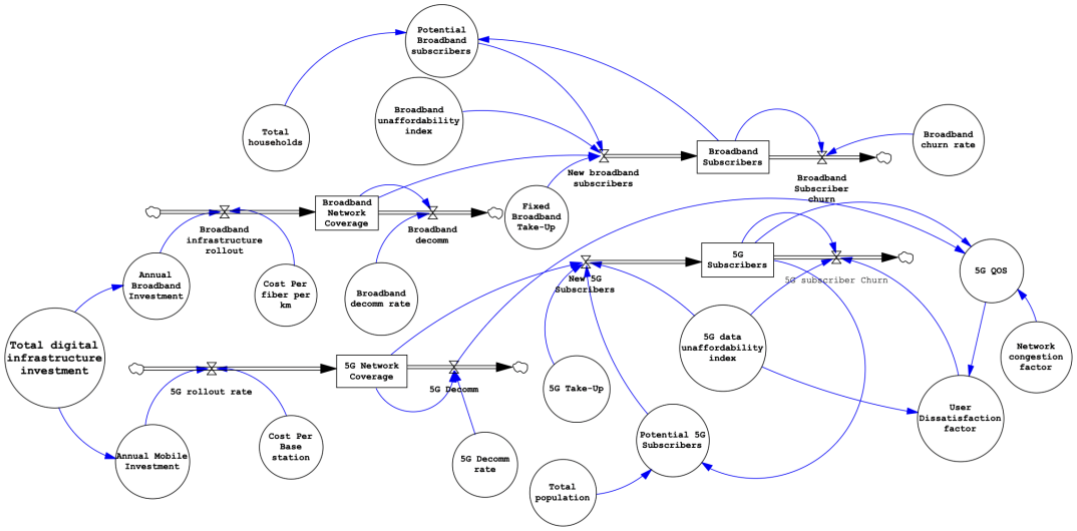


Figure 34: Digital Infrastructure SFD

4.5.3.2 *Digital Infrastructure Stocks*

The first stock, Broadband coverage, can be described as the value of Broadband coverage at any time t, plus an increase in Broadband coverage at time t, minus any decommissioning coverage at time t. This can be expressed mathematically as in equation 16 below.

$$Broadband\ Coverage\ (t) = Broadband\ Coverage\ (t-1) + Increase\ in\ Coverage\ - Decommissioning\ of\ Coverage\ (t) \qquad EQ16$$

The second stock, 5G coverage, can also be described similarly: the value of 5G coverage at any time t plus an increase in 5G coverage at time t minus any decommissioning coverage at time t. This can be expressed mathematically as in equation 17 below.

$$5G\ Coverage\ (t) = 5G\ Coverage\ (t-1) + New\ 5G\ Rollouts\ (t) - Decommissioning\ (t) \qquad EQ17$$

The third stock, Broadband subscribers, can also be described in a similar fashion, which is the value of Broadband subscribers at any time t, plus an increase in Broadband subscribers at time t, minus any churn rate of Broadband subscribers at time t. This can be expressed mathematically as in equation 18 below.

$$Broadband\ Subscribers\ (t) = Broadband\ Subscribers(t\text{-}1) + Broadband\ Subscribers\ -\ Cancelled\ Broadband\ Subscribers\ (t)$$

EQ18

The fourth stock, 5G subscribers, can be described as the value of 5G subscribers at any time t, plus an increase in 5G subscribers at time t, minus any the churn rate of 5G subscribers at time t. This can be expressed mathematically as in equation 19 below.

5G Subscribers (t) = 5G Subscribers(t-1) + New 5G Subscribers - Cancelled 5G Subscribers *EQ19*

4.5.3.3 *Digital Infrastructure Flows*

The first flow, Broadband rollout rate, can be described as a function of investment and cost per infrastructure unit. For Broadband, the infrastructure would be an installation of fibre. This can be expressed mathematically as in equation 20 below.

Broadband Rollout Rate (t) = Investment (t) / Cost Per fibre Installation (t) *EQ20*

The second flow, the 5G rollout rate, can also be described as a function of investment and cost per infrastructure unit. The infrastructure unit would consist of installing a base 5G base station. This can be expressed mathematically as in equation 21 below.

5G Rollout Rate (New 5G Base Stations) (t) = Investment (t) / Cost Per Base Station (t) *EQ21*

The third flow, the New 5G Subscribers, can also be described as a function of 5G coverage, Population, affordability index and 5G Take-up rate. 5G coverage is included because people can only subscribe if coverage exists. This can be expressed mathematically as in equation 22 below.

*New 5G Subscribers (t) = 5G Network Coverage (t) * 5G Take-Up *(1 - Unaffordability index) * Potential Subscribers* *EQ22*

The fourth flow, the New Broadband, can also be described as a function of Broadband coverage, total number of households, affordability index and broadband Take-up rate. This can be expressed mathematically as in equation 23 below.

*New Broadband Subscribers (t) = (1/Broadband Network Coverage (t)) * Fixed Broadband Take-Up (t) * (1 - Broadband unaffordability index) * Potential Broadband subscribers (t)* *EQ23*

The fifth flow, 5G decommissioning, can also be described as a function of 5G coverage and 5G rate decommissioning. This can be expressed mathematically as in equation 24 below.

$$5G\ decomm\ (t) = 5G\ Network\ Coverage\ (t) * 5G\ Decomm\ rate \quad EQ24$$

The sixth flow, Broadband decommissioning, can be described as a function of Broadband coverage and Broadband rate decommissioning. This can be expressed mathematically as in equation 25 below.

$$Broadband\ decomm\ (t) = Broadband\ Network\ Coverage\ (t) * Broadband\ Decomm\ rate \quad EQ25$$

The seventh flow, 5G subscriber churn, can be described as a function of 5G subscribers, 5G data affordability, and 5G user dissatisfaction factor. This can be expressed mathematically as in equation 26 below.

$$5G\ subscriber\ churn\ (t) = 5G\ Subscribers\ (t) * 5G\ data\ unaffordability\ index * User\ Dissatisfaction\ factor \quad EQ26$$

The eighth flow, Broadband subscriber churn, can be described as a function of Broadband subscribers and Broadband churn rate. Unlike the 5G churn, the Broadband churn was deliberately limited to 2 parameters to avoid model complexity with too much parametisation. This can be expressed mathematically as in equation 27 below.

$$Broadband\ subscriber\ churn\ (t) = Broadband\ Subscribers\ (t) * Broadband\ churn\ rate \quad EQ27$$

4.5.3.4 *Digital Infrastructure Auxiliary Variables*

The digital infrastructure stock and flow model also includes auxiliary variables: Potential subscribers, 5G QS, and 5G user dissatisfaction factor. These can be expressed mathematically as in equations 28, 29 and 30 below.

$$Potential\ Subscribers\ (t) = Total\ population - 5G\ Subscribers\ (t) \quad EQ28$$

$$5G\ QOS\ (t) = "5G\ Decomm * (1/5G\ Subscribers\ (t)) * Network\ congestion\ factor \quad EQ29$$

$$5G\ user\ dissatisfaction\ factor\ (t) = 5G\ data\ unaffordability\ index * 5G\ QOS\ (t) \quad EQ30$$

4.5.3.5 *Digital Infrastructure Constant Variables*

The table below outlines the constant variable for Digital Infrastructure.

Table 12: Digital Infrastructure constants

Variable	Minimum	Maximum	Baseline	Source
Population	0	100 million	63.21 million	(StatsSA, 2024b)
Households	0	100 million	17.8 million	
Annual Broadband Investment	0	1 trillion	3.8 billion	(ICASA, 2024)
Annual mobile network Investment	0	1 trillion	14 billion	(ICASA, 2024)
Cost of fibre per KM	0	10 million	500 000	Estimate; (Businesstech, 2013)
5G decommissioning rate	0	1	0.0000001	Estimate
Cost per Base station	0	20 million	7 650 000	Estimate - (CIOHub, 2024)
5G Take-up rate	0	1	0.0331	(ICASA, 2024)
5G Unaffordability index	0	1	0.7625	Estimate - (The Global Economy, 2021)

4.5.4 *Technology Integration*

4.5.4.1 *The Model Structure*

The third SD model illustrated in Figure 35 represents the structural mechanisms governing the evolution of small and medium-sized enterprises (SMEs) within the digital economy, with a specific focus on e-commerce participation and technological adoption. Developed in alignment with Sterman's (2000) modelling methodology, the framework captures the causal interdependencies among ICT investment, market demand, adoption barriers, and cost-related constraints that influence SME digitalisation trajectories. The model differentiates between domestic e-commerce engagement, cross-border trade participation, and the integration of advanced technologies, thereby encompassing multiple dimensions of SME digital transformation. Reinforcing feedback loops—such as the relationship between ICT investment and the rate of technology adoption—interact with balancing loops linked to market saturation, churn, and cost factors. Additionally, the model embeds cross-cutting influences from digital skills availability, reflecting the role of human capital in enabling technology diffusion. Collectively, this model provides a dynamic representation of how SMEs transition toward digitally enabled business models, supporting simulation-based analysis of policy interventions aimed at promoting SME competitiveness, innovation, and internationalisation within South Africa's emerging digital economy.

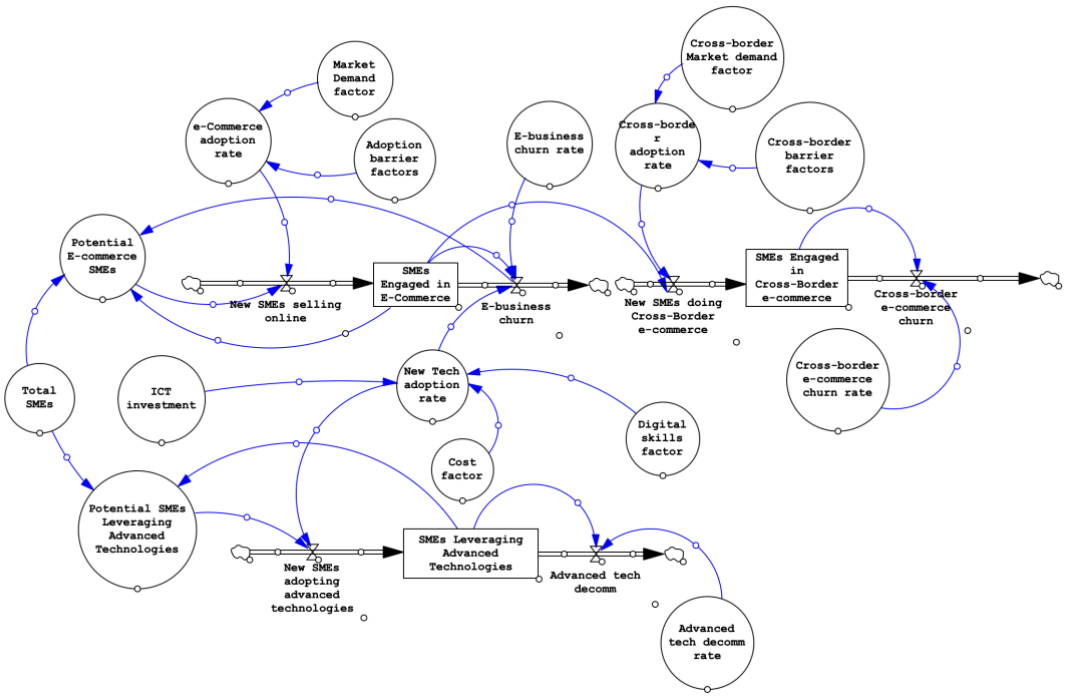


Figure 35: Technology Integration SFD

The third dimension, Technology Integration, assesses the extent to which SMEs adopt and integrate digital technologies, with sub-dimensions such as the use of digital tools, e-commerce, and advanced technologies like big data and AI. Stocks in this dimension include businesses adopting digital tools (e.g., cloud services, ERP systems), SMEs engaging in e-commerce, and SMEs engaging in cross-border sales. Flows represent the rates of change in these stocks, driven by factors like ICT investment, digital skills factor, e-commerce market attractiveness and adoption barrier factors. The adoption barrier factor is a composite attribute to represent qualitative factors such as regulatory barriers, cross-border legislature, policies, etc.

4.5.4.2 *Technology Integration Stocks*

The first stock, SMEs engaged in e-commerce, can be described as the value of SMEs engaged in e-commerce at any time t plus an increase in SMEs that adopt e-commerce at time t, minus any SMEs that terminate their e-business at time t. This can be expressed mathematically as in equation 30 below.

"SMEs engaged in e-Commerce" (t) = "SMEs engaged in e-Commerce" $(t-1)$ + $New\ SMEs\ selling\ online\ (t)$ − "$e-business\ churn$" (t) $EQ30$

The second stock, SMEs that engage in cross-border sales, can be described as the value of SMEs that engage in cross-border sales at any time t plus an increase in SMEs that do cross-border sales at time t minus any SMEs that terminate their cross-border operations at time t. This can be expressed mathematically as an equation 31 below.

"SMEs Engaged in Cross-Border sales " = "SMEs Engaged in Cross-Border sales " (t – 1) + New SMEs adopting advanced technologies (t) - Advanced tech decomm EQ31

The third stock, SMEs that leverage advanced technologies, can be described as the value of SMEs that leverage advanced technologies at any time t plus an increase in SMEs that leverage advanced technologies at time t minus any SMEs that decommission their advanced technologies at time t. This can be described mathematically as an equation 32 below.

SMEs Leveraging Advanced Technologies (t) = SMEs Leveraging Advanced Technologies (t -1) + New SMEs adopting advanced technologies (t) - Advanced tech decomm (t) EQ32

4.5.4.1 *Technology Integration Flows*

The first flow, New SMEs selling online, can be described as a function of Potential E-commerce SMEs and the e-commerce adoption rate. This can be expressed mathematically as in equation 33 below.

*New SMEs selling online (t) = Potential E-commerce SMEs (t) * e-Commerce adoption rate* *EQ33*

The second flow, SMEs engaged in cross-border sales, can be described as a function of SMEs already engaged in e-commerce Cross-border adoption rate. This can be expressed mathematically as in equation 34 below.

*New SMEs doing cross-border sales (t) = SMEs Engaged in E-Commerce (t) * Cross-border adoption rate* *EQ34*

The third flow, New SMEs leveraging advanced technologies, can be described as a function of Potential SMEs Leveraging Advanced Technologies and New Tech adoption rate. This can be expressed mathematically as in equation 35 below.

*New SMEs leveraging advanced technologies (t) = Potential SMEs Leveraging Advanced Technologies (t) * New Tech adoption rate* *EQ35*

The fourth flow, New SMEs leveraging advanced technologies, can be described as a function of Potential SMEs Leveraging Advanced Technologies and New Tech adoption rate. This can be expressed mathematically as in equation 36 below.

*Advanced tech decomm (t) = SMEs Leveraging Advanced Technologies (t) * Advanced tech decomm rate* *EQ36*

The fifth flow, E-business churn, can be described as a function of SMEs engaged in E-Commerce, New Tech adoption rate, and E-business churn rate. This can be expressed mathematically as in equation 37 below.

*E-business churn (t) = SMEs Engaged in E-Commerce (t) * E-business churn rate * (1 - New Tech adoption rate)* *EQ37*

The sixth flow, Cross-border e-commerce churn, can be described as a function of SMEs engaged in Cross-Border e-commerce and Cross-border e-commerce churn rate. This can be expressed mathematically as in equation 38 below.

*Cross-border e-commerce churn (t) = SMEs Engaged in Cross-Border e-commerce (t) * Cross-border e-commerce churn rate* *EQ38*

4.5.4.2 *Technology Integration Auxiliary Variables*

The technology integration stock and flow model also includes auxiliary variables: Potential SMEs Leveraging Advanced Technologies, Potential E-commerce SMEs, e-commerce adoption rate, and Cross-border adoption rate. These can be expressed mathematically as in equations 39, 40, 41 and 42 below.

Potential SMEs Leveraging Advanced Technologies (t) = Total SMEs - SMEs Leveraging Advanced Technologies *EQ39*

Potential E-commerce SMEs (t)= Total SMEs - SMEs Engaged in E-Commerce (t) + E-business churn(t) *EQ40*

*Commerce adoption rate = Market Demand factor * (1 - Adoption barrier factors)* *EQ41*

*Cross-border adoption rate = Cross-border Market demand factor * (1 - Cross-border barrier fac*tors) *EQ42*

4.5.4.1 *Technology Integration Constant Variables*

The table below outlines the constant variable for Technology Integration.

Table 13: Technology Integration constants

Variable	Minimum	Maximum	Baseline	Source
Total SMEs	0	10 000 000	792 838	Estimate - (SEDA, 2023)
New tech adoption rate	0	1	0.2	Estimate
Advanced tech decommissioning rate	0	1	0.0001	Estimate
e-Business churn rate	0	1	0.004	Estimate
Cross-border e-commerce adoption rate	0	1	0.003	Estimate
Cross-border market demand	0	1	0.03	Estimate
Cross-border churn rate	0	1	0.007	Estimate
e-Commerce adoption rate	0	1	0.3	Estimate
e-Commerce market demand	0	1	0.12	Estimate;(ITA, 2024)

e-Commerce adoption barrier factors	0	1	0.005	Estimate
Cross-border sales adoption barrier factors	0	1	0.0043	Estimate

4.5.5 *Digital Public Services*

4.5.5.1 *The Model Structure*

This fourth SD model explores the complex, non-linear factors driving the digitalisation of public services and the subsequent adoption of e-Government by citizens. The core structure focuses on the interaction between two main systems: the supply side (the rate at which services are digitised) and the demand side (the rate at which citizens become e-Government users). Key feedback mechanisms are hypothesised, linking ICT Investment to the Rate of Digitalisation of government services, and connecting the Digitalised Public Services with the resulting pool of e-Government users. The model explicitly incorporates essential moderating factors such as Digital Skills, Digital Literacy, and Awareness of digital public services, which govern the critical flows of Service digitalisation and new e-Government users. The model is designed to analyse the system's sensitivity to policy changes and resource allocation over time, ultimately seeking to understand the dynamics of successful, widespread e-Government implementation.

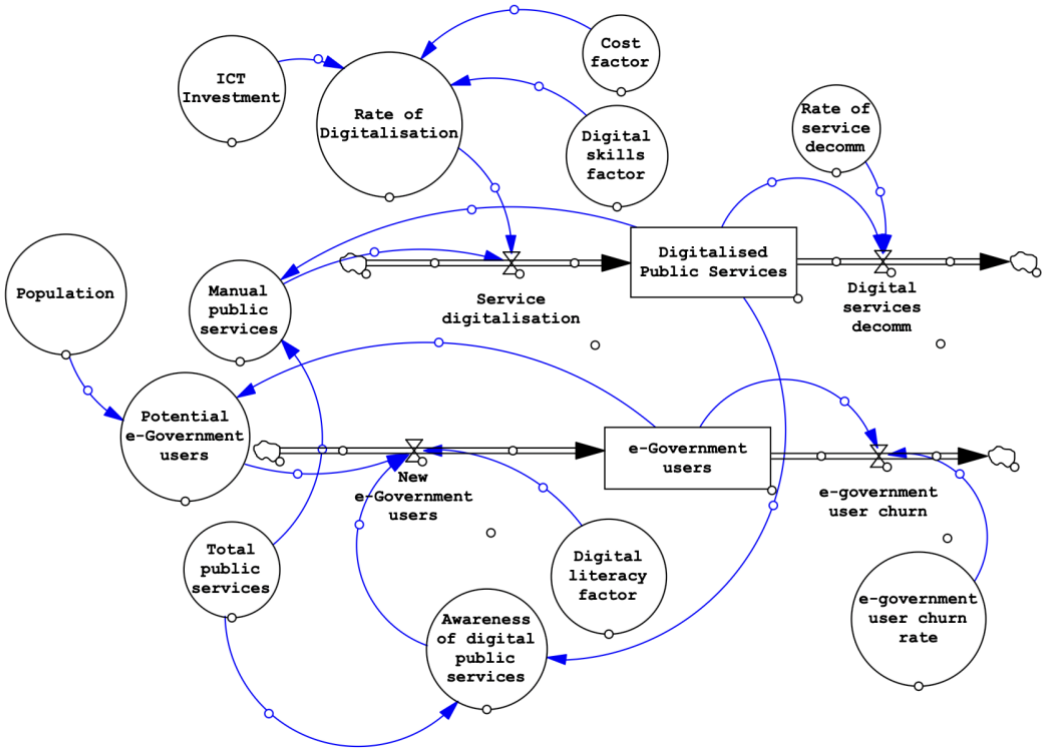


Figure 36: Digital Public Services SFD

The last dimension, Digital Public Services, evaluates the availability, accessibility, and use of digital platforms for government services. Stocks in this dimension include digital government platforms, digitalised public services, and citizens and businesses actively using eGovernment services. Flows represent stock changes driven by service digitisation and e-government adoption.

4.5.5.2 *Digital Public Services Stocks*

The first stock, digitalised public services, can be described as the value of digitalised public services at any time t, plus an increase in digitalised public services at time t, minus service decommissioning at time t. This can be expressed mathematically as in equation 43 below.

Digitalised Public Services (t) = Digitalised Public Services (t-1) + Service digitalisation - Digital services decomm (t) EQ43

The second stock, Broadband coverage, can be described as the value of Broadband coverage at any time t, plus an increase in Broadband coverage at

time t, minus any decommissioning coverage at time t. This can be expressed mathematically as in equation 44 below.

$$e - Government\ users\ (t) = e - Government\ users\ (t-1) + e - Government\ users\ - user\ churn\ (t) \quad EQ44$$

4.5.5.3 *Digital Public Services Flows*

The first flow, Service digitalisation, can be described as a function of Manual public services and Rate of digitalisation. This can be expressed mathematically as in equation 45 below.

*Service digitalisation (t) = Manual public services (t) * Rate of Digitalisation* *EQ45*

The second flow, new e-government users, can be described as a function of Potential e-government users, Awareness of digital public services and Digital literacy factor. This can be expressed mathematically as in equation 46 below.

*New e-Government users (t) = Potential e-Government users (t) * Awareness of digital public services * (1 - Digital literacy factor))* *EQ46*

The third flow, Digital services decomm, can be described as a function of Digitalised Public Service and Rate of service decomm. This can be expressed mathematically as in equation 47 below.

*Digital services decomm (t) = Digitalised Public Services * Rate of service decomm* *EQ47*

The fourth flow, new e-government user churn, can be described as a function of e-government user and e-government user churn rate. This can be expressed mathematically as in equation 48 below.

*"e-Government user churn" (t) = "e-Government users" (t) * "e-government user churn rate"* *EQ48*

4.5.5.4 *Digital Public Services Auxiliary Variables*

The Digital public services stock and flow model also includes auxiliary variables: Potential e-government users, Manual public service, rate of digitalisation and Leveraging Advanced Technologies, Potential E-commerce SMEs, e-commerce adoption rate, and Awareness of digital public services. These can be expressed mathematically as in equations 49, 50, 51 and 52 below.

Potential e-Government users (t) = Population - "e-Government users" *EQ49*

Manual public services = Total public services - Digitalised Public Services *EQ50*

*Rate of Digitalisation = (1 - (1/ICT Investment)) * Digital skills factor - Cost factor* *EQ51*

Awareness of digital public services = Digitalised Public Services / Total public services *EQ52*

4.5.5.5 *Digital Public Services Constant Variables*

The table below outlines the constant variable for Digital Public Services

Table 14: Digital Public Services constants

Variable	Minimum	Maximum	Baseline	Source
Population	0	100 million	63.21 million	(StatsSA, 2024b)
Total public services	0	10 000	4000	Estimate
Manual public services	0	10 000	3865	Estimate – (DCDT, 2024a)
Rate of service digitilisation	0	1	0.003	Estimate
Rate of service decommissioning	0	1	0.000001	Estimate
e-Government users	0	100 million	300 000	Estimate – (South African Government, 2023)
User churn rate	0	1	0.00001	Estimate

Awareness of public services	0	1	0.0101	(SA e-portal services, 2025)

4.6 Chapter Summary

The chapter's core contribution is the development and integration of the following four dynamic models: Model 1 (Figure 33): Digital Skills Formation. This foundational model analyses the structural and behavioural complexity underpinning the evolution of digital skills in South Africa. It tracks the flow of population through various education pathways, training investments, and workforce integration, explicitly modelling the impact of factors like migration and dropout rates to provide a dynamic forecast of the national digital skills supply. Model 2 (Figure 34): Digital Infrastructure Development. It integrates the dynamics of digital infrastructure expansion, digital skills development, broadband and 5G adoption, and user experience factors such as affordability and service quality. Through interacting feedback loops, the model illustrates how improvements in connectivity and skills can reinforce one another, while constraints such as affordability barriers, network congestion, and slow investment cycles act as balancing forces. Overall, the model provides a simplified but coherent representation of the drivers and limitations shaping digital uptake, enabling the exploration of high-leverage interventions to accelerate inclusive digital transformation. Model 3: (Figure 35): SME Digitalisation and E-Commerce. This model focuses on Small and Medium-sized Enterprises (SMEs), capturing the mechanisms governing their e-commerce participation and technological adoption. It analyses the interplay of ICT investment, market demand, adoption barriers, and cost constraints, with its trajectory directly influenced by the availability of digital skills generated by M1. Model 4 (Figure 36): Digital Public Services. This model explores the complex factors driving the digitalisation of public services and subsequent citizen adoption. It models the interaction between the supply side (rate of service digitalisation) and the demand side (rate of citizen uptake), explicitly incorporating moderating factors like Digital Skills (from M1), Digital Literacy, and Awareness. Key Contribution chapter demonstrates how the System Dynamics methodology moves beyond static

analysis by capturing feedback loops, time delays, and non-linearities crucial to digitalisation. By connecting all four models, the framework serves as a robust quantitative tool for policy experimentation. It helps stakeholders predict unexpected outcomes of decisions about ICT investment, education funding, and regulatory support, making it easier to develop strategies for sustainable and inclusive digital transformation in South Africa.

CHAPTER 5. Results and Discussion

This chapter addresses the final two phases of Sterman's five-step modelling process by detailing the verification and validation of the system dynamics models discussed in Chapter 4, followed by the formulation of relevant policy interventions. It establishes the foundation for the subsequent simulation analysis by demonstrating the models' structural soundness and behavioural reliability. The simulation results are presented immediately thereafter, building directly on the outcomes of the verification and validation procedures.

5.1 Model Verification and Validation.

System Dynamics model verification and validation are crucial steps to ensure that a model accurately represents real-world systems and produces reliable results. Verification checks whether the model is correctly implemented—ensuring equations, logic, and simulations work as intended. Validation assesses whether the model adequately represents the real system, often through empirical data comparison and expert judgment (Barlas, 1996).

The origins of System Dynamics model verification and validation can be traced back to early works in system dynamics by Jay W. Forrester (1961), who emphasised the need for rigorous testing to build confidence in simulation models. Model verification and validation are essential for policy decision-making, strategic planning, and forecasting, as unreliable models can lead to poor decisions (Sterman, 2000).

The process involves structural verification (ensuring equations and causal relationships match theoretical and real-world understanding), behaviour validation (checking whether simulated outputs align with historical data or expected trends), and sensitivity analysis (testing the model's robustness by varying key parameters). Techniques such as Theil's inequality statistics, extreme condition testing, and Monte Carlo simulations are commonly used to validate SD models (Oliva, 2003). By ensuring accuracy and reliability, model verification and validation enhance model credibility and usability for decision-makers in complex dynamic systems.

5.1.1 *Structure Confirmation Tests*

Structure confirmation tests are used to ensure that a model's causal relationships, feedback loops, and equations accurately represent the real-world system it aims to simulate. These tests focus on validating the structural soundness of a model before analysing its behaviour. Barlas (1996) classifies these tests into direct and indirect structure validation.

Direct structure tests compare the model's equations and causal links with expert knowledge, empirical data, and established theories, ensuring that assumptions are logically sound and consistent with reality (Forrester, 1961).

Indirect structure tests assess whether the model's internal mechanisms produce expected patterns, even before comparing it with real-world data. Techniques such as causal loop diagram validation, extreme condition testing, and parameter verification are widely used to conduct structure confirmation tests (Oliva, 2003).

These tests are critical for building model credibility, as a structurally flawed model can produce misleading results even if its outputs match real-world data (Sterman, 2000). Ensuring structural validity improves the robustness and reliability of system dynamics models, making them more effective for policy and decision-making.

The four models presented in Chapter Four underwent several iterations and modifications to ensure that they capture the structural framework of DESI and are as close to reality as possible without introducing too much complexity and rendering them unwieldy. Due to time constraints, expert review was not conducted. Consequently, this forms part of the limitations of the study. The figures below show the iterative version of the Digital Skills model from version 1 to the final version.

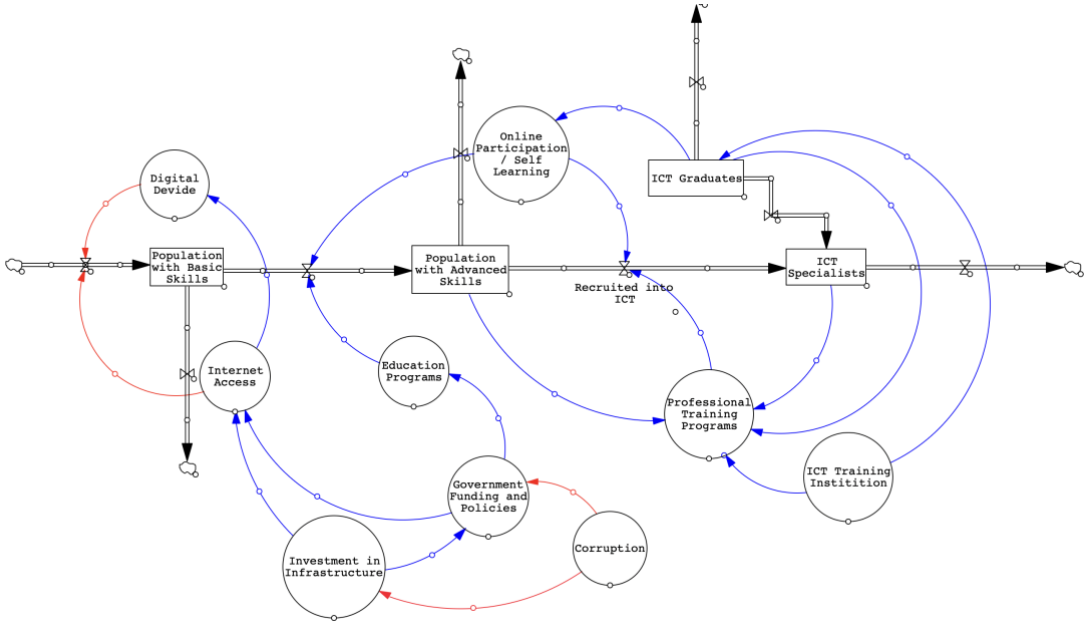


Figure 37: Digital Skills SFD version 1

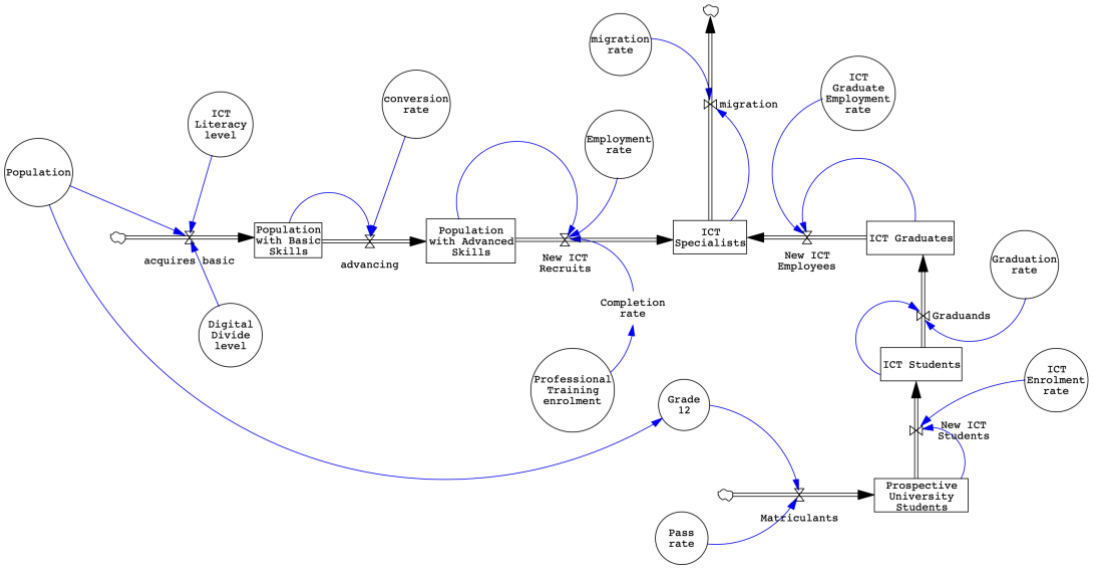


Figure 38: Digital Skills SFD version 5

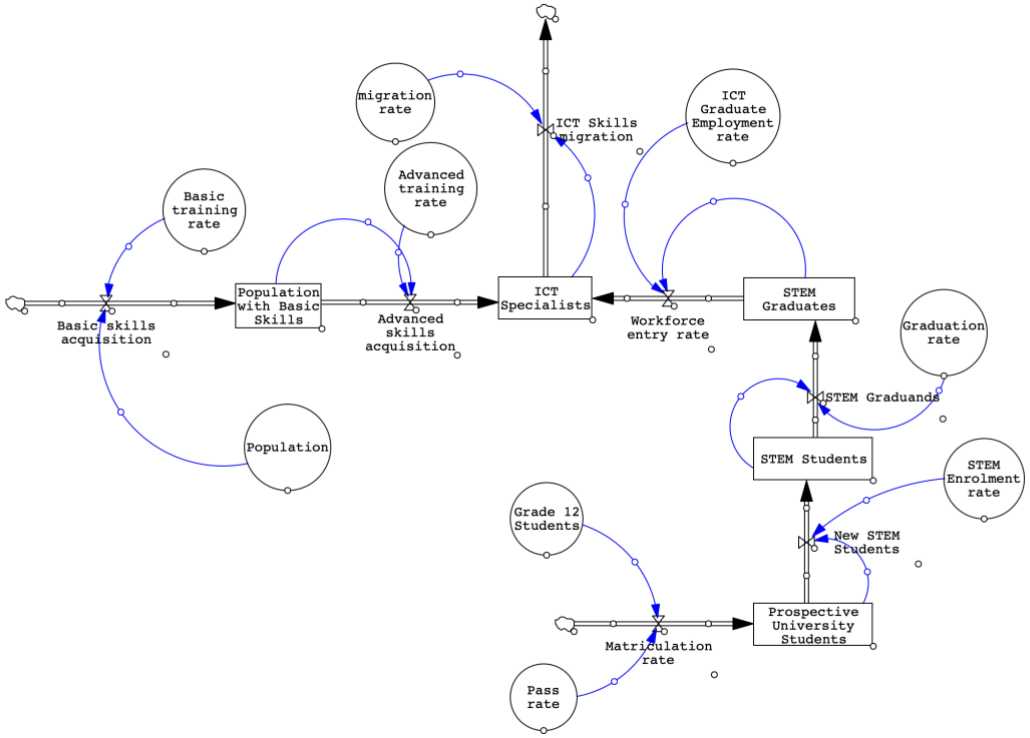


Figure 39: Digital Skills SFD final version

5.1.2 *Structure-oriented Behaviour Tests*

Structure-oriented behaviour tests assess whether a model's behaviour is consistent with its underlying structure, ensuring that simulated outputs logically emerge from causal relationships and feedback loops (Barlas, 1996). These tests focus on whether the model's dynamic behaviour aligns with expected patterns based on system theory and expert knowledge, rather than just fitting historical data (Sterman, 2000).

A key method involves extreme condition testing, where model inputs are set to extreme values to verify that the resulting behaviour remains logical and stable (Forrester & Senge, 1980). Behaviour sensitivity analysis is another technique that examines how small changes in structural parameters affect long-term model behaviour, ensuring that the system remains robust under varying conditions (Oliva, 2003). Additionally, phase relationship testing evaluates whether oscillatory or exponential trends in the model correspond to real-world observations (Richardson, 2015). These tests are critical for validating causal

mechanisms and ensuring that the model is behaviourally realistic, structurally sound, and suitable for decision-making.

5.1.3 *Dimensional Consistency Tests*

Dimensional consistency tests ensure that all equations within a model maintain unit consistency, meaning that variables and parameters correctly align in terms of their measurement units (Forrester, 1961). This test helps prevent logical errors where variables with incompatible dimensions—such as adding a stock variable (e.g., the population in persons) to a flow variable (e.g., the birth rate in persons per year) are incorrectly combined (Sterman, 2000). Dimensional consistency testing is a fundamental aspect of structural validation, ensuring that model equations reflect real-world relationships in a mathematically sound way (Barlas, 1996).

Tools such as automated unit-checking algorithms in modelling software can be used to help modellers detect unit mismatches early. Additionally, extreme condition testing can highlight potential dimensional inconsistencies by pushing model parameters to their limits (Richardson, 2015). Failing to enforce dimensional consistency can lead to erroneous outputs, misleading conclusions, and poor decision-making, making this test a crucial step in model verification and validation.

Vensim PLE unit checking functionality was utilised to validate the units of all the models. Figure 39 below shows the output after running the unit check.

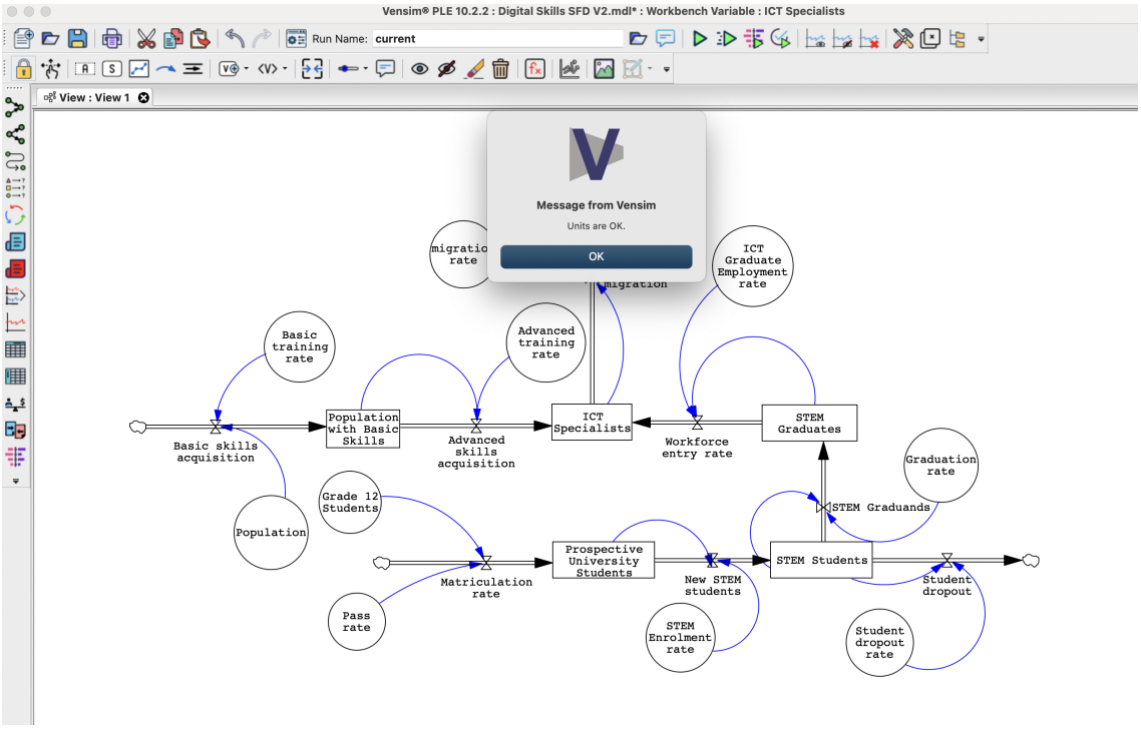


Figure 40: Unit check output from Vensim PLE

The Digital Infrastructure, Technology Integration, and Digital public service models failed the unit consistency test.

5.1.4 *Parameter Confirmation Tests*

Parameter confirmation tests ensure that the numerical values assigned to model parameters are realistic, justifiable, and representative of the actual system. These tests help validate whether parameter values are based on empirical data, expert judgment, or theoretical foundations (Barlas, 1996).

Direct parameter confirmation involves comparing model parameters with real-world data sources, including historical records and scientific studies, ensuring they fall within plausible ranges (Sterman, 2000).

Indirect parameter confirmation assesses the model's sensitivity to parameter variations, verifying that small changes in parameter values do not produce unrealistic or unstable behaviours (Oliva, 2003). Techniques such as statistical estimation, historical data fitting, and sensitivity analysis are commonly used for parameter validation (Kleijnen, 1995). If parameter values are uncertain,

calibration methods like optimisation algorithms or Bayesian estimation can refine them to improve model accuracy (Richardson, 2015). Proper parameter validation enhances the credibility, reliability, and predictive power of system dynamics models, ensuring that decision-makers can trust simulation results. This study performed the parameter estimation test concurrently with the structure estimation tests as they are related.

5.1.4.1 *Boundary Adequacy Test*

The boundary adequacy test evaluates whether a model includes all relevant variables, feedback loops, and causal relationships necessary to represent the real-world system accurately (Barlas, 1996). This test ensures that the model is neither too narrow (missing critical elements) nor too complex (including unnecessary details that do not contribute to system behaviour) (Sterman, 2000).

A key approach is expert review, where domain specialists assess whether essential structures—such as key policies, external influences, and feedback mechanisms—are properly included (Forrester & Senge, 1980). Additionally, sensitivity testing can help identify whether excluded factors significantly impact model behaviour, indicating potential boundary shortcomings (Oliva, 2003). Comparative simulations against real-world data also help validate whether the model's scope can replicate observed trends (Richardson, 2015). If a model's boundary is too limited, its policy insights may be misleading or incomplete. Ensuring boundary adequacy enhances the reliability, relevance, and applicability of system dynamics models for decision-making.

The models' construction in this research was guided by the DESI framework as outlined by the European Commission (2016). However, as previously stated, the models do not include all the indicators in every dimension but rather the key indicators in each dimension. For instance, for this exploratory research, it was not necessary to include stock and flows for the ultra-high networks sub-dimension as the broadband stock and flows represent similar networks, only differing in speed.

5.1.4.2 *Extreme Conditions Test*

The extreme conditions test evaluates whether a model produces logical and realistic behaviour when subjected to extreme values of input parameters (Senge & Forrester, 1980). This test ensures that the model's structure is robust and behaves consistently even under extreme scenarios, helping to identify hidden flaws in equations, feedback loops, or assumptions (Barlas, 1996). A well-constructed model should generate results that align with theoretical expectations rather than producing unrealistic or unstable behaviour (Sterman, 2000).

Extreme conditions testing is typically performed through stress testing, boundary value analysis, and simulation runs where parameters are pushed to their limits (Oliva, 2003). If a model fails the extreme conditions test, it suggests structural logic inconsistencies, requiring modifications of equations or feedback loops. This test ensures model validity, reliability, and credibility in decision-making applications (Richardson, 2015).

During this assessment, critical input variables (stocks and flows, or parameters) that influence system behaviour were selected and assigned minimum (zero or near-zero values) and maximum (very high values) to test how the models respond. Below are the results for the Digital Skills model under extreme conditions.

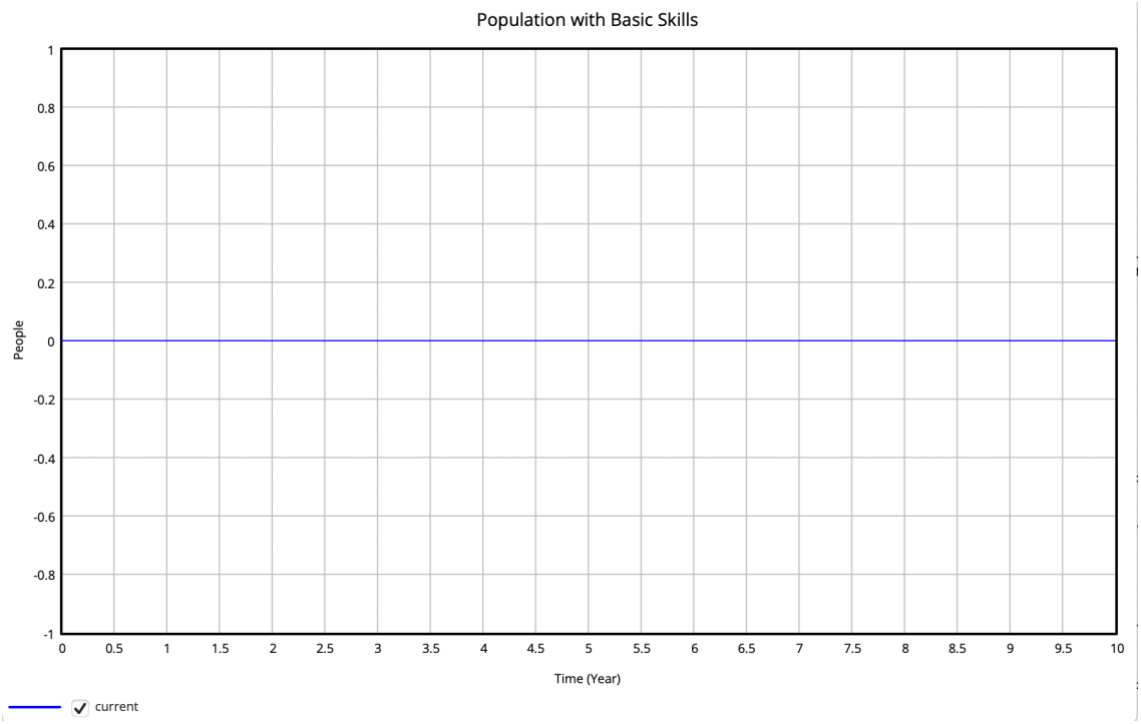


Figure 41: Population with Basic Skills under extreme conditions (Zero values)

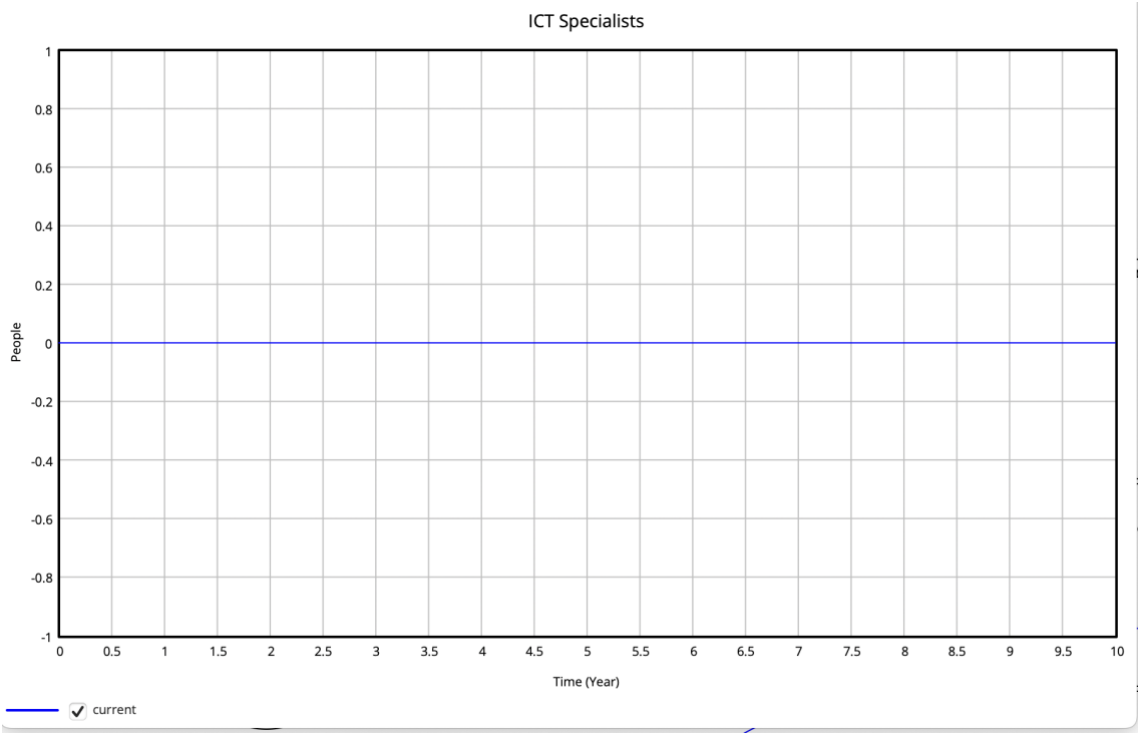


Figure 42: ICT Specialists under extreme conditions (Zero values)

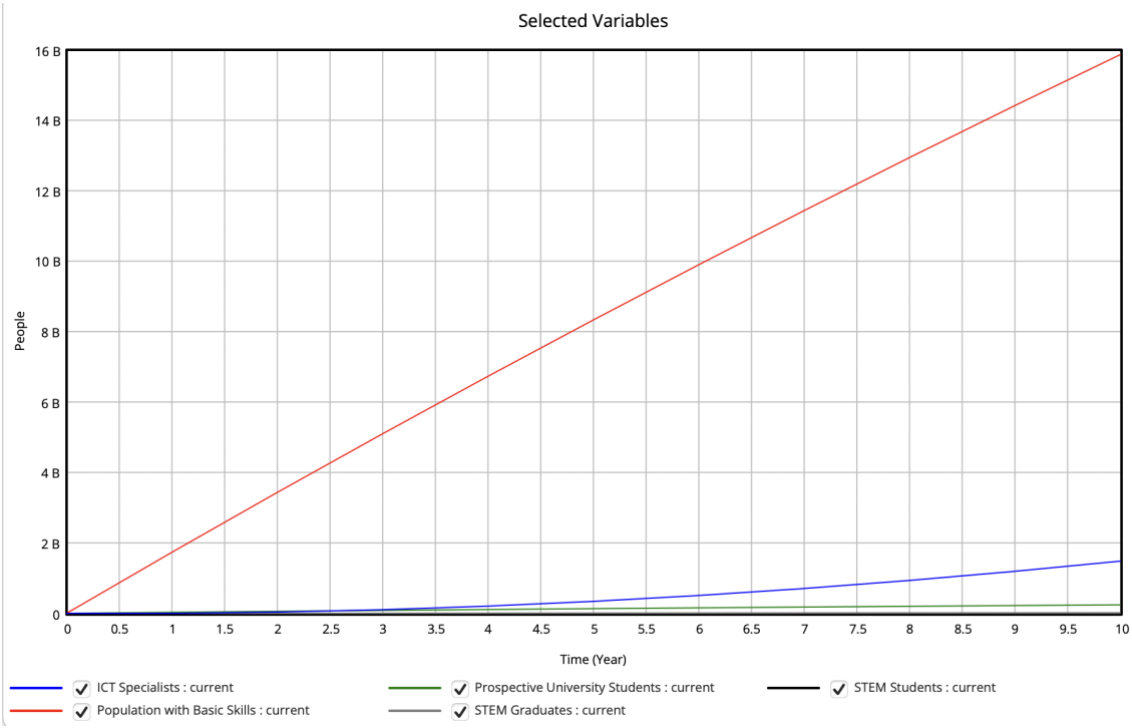


Figure 43: Digital Skills variables under extremely high conditions (High values)

5.1.5 *Behaviour Pattern Tests*

Behaviour pattern tests are used to evaluate whether a model's simulated behaviour aligns with real-world trends over time. These tests focus on qualitative and quantitative validation, ensuring that the model replicates expected growth, decline, oscillations, or equilibrium states observed in historical data. Key behaviour pattern tests include trend comparison, where simulated outputs are compared to historical trends, and phase relationship tests, which assess whether different variables interact as expected over time. Additionally, extreme condition tests examine the model's response to extreme inputs to verify robustness.

According to Sterman (2000), behaviour pattern validation is crucial because system dynamics models aim to capture the underlying feedback structures driving system behaviour rather than just fitting data statistically. Similarly, Barlas (1996) emphasises that validation should assess whether the model's behaviour adheres to fundamental system principles rather than merely replicating

numerical data. These tests help refine models, improving their credibility for policy analysis and decision-making.

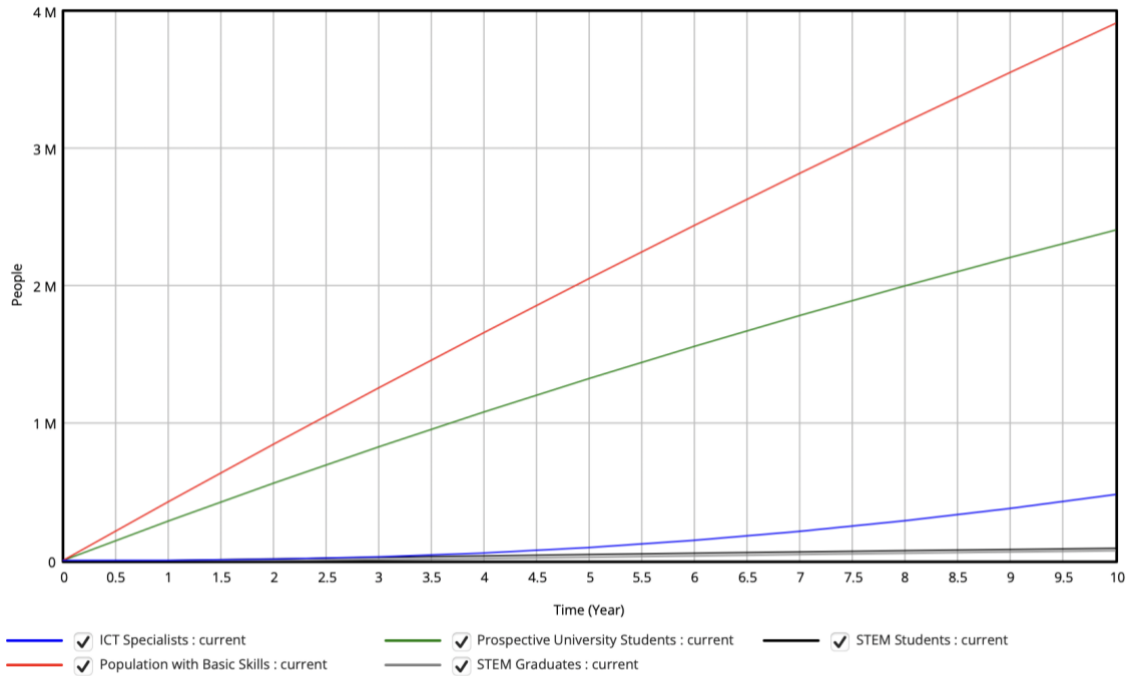


Figure 44: Baseline simulation results for Digital Skills

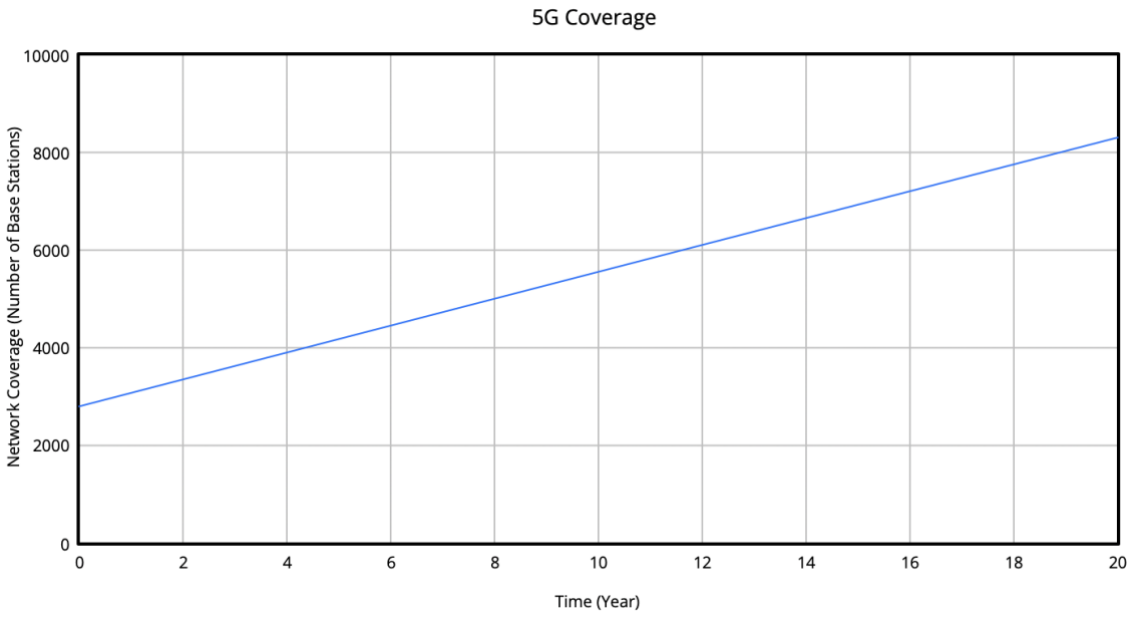


Figure 45: Baseline simulation results for 5G Coverage

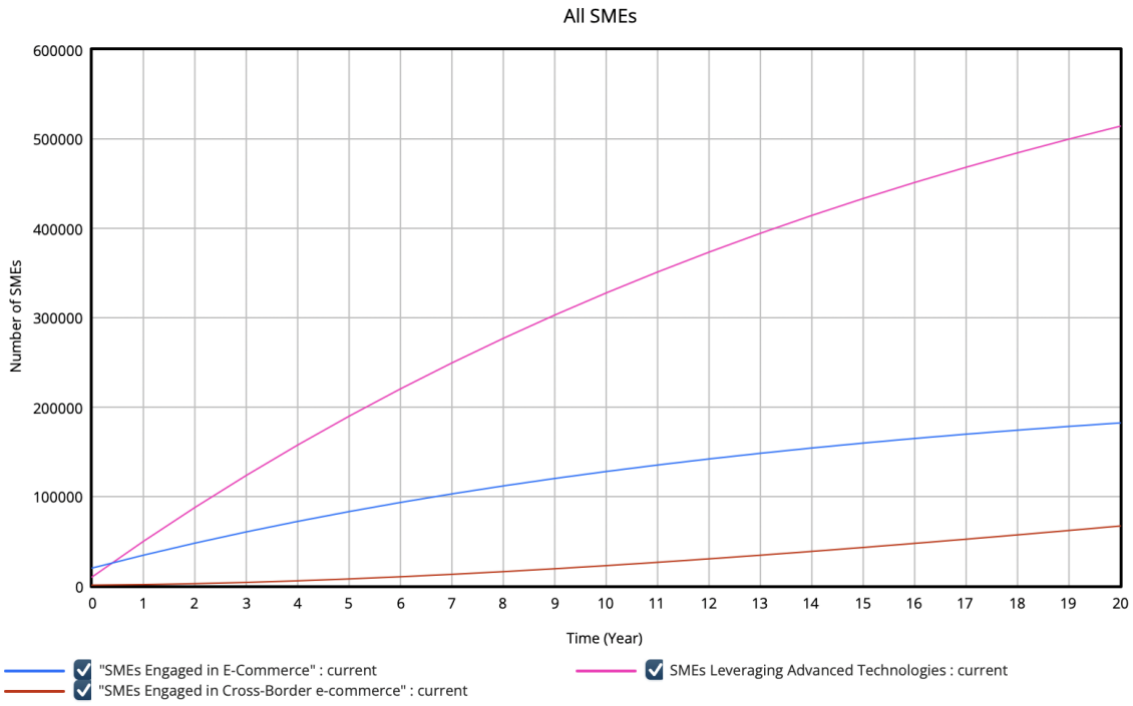


Figure 46: Baseline simulation results for Technology Integration

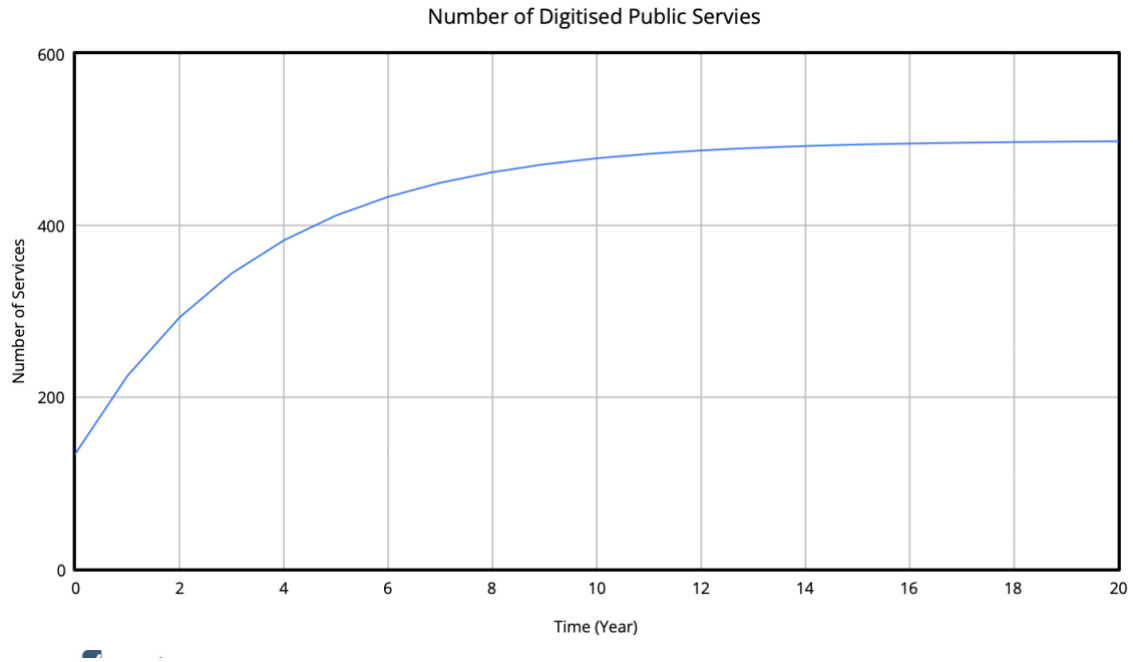


Figure 47: Baseline simulation results for Digital Public Services

5.2 Policy Analysis and Design

Policy design is a methodology for developing, testing, and refining policies by using system dynamics models to simulate complex interactions within a system.

This originated from the work of Jay Forrester in the 1950s at the Massachusetts Institute of Technology (MIT). The purpose of system dynamics policy design is to provide policymakers with insights into the long-term effects of different interventions by simulating how various system components interact over time. It helps identify leverage points, test policy scenarios, and anticipate unintended consequences, thus enabling more informed, effective, and adaptive decision-making. By incorporating dynamic feedback and delays into decision models, system dynamics offers a deeper understanding of the behaviour of complex systems, ultimately aiding in the creation of sustainable and resilient policies.

5.2.1 *Baseline scenarios*

The base scenarios for the four Stock and Flow diagrams (Digital Skills, Digital Infrastructure, Technology integration and Digital public services) were constructed using publicly available data from South African government reports, industry surveys, and international datasets (e.g., ITU, World Bank, and GSMA). For Digital Infrastructure, metrics like broadband and 5G take-up were sourced from ICASA (Independent Communications Authority of South Africa) and network operators' reports. Digital skills indicators, including digital skills and ICT employment, were derived from Statistics South Africa (StatsSA) and academic studies. Where direct data were unavailable, plausible values were estimated by benchmarking against countries with similar economic and digital maturity and by interpolating known trends. These estimations ensured a coherent, realistic baseline for scenario modelling while acknowledging potential data gaps. The results for the baseline scenarios for the four models were presented in Section 5.1.5.

5.2.2 *Digital Skills*

5.2.2.1 *Digital Skills Improvement (Best-case scenario)*

In the baseline scenario, the key constants, population, unemployment rate, and grade 12 students, remain consistent with the South African context to model the near-to-real situation of South Africa. The current population of South Africa is 63

015 904 according to StatsSA (2024a), the unemployment rate is 32.9% (StatsSA (2024a), and the grade 12 students were 678000 in 2024 (South African Government, 2025). Other constants were also defined in Table 7 (refer to Chapter 4, Section 4.5.1). These values ultimately determine the percentages for various policy configurations of the system. Case in point, South Africa is experiencing an ICT skills shortage of around 90,000 ICT professionals (Gungubele, 2023). This number denotes just 0.14% of the population. The best-case scenario for Digital Skills focuses on achieving a high output of advanced digital skills, addressing the shortage of ICT specialists.

The state configuration of the system for digital improvement would be as follows:

- 80% initial workforce with basic digital skills.
- 0.9% initial workforce ICT specialists.
- Basic ICT training rate (refer to section 4.3.1): 0.02%.
- Advanced training rate (refer to section 4.3.1): 0.02%.
- ICT Skills migration rate: 0.02%.
- STEM enrolment rate: 0.12.
- Student dropout rate: 20%.
- ICT graduate employment rate: 70%

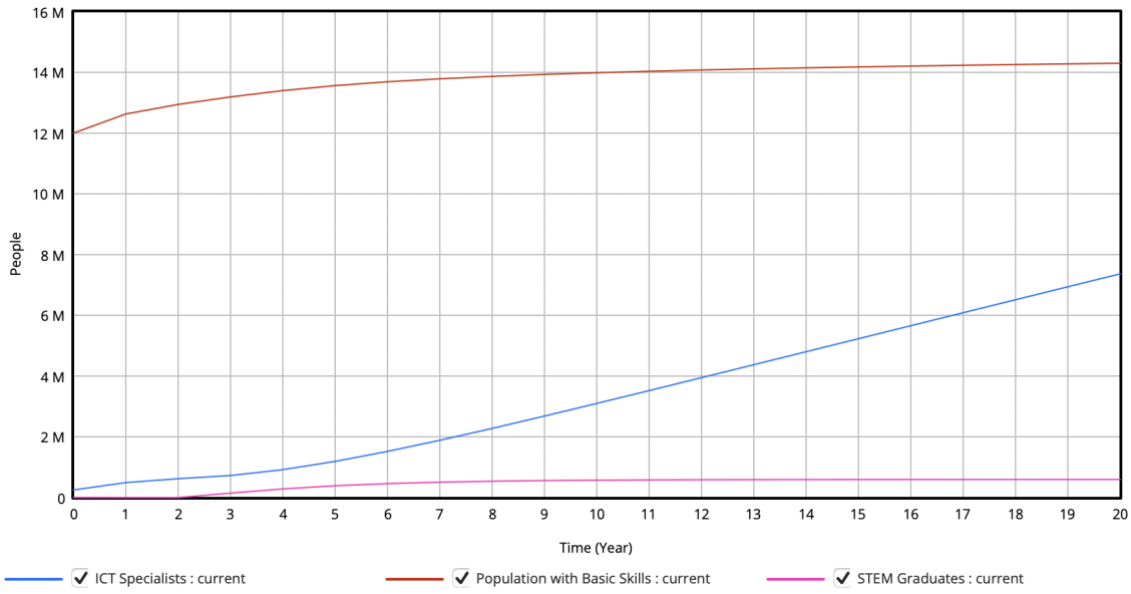


Figure 48: Best-case Scenario Digital Skills Simulation Output

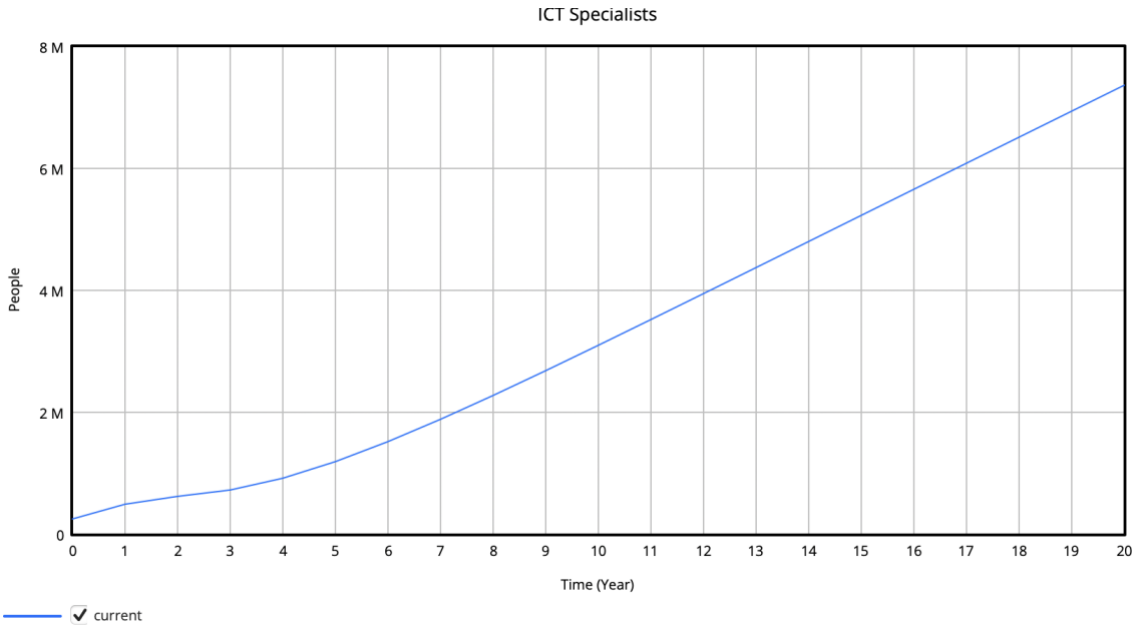


Figure 49: Best-case Scenario ICT Specialists Simulation Output

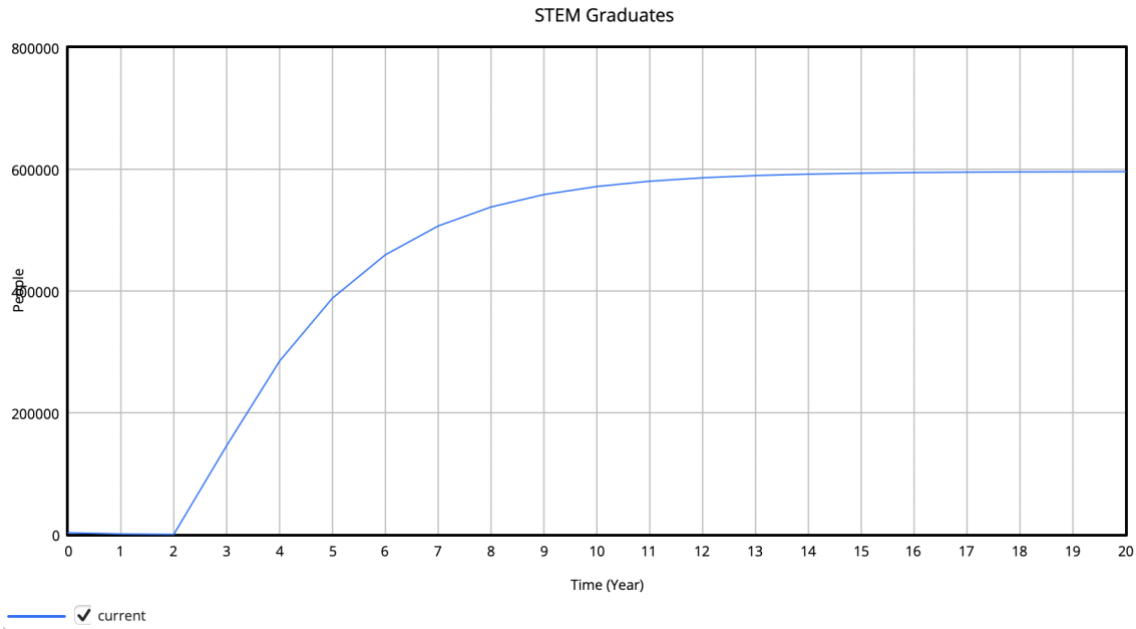


Figure 50: Best-case Scenario STEM Graduates Simulation Output

The Vensim PLE simulation results for the best-case scenario of digital skills development indicate a steady and sustained increase in both basic and

advanced digital skills across the population. With high investment in training programs, the inflow of individuals acquiring digital skills is significantly boosted, leading to a larger workforce equipped with the necessary competencies. High investment in advanced skills ensures a continuous pipeline of talent progressing from basic to advanced digital skills, further reinforcing the digital economy. The model predicts that an additional 152,000 advanced ICT skills will be added to the ecosystem after a year. This starkly contrasts Boltt (2025), who purports that Microsoft would have equipped 1 million South Africans with advanced skills by 2026. However, the model predicts that after 5 years, over a million people will have been equipped with advanced digital skills. After 20 years, more than 11% of the population will have advanced skills, which gives South Africa a competitive edge over some of the top countries with a high ICT workforce (refer to Figure 45). Currently, Sweden, Luxembourg and Finland have notable percentages, with ICT specialists representing 8.0% and 7.6% of their respective workforces (European Commission, 2024). This is also in harmony with the desired reference mode discussed in Section 4.1.1.2 (refer to Figure 21). The balancing loop of low migration of ICT-skilled professionals minimises the loss of expertise, allowing for strong mentorship, knowledge transfer, and innovation within the country. The STEM graduate output remains stagnant with the baseline output of 2843 for almost two years, then grows exponentially as a result of the high STEM enrolment rate and low dropout. Furthermore, high employment rates of STEM graduates (refer to Figure 46) create a positive feedback loop, with an output of almost 600,000 STEM graduates, as more individuals are motivated to pursue digital skills, knowing that job opportunities are available. This scenario results in a self-sustaining digital ecosystem where the growing supply of skilled professionals meets the increasing demand for digital transformation in various industries, driving economic growth and technological advancement.

Lastly, the workforce with basic digital skills has risen to over 14 million people, which is lower than the projected NDP (2030) and might indicate the model's shortfall.

5.2.2.2 *Digital Skills Decline (Worst-case scenario)*

In the worst-case scenario, while the baseline constants remain the same, the state configuration of the system favours the balancing loop with a high ICT Skill migration rate and low STEM enrolments coupled with high dropout rates. The investments in both basic and advanced training remain minimal. The configuration would be as follows:

- Basic training rate: 0.00001.
- Advanced training rate: 0.000001.
- ICT Skills migration rate: 0.35.
- STEM enrolment rate: 0.012.
- Student dropout rate: 0.91.
- ICT graduate employment rate: 0.1.

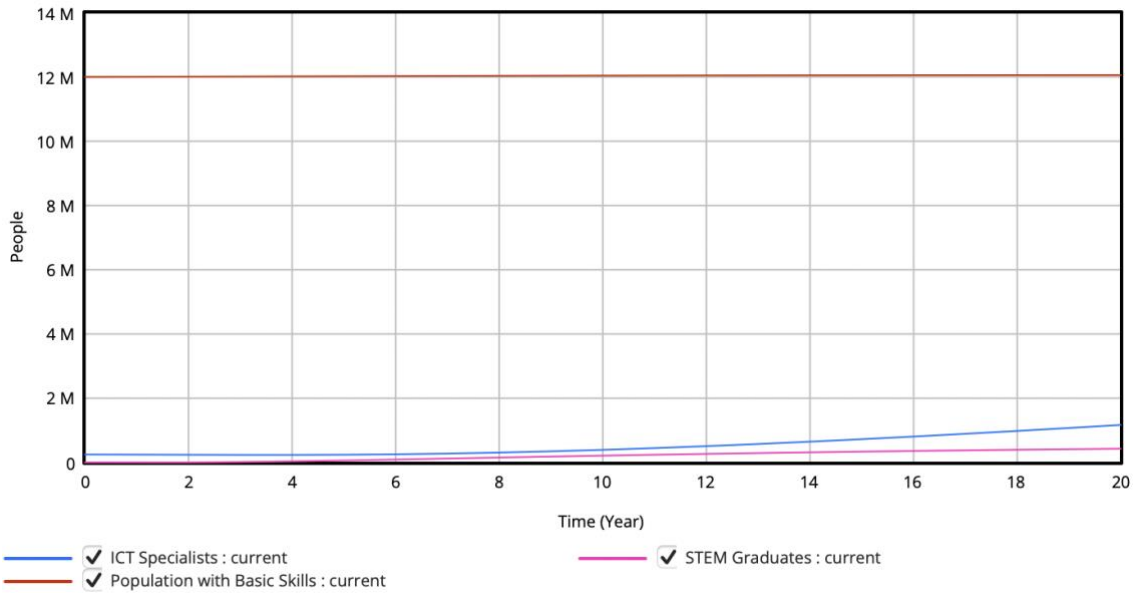


Figure 51: Worst-case Scenario Digital Skills Simulation Output

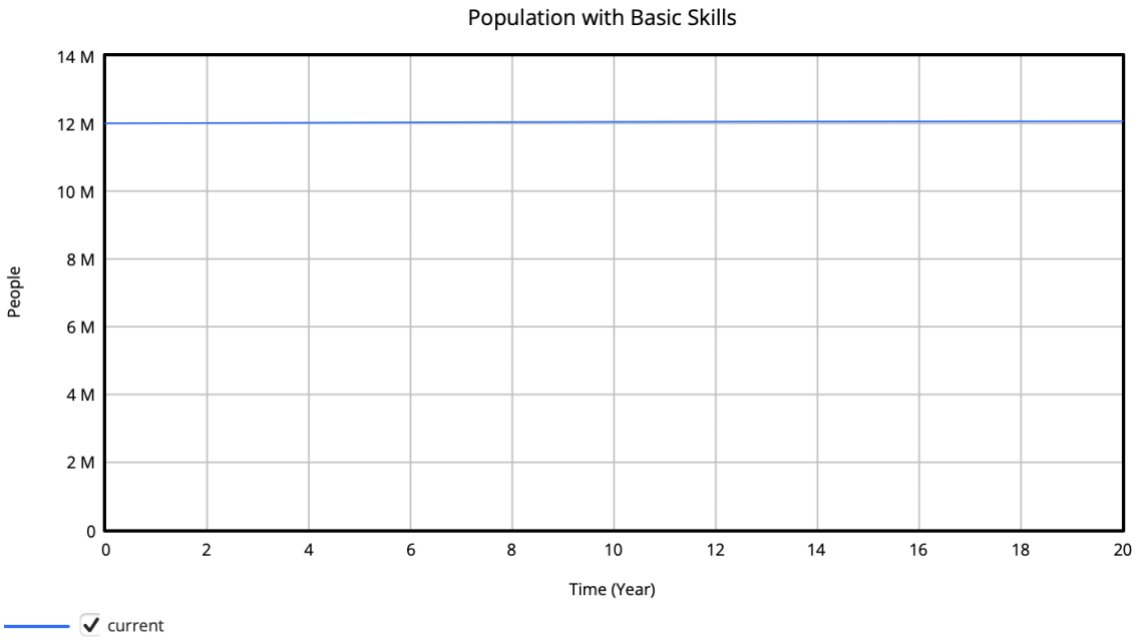


Figure 52: Worst-case Scenario Population with Basic Skills Simulation Output

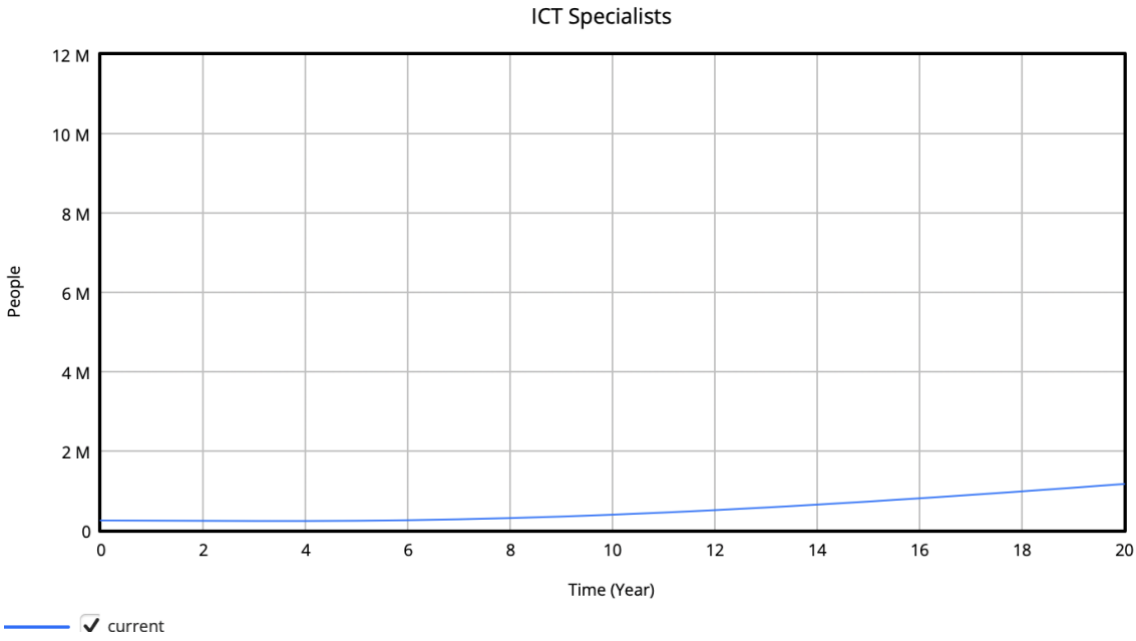


Figure 53: Worst-case Scenario ICT Specialists Simulation Output

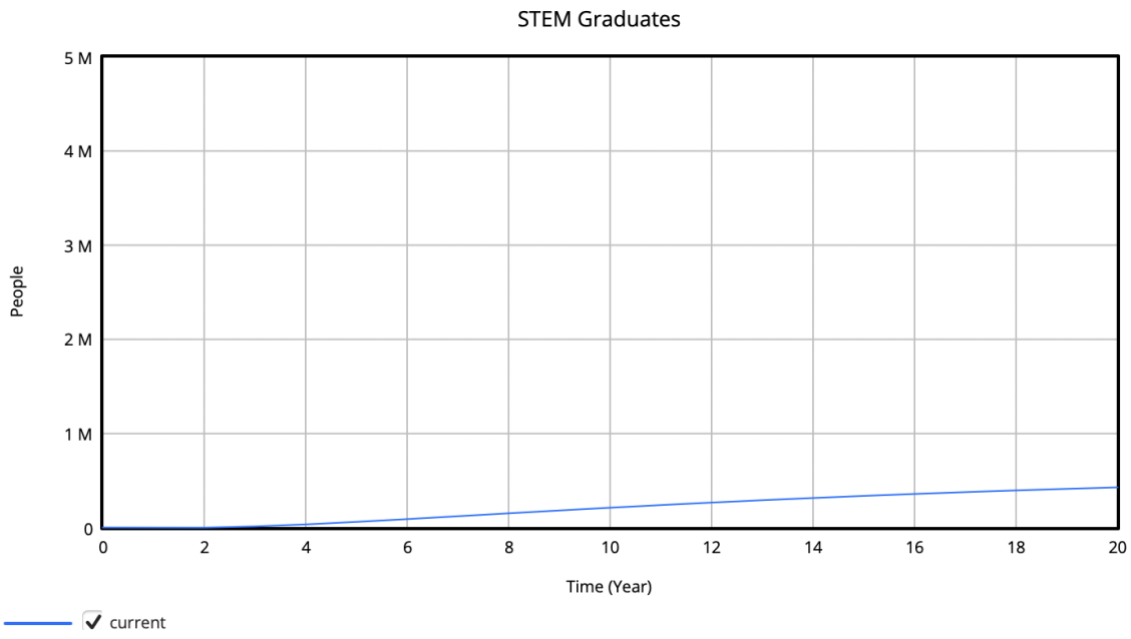


Figure 54: Worst-case Scenario STEM Graduates Simulation Output

The Vensim simulation results for the worst-case scenario of digital skills development over 20 years reveal a stagnation of basic skills acquisition with a population with basic skills remaining within the bracket of 12 million in 20 years due to low investment in digital skills training, the inflow into the basic digital skills stock remains minimal, slowing the overall growth of digital literacy. This is congruent with the undesired reference mode for digital skills discussed in section 4.2.4. (refer to Figure 23)

Low STEM enrolment and high dropout rates further weaken the pipeline of individuals acquiring advanced digital skills, with a production of 62,700 STEM graduates in 5 years and less than 500,000 in 20 years, creating a long-term shortage of skilled professionals (refer to Figure 48). Additionally, high digital skills migration of 5.4% accelerates the loss of trained professionals, reducing the availability of mentors and trainers and further decreasing skill development rates (refer to Figure 49). With low employment rates for STEM graduates, many trained individuals either leave the sector or fail to apply their skills effectively, further discouraging new entrants into digital careers (refer to Figure 50).

5.2.2.3 *Proposition validation*

The results from both best-case and worst-case scenarios for Digital Skills confirm the proposition that underinvestment in digital skills, coupled with low ICT graduate output and high levels of ICT skills migration, inhibits the effective development and utilisation of digital skills in South Africa.

This has multiple implications. First, it underscores the need for sustained public and private sector co-investment in digital skills pipelines, particularly in foundational, intermediate, and advanced ICT competencies. This requires not only increased funding but also long-term continuity and coordination to avoid fragmented skills initiatives. Second, the results signal the necessity of strengthening higher education capacity, both in quality and volume, to expand the annual supply of ICT graduates. This involves curriculum modernisation, industry–academia partnerships, and incentives for institutions to scale ICT-related programmes. Third, high ICT skills migration highlights the importance of retention-focused policies, such as competitive compensation, improved working conditions, and clear career pathways within the domestic digital economy.

5.2.3 *Digital Infrastructure*

5.2.3.1 *Digital Infrastructure Improvement (Best-case scenario)*

In the baseline scenario, the key constants, population, total number of households, and Total value of infrastructure investment remain consistent with the South African context to model the near-to-real situation of South Africa. The total investment in 2023 was R366B (ICASA, 2024), and the number of 5G base stations in 2022 was 2800 (Mzekandaba, 2022), with cost per base station ranging from R3.6M – R18M (CIOHub, 2023), 5G subscribers in December 2024 was 10.8M (TechCentral, 2025). Broadband fibre optic was over 11,000 KMs in 2025 (Illidge, 2025), with the cost of Fiber per KM of between R220,000 to R1M (BusinessTech, 2013). The 2022 South African census reports 17.8 million

households (StatsSA, 2023). There were 1,488,483 fibre-to-home subscriptions in 2023 (ICASA, 2024). Other constants were also defined in Table 8 (refer to Chapter 4, Section 4.5.2).

The best-case scenario for Digital Infrastructure focuses on the high growth of broadband coverage and 5G deployment, and the corresponding user base growth of both networks. The state configuration of the system would be as follows:

- R54B Broadband Infrastructure Investment.
- R210B Mobile Infrastructure Investment.
- 5G take-up: 0.012%.
- 5G data unaffordability index: 32%.
- 5G decommissioning rate: 0.02%.
- Broadband unaffordability index: 45%.
- Broadband take-up: 5.4%.
- 5G Subscriber churn: 0.003%.
- Broadband subscriber churn: 0.006%.

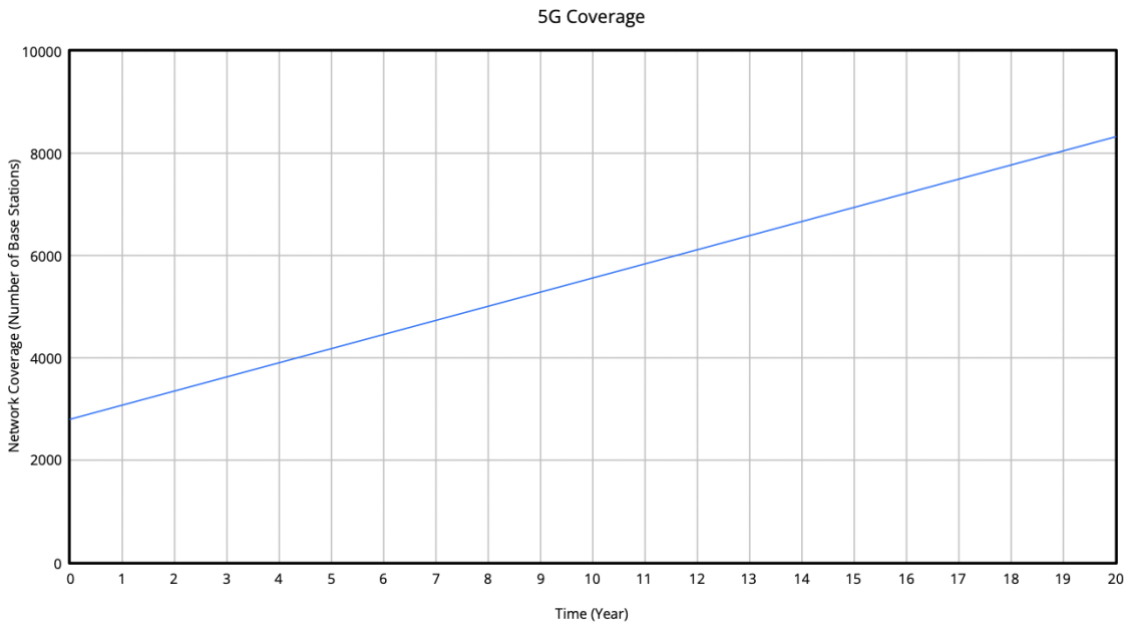


Figure 55: Best-case Scenario 5G coverage Simulation Output

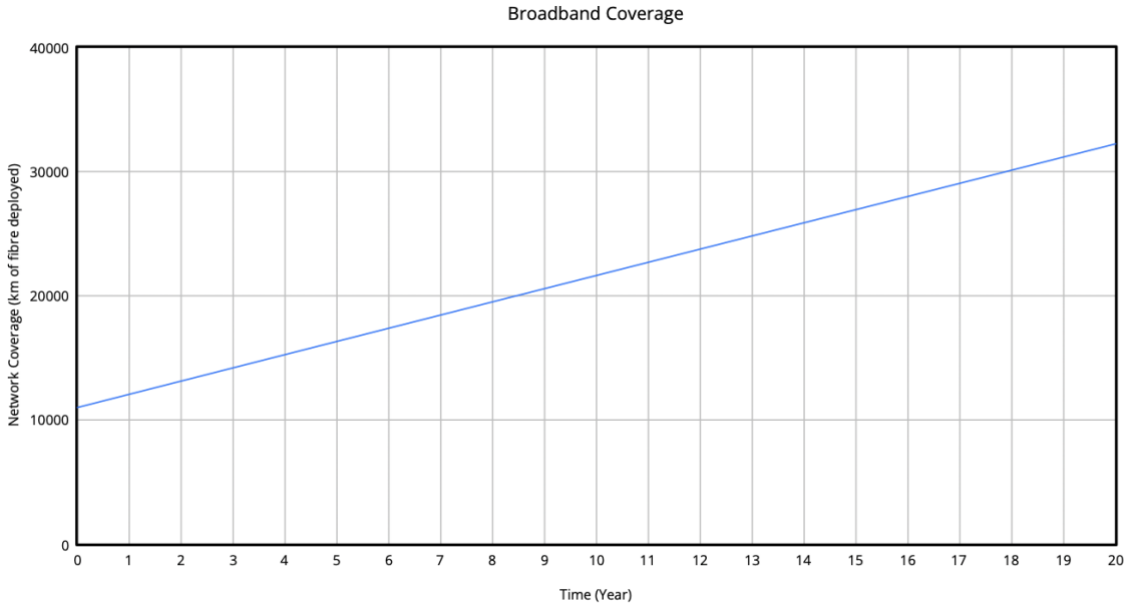


Figure 56: Best-case Scenario Broadband Coverage Simulation Output

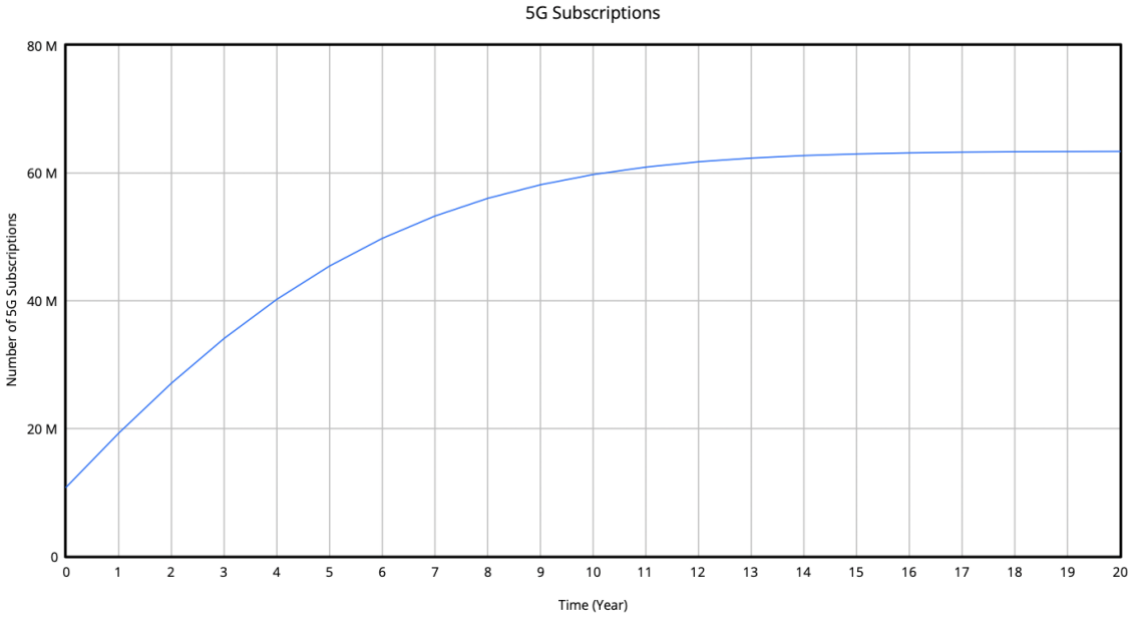


Figure 57: Best-case Scenario 5G Subscriptions Simulation Output

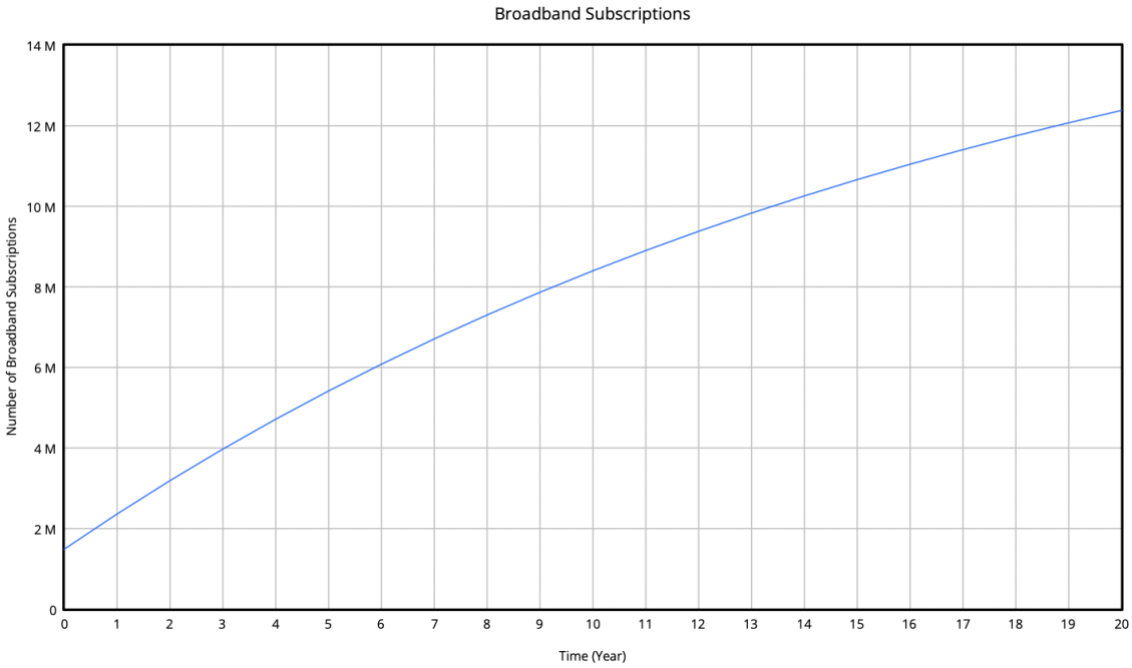


Figure 58: Best-case Scenario Broadband Subscriptions Simulation Output

The Vensim simulation results for the best-case scenario of digital infrastructure development over 20 years indicate a linear growth for Broadband and 5G coverage, reaching 5800 base stations in 10 years for 5G and Broadband (refer to Figures 52 and 53). This is a testament to South Africa's high investment in digital infrastructure, which is amongst the highest in Africa, topped by Nigeria (Business Insider Africa, 2023). The linear growth ensures that urban and rural areas gain reliable and high-speed Internet access.

The 5G and Broadband subscriber trajectory follows an initial rapid growth, followed by slower growth culminating in a plateau imposed by the balancing loop of take-up rate, unaffordability index and the carrying capacity of the system. At year 4, the 5G subscriber base is expected to reach 42M (Refer to Figures 54 and 55). This is in congruence with the prediction from TechCentral (2025). The Broadband subscriber base is expected to reach 4M. This is almost double the prediction of 2.4M in 2028 by ReportLinker (2024).

The balancing loop of a low churn rate of 0.0003 % of 5G users ensures that once users are connected, they remain within the network, stabilising revenues and allowing providers to reinvest in further network expansion and technological upgrades. By year 20, the simulation predicts near-universal broadband and 5G

penetration, fostering economic growth, digital innovation, and improved access to online services. The results suggest that under these conditions, the country can achieve a digitally inclusive society, enhance productivity, and compete in the global digital economy.

The coverage and subscriptions of both 5G and broadband networks are in congruence with the desired reference mode for digital infrastructure discussed in Figure 25 of Section 4.4.2.2. The results confirm the proposition that infrastructure investment drives digital maturity. However, the emergence of a 'Limits to Growth' dynamic suggests that without parallel investment in skills development, digital progress slows.

5.2.3.2 *Digital Infrastructure Decline (Worst-case scenario)*

In the worst-case scenario, while the baseline constants remain the same, the state configuration of the system favours the balancing loops with a high Network decommissioning rate and a high user churn rate for both 5G and Broadband networks. The investments in both 5G and Broadband remain minimal. 5G and Broadband take-up rates remain low. The state configuration of the system would be as follows:

- R27B of Broadband Infrastructure Investment.
- R105B of Mobile Infrastructure Investment.
- 5G take-up: 0.0012%.
- 5G data unaffordability index: 65%.
- 5G decommissioning rate: 0.2%.
- Broadband unaffordability index: 70%.
- Broadband take-up: 5.4%.
- 5G Subscriber churn: 0.03%.
- Broadband subscriber churn: 0.06%.

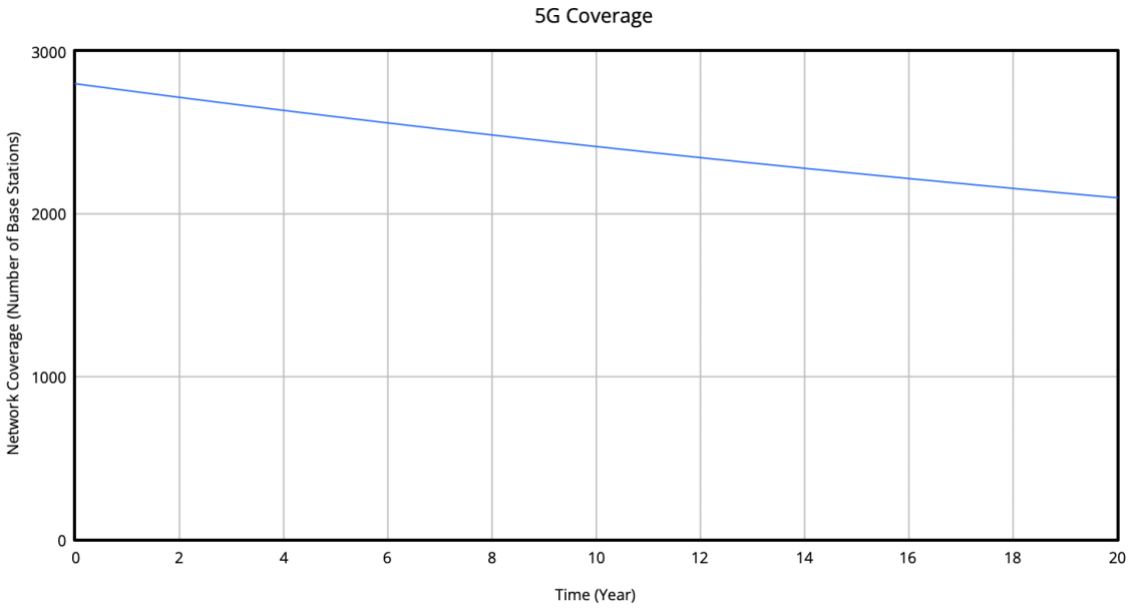


Figure 59: Worst-case Scenario 5G Coverage Simulation Output

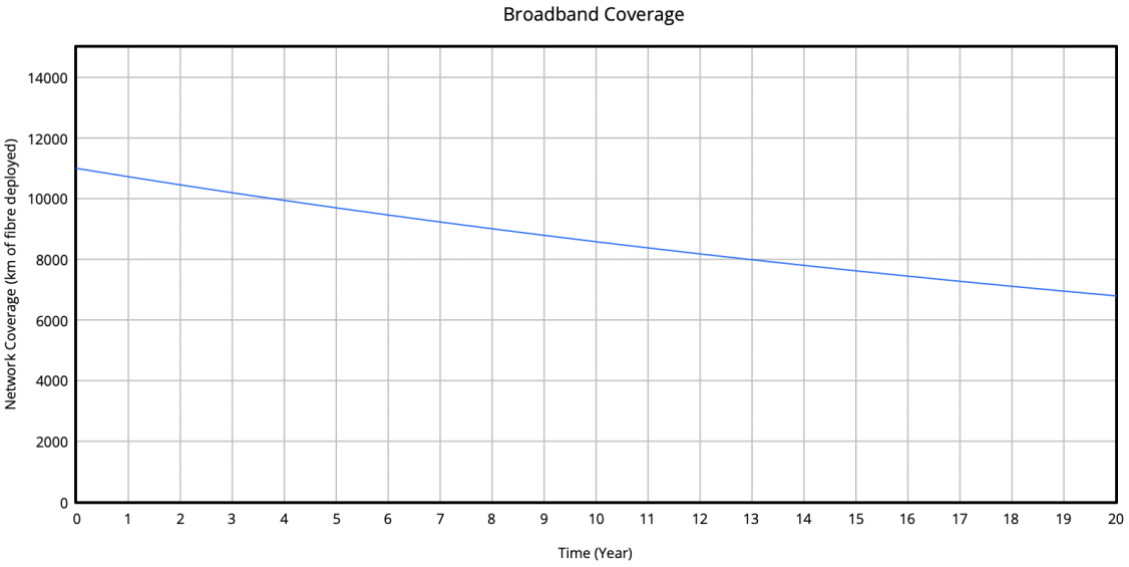


Figure 60: Worst-case Scenario Broadband Coverage Simulation Output

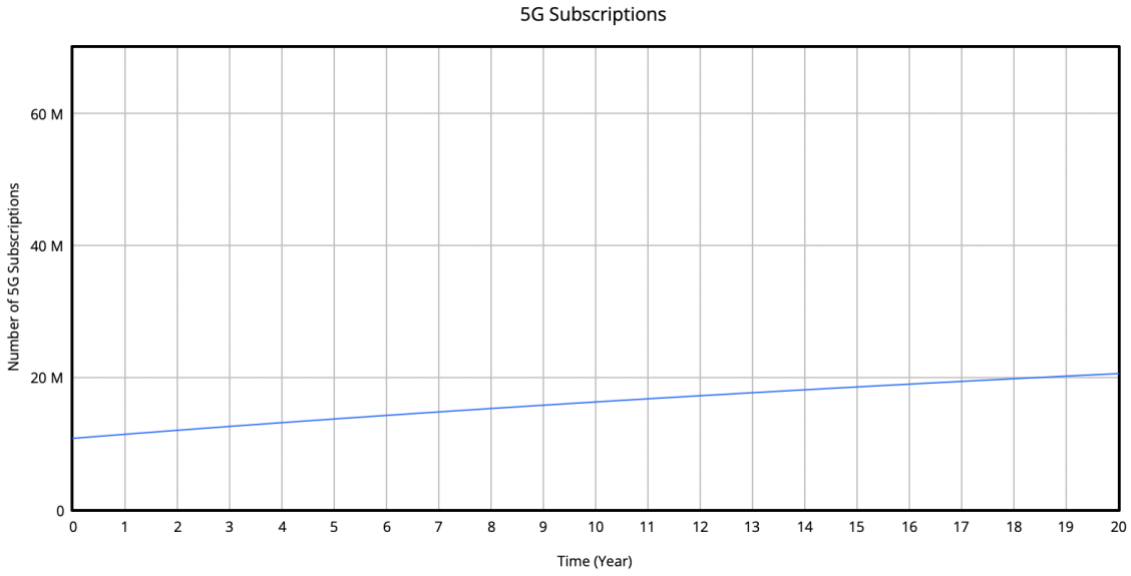


Figure 61: Worst-case Scenario 5G Subscriptions Simulation Output

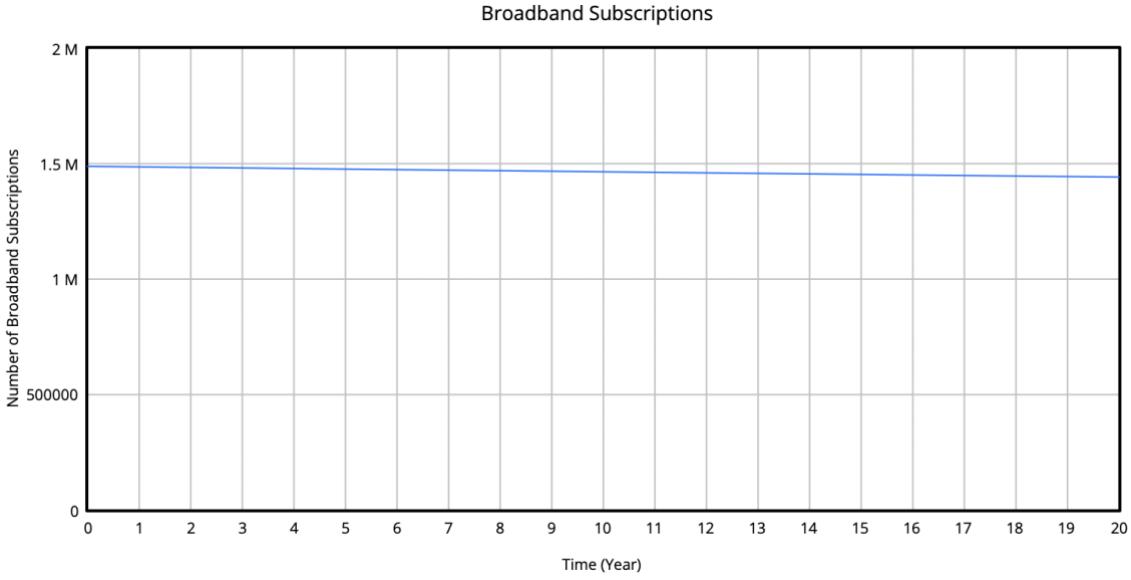


Figure 62: Worst-case Scenario Broadband Subscriptions Simulation Output

The Vensim simulation results for the worst-case scenario of digital infrastructure development over 20 years reveal a stagnant and declining growth of broadband and 5G networks, leading to widening digital inequality and limited connectivity (refer to Figures 56 and 57). Due to low investment in 5G expansion, by year 8, the aging infrastructure would result in high decommissioning rates of mobile networks and would lose 10.7% of the base stations because of limited maintenance. The loss of base stations affects the network quality of service and the network congestion, which ultimately leads to a high 5G user churn rate.

Consequently, the low 5G take-up and high use churn rate result in 5G subscriptions increasing from 12M to 18M in 10 years (refer to Figure 58). Low take-up of broadband services sees Broadband subscriptions stagnating and then further declining (refer to Figure 59). Additionally, low data affordability exacerbates the situation, as many users are unable to sustain internet subscriptions, further reducing adoption rates. The high churn rate of broadband users means that even those who initially connect are frequently dropping out, leading to financial instability for providers and preventing sustained network improvements. These trajectories of both 5G and Broadband subscriptions further discourage network expansion, creating a feedback loop where service providers see little incentive to invest.

The coverage and subscriptions of both 5G and broadband networks are in congruence with the undesired reference mode for digital infrastructure discussed in Figure 26 of Section 4.2.4.1.

5.2.3.1 *Proposition validation*

The results from both best-case and worst-case scenarios of Digital Infrastructure confirm the proposition that low investment in ICT infrastructure, combined with affordability constraints and low adoption of digital services, slows the development of digital infrastructure. This carries several implications.

First, it highlights the necessity for a coordinated national strategy that prioritises sustained capital investment in broadband networks, last-mile connectivity, and emerging technologies such as cloud computing and 5G. Without a predictable investment pipeline, infrastructure expansion remains uneven and disproportionately benefits urban areas, thereby deepening spatial digital divides. Second, the findings underscore the role of affordability policies, such as targeted subsidies, pricing regulations, and wholesale cost reductions, to ensure that households and small businesses can meaningfully engage with digital services. Enhancing affordability is likely to stimulate demand, which in turn improves the commercial viability of further infrastructure investment. Third, the slow adoption of digital services signals the need for complementary interventions—such as digital literacy programmes, public awareness campaigns, and incentives for

government and businesses to digitalise services, to stimulate usage and create a virtuous cycle of demand-driven infrastructure expansion.

5.2.4 *Technology Integration*

5.2.4.1 *Technology Integration Improvement (Best-case scenario)*

In the baseline scenario, the key constant, the total number of SMEs, although difficult to determine, remains consistent with the South African context to model the near-to-real situation of South Africa. The 2023 SEDA report indicates that there were 792,838 formal SMMEs in Q3 of 2022 (SEDA, 2023). Other constants were also defined in Table 9 (refer to Chapter 4, Section 4.6.2).

The best-case scenario for the Technology integration focuses on SMMEs' high adoption of digital technologies, e-commerce, and cross-border e-commerce sales. The state configuration of the system is as follows:

- ICT Investment: R50M.
- E-business churn rate: 0.5%.
- Cost-factor: 16.9%.
- Digital Skills factor: 35%.
- Advanced tech decommissioning rate: 0.088%.
- Market demand factor: 2%.
- Adoption barrier factor: 1%
- Cross-border Market demand factor: 2%
- Cross-border barrier factors: 0.2%,
- Cross-border e-commerce churn rate: 0.4%.

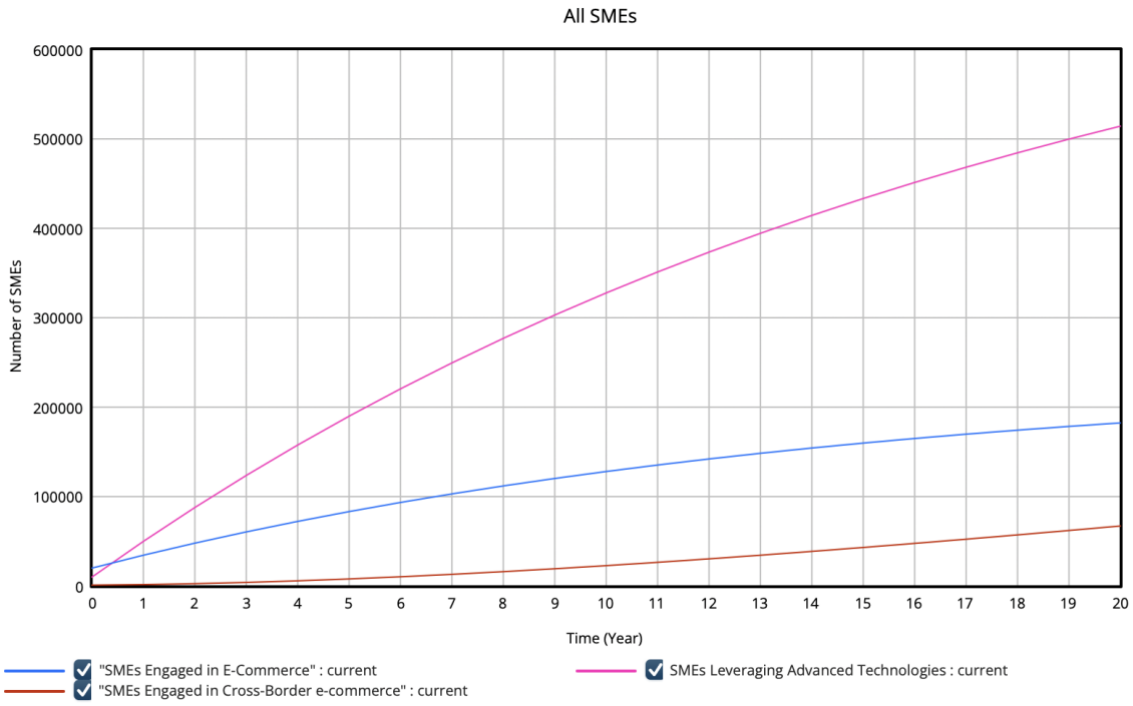


Figure 63: Best-case Scenario Technology Integration Simulation Output

The Vensim simulation results for the best-case scenario of technology integration over 20 years show a strong and sustained growth in the adoption and utilisation of digital technologies across various sectors. With high investment in ICT infrastructure and new technologies and skills, SMEs' growth is linear, reaching over 100K in 3 years. The adoption of new technologies by SMEs in a lynchpin to the high adoption of e-commerce, which leads to a significant increase in online transactions. With this increase in e-commerce adoption, more SMEs venture into cross-border sales.

The low churn rate of SMEs in e-commerce and cross-border sales is indicative of low barriers and high market demand. As discussed in Section, the barrier factor is a composite attribute of cost, regulation, etc. By year 20, the simulation predicts widespread digital transformation, increased SME profitability, and deeper integration into the global digital economy. These results highlight the critical role of sustained investment and supportive policies in ensuring that technology adoption continues to drive economic growth, innovation, and long-term digital maturity.

The growth pattern of SMEs that adopt new digital technologies, e-commerce, and cross-border e-commerce is in congruence with the desired reference mode of technology integration discussed in Figure of 27 Section 4.4.3.2.

5.2.4.2 *Technology Integration Decline (Worst-case scenario)*

The worst-case scenario for Technology Integration results in SMEs that fail to adopt key digital technologies, e-commerce, and cross-border e-commerce. The state configuration of the system would be as follows:

- ICT Investment: R25M.
- E-business churn rate: 15%.
- Cost-factor: 22%.
- Digital Skills factor: 16%.
- Advanced tech decommissioning rate: 0.88%.
- Market demand factor: 0.82%.
- Adoption barrier factor: 4.5%.
- Cross-border Market demand factor: 6.5%.
- Cross-border barrier factors: 0.2%.
- Cross-border e-commerce churn rate: 4%.

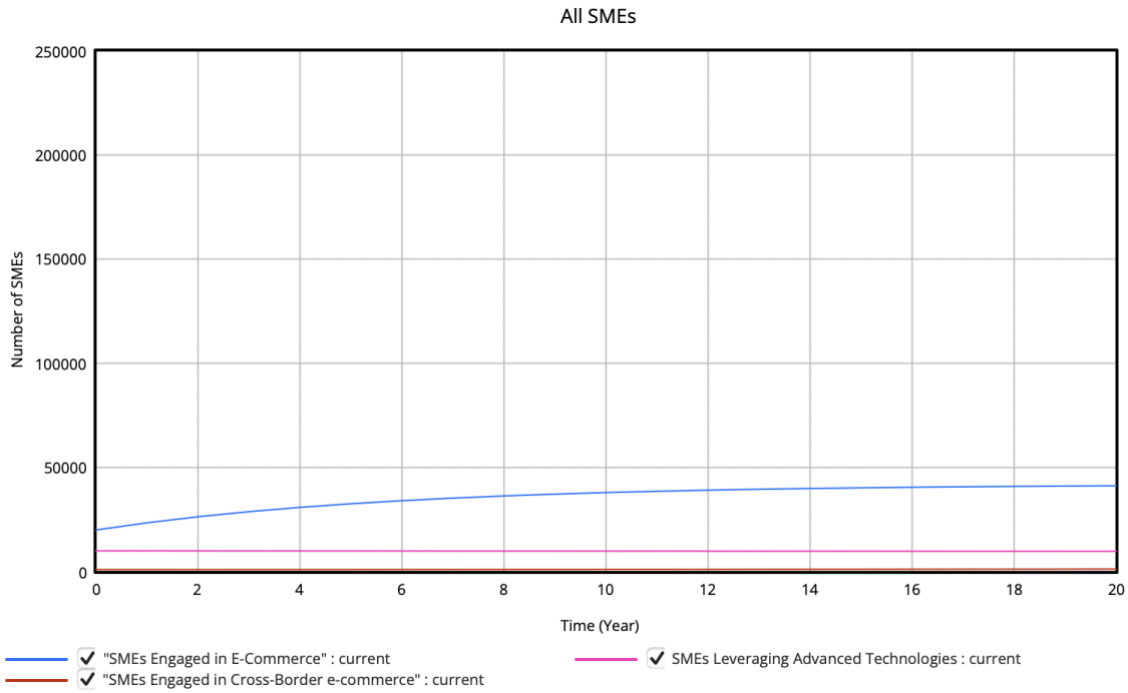


Figure 64: Worst-case Scenario Technology Integration Simulation Output

The Vensim simulation results for the worst-case scenario of technology integration reveal a slow and declining adoption of digital technologies among SMEs. The minimal number of SMEs that adopt new technologies and the accompanying ones that decommission new technologies result in a zero-sum phenomenon after 20 years (refer to Figure 61). As previously postulated, new technologies are catalysts for e-businesses. Hence, the low adoption of new technologies has a ripple effect on the adoption of e-commerce and cross-border sales. Furthermore, a high churn rate of SMEs in e-commerce and cross-border sales suggests that even businesses that initially adopt digital platforms eventually exit due to financial constraints, lack of skills, or poor digital infrastructure.

With low investment in ICT and digital skills, businesses struggle to adopt and effectively utilise emerging technologies, leading to stagnant productivity and innovation.

5.2.4.3 *Proposition validation*

The results from both best-case and worst-case scenarios for Technology Integration confirm the proposition that the adoption of Industry 4.0 technologies (e.g., AI, blockchain, IoT) is hindered by both underinvestment in technology and a shortage of relevant digital skills. The finding that the adoption of Industry 4.0 technologies—such as AI, blockchain, and IoT, is constrained by underinvestment in technology and a shortage of relevant digital skills gives rise to several important policy implications.

First, it underscores the need for targeted investment incentives, including tax credits, innovation grants, and subsidised digital transformation programmes, to reduce the cost burden faced by firms seeking to adopt advanced technologies. Such incentives are particularly important for SMEs, which often lack the capital and risk appetite to invest in frontier technologies. Second, the persistent shortage of specialised digital skills indicates that national education and training systems require substantial reform to align curricula with emerging Industry 4.0

competency requirements. This involves strengthening STEM education, expanding technical and vocational training, and embedding Industry 4.0 modules into higher education programmes. Third, the results highlight the importance of fostering collaborative innovation ecosystems, where government, industry, and research institutions co-develop technology testbeds, regulatory sandboxes, and shared R&D platforms to accelerate experimentation and reduce adoption barriers.

5.2.5 *Digital Public Services*

5.2.5.1 *Digital Public Services (Best-case scenario)*

In the baseline scenario, the key constants, the total population, the number of public services offered by the South African government, and the number of e-government users, remain consistent with the South African context to model the near-real situation of South Africa. DCDT (2024a) reports 134 services accessible through the e-services portal. Other constants were also defined in Table 10 (refer to Chapter 4, Section 4.7.2).

The best-case scenario for Digital Public Services focuses on the high digitalisation of most public services and e-government user acquisition and engagement. The state configuration of the system would be as follows:

- ICT investment: R50M.
- Digital skills factor: 25%.
- Cost factor: 20%.
- Rate of service decommissioning: 0.05%.
- E-government user churn rate: 0.005%.
- Digital literacy factor: 70%.

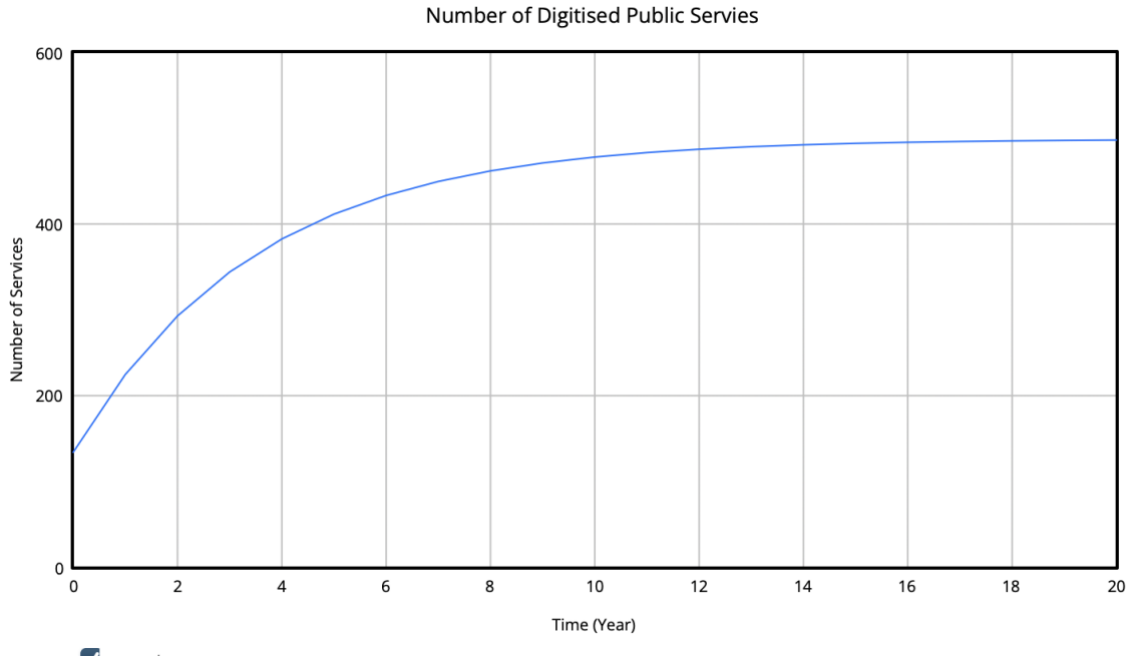


Figure 65: Best-case Scenario Digitised Public Services Simulation Output

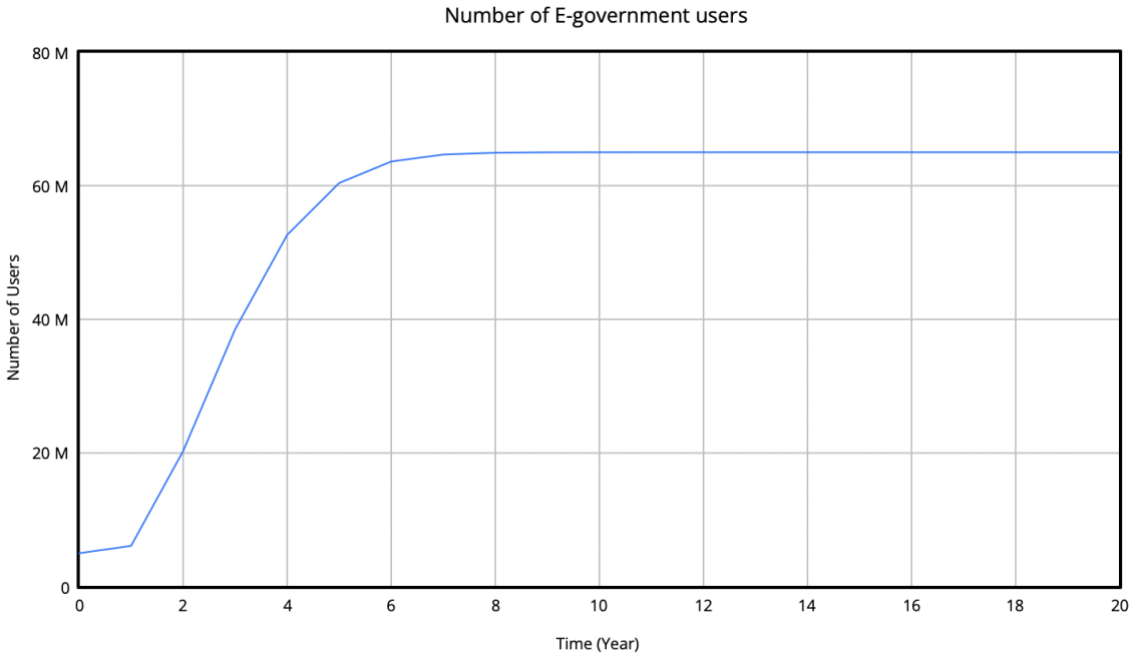


Figure 66: Best-case Scenario E-Government Users Simulation Output

The Vensim simulation results for the best-case scenario indicate a significant and sustained growth in the adoption and utilisation of digital services. High investment in ICT infrastructure and digital skills drives a rapid rate of service digitalisation, with 26.8% more digitalised services in 2 years (refer to Figure 48). This growth then leads to a substantial increase of 20M citizens engaging with

digital public services (refer to Figure 62). The trajectory of both the digitalisation of public services and e-government user adoption would reach a plateau after 10 years.

Furthermore, the low churn rate of e-government users reflects the high satisfaction and continued engagement of citizens with the digital services offered, ensuring a stable and growing user base. However, the model predicts 60M e-government users in 10 years. This figure is exaggerated, considering the current digital literary landscape of South Africa. This can be attributed to the inaccuracy of the model

The simulation suggests that with sustained efforts and investments, the country can maintain a high level of digital service provision, contributing to improved public sector efficiency and greater citizen satisfaction. The growth pattern of service digitalisation and e-government users is in congruence with the desired reference mode of technology integration discussed in Figure 31 of Section 4.4.4.1

5.2.5.2 *Digital Public Services Decline (Worst-case scenario)*

The worst-case scenario for Digital Public Services focuses on the stagnation or decline of the digitalisation of public services and low user adoption of digital public services. The state configuration of the system would be as follows:

- ICT investment: R20M.
- Digital skills factor: 15%.
- Cost factor: 30%.
- Rate of service decommissioning: 15%.
- E-government user churn rate: 5%.
- Digital literacy factor: 70%.

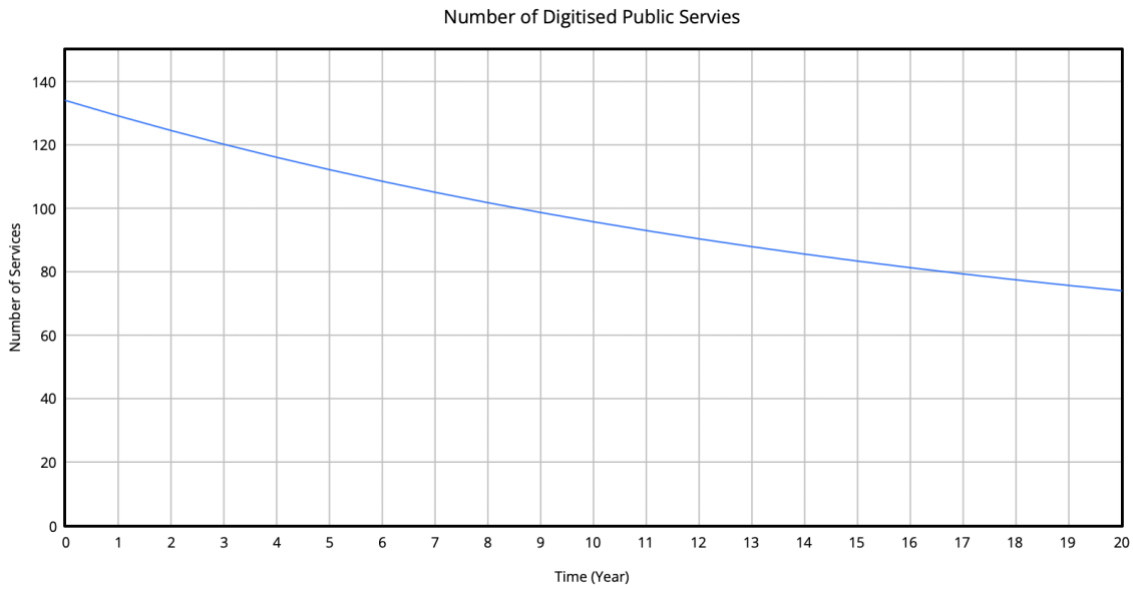


Figure 67: Worst-case Scenario Digitised Public Services Simulation Output

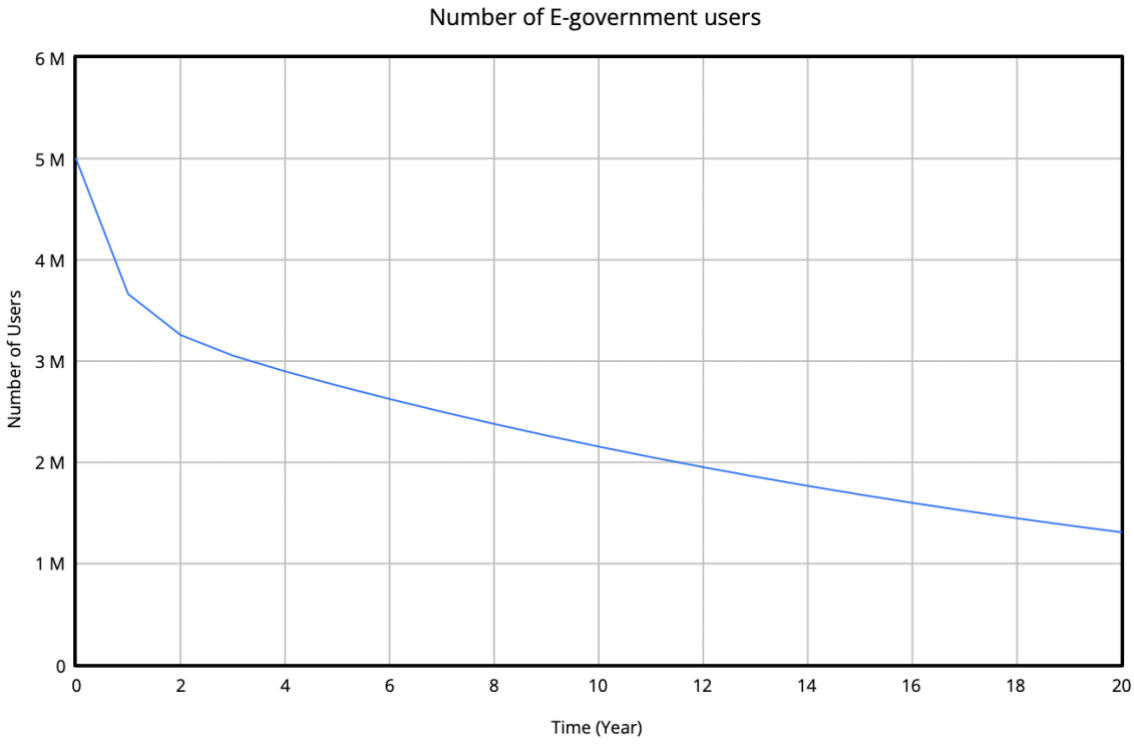


Figure 68: Best-case Scenario E-Government Users Simulation Output

The Vensim simulation results for the worst-case scenario of digital public services reveal a concerning trend of stagnation and decline in digital service provision and e-government user adoption. Low investment in ICT infrastructure and new technologies has led to a slow rate of service digitization, which in turn has resulted in minimal uptake of digital public services by citizens. This lack of

adoption is exacerbated by a high rate of digital service decommissioning, meaning that any gains made in digital service offerings are quickly undone, and outdated services are removed without suitable replacements.

Additionally, the high churn rate of e-government users suggests a lack of engagement and trust in digital platforms, further hindering the growth and sustainability of digital public services. As a result, the stock of available digital public services has remained low or even declined over time, leading to inefficiencies and a missed opportunity for improving governance and public sector performance. The simulation underscores the critical importance of sustained investment and engagement efforts to avoid such a detrimental scenario.

The growth pattern of service digitalisation and e-government users is in congruence with the desired reference mode of technology integration discussed in Figure 31 of Section 4.4.4.1

5.2.5.1 *Proposition validation*

The results from both best-case and worst-case scenarios for Technology Integration confirm the proposition that Insufficient investment in digital technologies and skills hampers the digitalisation of public services and reduces citizen adoption of e-government services. The recognition that insufficient investment in digital technologies and skills constrains the digitalisation of public services and limits citizen adoption of e-government services suggests the need for a more integrated and sustained approach to public-sector digital transformation. Beyond increasing budget allocations, government must prioritise capacity-building programmes that enhance the digital competencies of public servants, ensuring they can effectively design, manage, and deliver digital services. Furthermore, the low uptake of e-government services indicates that investment must also focus on user-centred design, accessibility, and public digital literacy initiatives to strengthen trust and engagement with digital platforms. Policies that promote interoperability, data-sharing standards, and secure digital identity systems are equally critical to ensure seamless service delivery and reduce administrative burdens. Ultimately, addressing both

technological and human-capital gaps is vital for establishing a digitally capable state and enabling the widespread adoption of inclusive, efficient, and citizen-centric e-government services.

5.3 Chapter Summary

This chapter outlines various tests to assess dynamic models, including boundary adequacy, structural assessment, dimensional consistency, parameter assessment, extreme conditions, behaviour anomalies, and sensitivity analysis. These tests help uncover flaws and improve the models, ensuring they accurately represent the real-world system and can reliably predict its behaviour. The chapter also highlights the significance of engaging stakeholders early in the process to align perspectives and ensure the problem definition accurately reflects real-world dynamics.

This chapter further demonstrates that the effectiveness of South Africa's digital transformation agenda is fundamentally shaped by systemic constraints across digital skills development, ICT infrastructure investment, Industry 4.0 adoption, and public-sector digitalisation. The analyses reveal that underinvestment in digital skills, combined with weak ICT graduate output and persistent skills migration, undermines the growth of a robust national skills pipeline and limits the productive utilisation of digital capabilities. Similarly, inadequate investment in ICT infrastructure, exacerbated by affordability constraints and low adoption of digital services, slows the diffusion of broadband connectivity and reinforces spatial and socio-economic digital divides. The findings further indicate that the adoption of Industry 4.0 technologies is constrained by both capital shortages and a lack of specialised competencies, signalling the need for coordinated interventions that integrate incentives for technological upgrading with reforms to the education and training system. Finally, insufficient investment in digital technologies and digital skills within the public sector hampers the digitalisation of government services and reduces citizen uptake of e-government platforms, thereby limiting the realisation of a modern, citizen-centric state. Collectively, these results point to the necessity of a systems-oriented policy approach that simultaneously strengthens digital skills, expands infrastructure, accelerates

industrial digitalisation, and enhances public-sector capability. Addressing these interdependencies is essential for building an inclusive, competitive, and sustainable digital economy.

CHAPTER 6. Conclusion and Recommendations

6.1 Conclusion

6.1.1 *Introduction*

While the DESI framework offers valuable benchmarks for assessing digital progress, its static, point-in-time measurements are limited in their ability to capture the dynamic feedback processes that shape digital transformation. This exploratory study therefore, integrates System Dynamics (SD) with the normative Digital Economy and Society Index (DESI) to investigate the complex, interdependent factors influencing South Africa's digital maturity trajectory. DESI provides a structured assessment across critical dimensions—including digital skills, digital infrastructure, technology integration, and digital public services—yet it does not account for the nonlinear interactions, delays, and reinforcing mechanisms that underpin digital ecosystem behaviour. By incorporating system dynamics modelling, this study extends the analytical capacity of DESI, enabling the examination of how these dimensions evolve over time and interact to produce emergent outcomes. This approach provides policymakers with deeper insight into potential leverage points for accelerating digital development and supports more effective long-term digitalisation strategies.

6.1.2 *Purpose and Objectives of the Research*

The dynamic hypothesis in Section 4.4.1 was employed to answer the research questions by elucidating the systemic challenges of digital maturity at a country level. By utilising system dynamics archetypes, the study uncovered recurring patterns of behaviour that affect digital maturity development in South Africa. These archetypes discussed in "Limits to Growth", "Growth and underinvestment and "Shifting the burden" were instrumental in uncovering and understanding the extant and systemic digital maturity challenges in South Africa, hence answering the research questions 1, 2, and 3 outlined in Section 1.4. By recognising these

system-wide patterns, policymakers and stakeholders can anticipate unintended consequences, mitigate risks, and develop more sustainable digital strategies.

The development of the novel system dynamics models through stock and flow diagrams of each of the four dimensions of DESI was a pronounced and critical outcome of the study. This was accomplished by adopting Sterman's five-step process and utilising Vensim Personal Learning Edition (PLE) modelling software. The simulation of the models allowed an exploration of best-case and worst-case scenarios, highlighting how policy interventions impact digital maturity over time. The simulation results were congruent with the extant desired and undesired reference modes for the different dimensions of a country's digital maturity. These results were discussed in detail in Sections 5.2.2.1, 5.2.2.2, 5.3.2.1, 5.3.2.1, 5.4.2.1, 5.4.2.2, 5.5.2.1, and 5.5.2.2. The simulation also answered research question 4 in Section 1.4. The simulation results further confirmed the research propositions as discussed in Sections 5.2.2.3, 5.2.3.1, 5.2.4.3 and 5.2.5.1

6.1.3 *Contributions to the Body of Knowledge*

Firstly, the application of system dynamics to the digital maturity index, such as the DESI framework, is novel in the study. This approach provides a holistic and structured approach to understanding the complexity involved in the digital maturity of a country. By using system dynamics archetypes, the study contributes to the body of knowledge on how recurring and systemic challenges in the digital maturity of a country can be exposed and explained. Second, by modelling digital maturity using causal loop diagrams, the study contributes to the body of knowledge on how the components of digital maturity interact in a dynamic setting. Lastly, by modelling the components of digital maturity using stocks and flows and the subsequent simulation thereof, the study contributes to the body of knowledge on how system dynamics enable policymakers, researchers, and industry leaders to visualise long-term trends, identify bottlenecks, and test policy interventions before implementation.

The proposed policy interventions offer policymakers a structured and evidence-informed foundation for accelerating South Africa's digital transformation. By

addressing systemic constraints across digital skills development, ICT infrastructure expansion, Industry 4.0 adoption, and public-sector digitalisation, these policies provide a coherent portfolio of levers that can generate long-term, mutually reinforcing improvements in digital maturity. Investing in digital skills and strengthening ICT graduate pipelines equips the workforce with the competencies required for a competitive digital economy, while targeted infrastructure investment and affordability measures expand access and stimulate demand for digital services. Policies that incentivise technological upgrading and foster collaborative innovation ecosystems help firms adopt Industry 4.0 technologies, positioning the country to participate in emerging global value chains. Similarly, enhancing public-sector digital capability and improving the usability of e-government platforms increases citizen trust and uptake, supporting a more efficient and inclusive state. Collectively, these policies offer a roadmap for decision-makers to prioritise high-impact interventions, identify leverage points, and coordinate actions across sectors—ultimately enabling a more resilient, equitable, and future-ready digital ecosystem.

6.1.4 *Recommendations*

This study provides exploratory insights into the dynamics of digital maturity by simulating best-case scenarios across digital skills, digital infrastructure, technology integration, and digital public services. Based on the findings, it is recommended that policymakers and stakeholders prioritise sustained investment in digital infrastructure, particularly in broadband and 5G expansion, to ensure universal connectivity and affordability. The best-case scenario results demonstrate that high investment and low churn rates contribute to stable and accessible digital networks, fostering increased digital adoption. Additionally, boosting digital skills development through higher STEM enrollment, advanced digital training, and employment support for ICT professionals is crucial to building a digitally skilled workforce. The findings indicate that reducing digital skills migration can further strengthen local expertise and innovation, reinforcing long-term digital transformation.

Furthermore, policymakers should focus on accelerating technology integration in businesses, particularly SMEs, by promoting e-commerce adoption and cross-border digital trade through financial incentives, training programs, and streamlined digital regulations. The best-case simulations suggest that strong technology adoption, combined with high digital public service efficiency, can drive economic growth, business competitiveness, and citizen engagement in digital governance. However, given that this study is exploratory, future research should expand on these findings by refining the models with expert validation, integrating more granular real-world data, and exploring additional policy levers. The insights from this research provide a valuable starting point for decision-makers to test different policy interventions, anticipate challenges, and develop strategic roadmaps for accelerating digital maturity at a national level.

6.1.5 *Limitations and Opportunities for Future Research*

One limitation of this study is that, due to time constraints of the research period, the system dynamics models were not reviewed by digital maturity experts, which may have affected their structural and relational (i.e. equations) accuracy and correctness. While the models were constructed based on the Digital Economy and Society Index (DESI) framework, expert validation could have provided additional insights, refinements, and validation of assumptions. Engaging with policymakers, ICT industry professionals, and digital maturity specialists could have ensured that the models align with real-world dynamics and reflect nuanced factors that influence digital maturity. Future research should incorporate expert reviews and stakeholder engagement to enhance the robustness and practical relevance of system dynamics modelling in digital maturity studies.

Another limitation is that the models were simplified to avoid excessive complexity and computational burden. While simplifications were necessary to ensure the models remained manageable and interpretable, they may have overlooked certain granular details in digital maturity. For example, adoption barriers for cross-border e-commerce for the Technology Integration dimension in Section 4.4.1 were modelled in generalised terms rather than incorporating micro-level factors such as cross-border customs regulations and trade policies, import

duties and taxes. Future research should explore ways to increase model complexity without sacrificing clarity, potentially by using modular approaches or hybrid modelling techniques that integrate agent-based models or machine learning to enhance predictive accuracy.

Additionally, the study could not combine the stock and flow diagrams for digital skills, digital infrastructure, technology integration, and digital public services into a single unified model, as doing so would have made the system too complicated, cumbersome, and unwieldy. Each component of digital maturity interacts with others in complex, nonlinear ways, and integrating all four dimensions would have required a highly intricate model with extensive parameterisation. While separating them allowed for focused analysis and scenario testing, it limited the ability to study cross-sectoral feedback loops comprehensively. Future research could attempt incremental integration of these models, potentially through multi-layered system dynamics frameworks that allow for interdependencies while maintaining usability. This approach could provide a more holistic understanding of digital transformation and its interconnected components.

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Appendix A: Model Equations in Text Form

Digital Skills

Advanced training rate = 1/ (ICT Skills migration) + Advanced training investment

Basic training rate=1/ (ICT Skills migration + Basic training investment)

Advanced skills acquisition = Population with Basic Skills * Advanced training rate

Employed workforce = Population - (Population * Unemployment rate)

New STEM students = Prospective University Students * STEM Enrolment rate

Basic skills acquisition = Employed workforce * Basic training rate

Student dropout = STEM Students * Student dropout rate

Graduation rate = 1 - Student dropout rate

Prospective University Students = INTEG (Matriculation rate - New STEM students)

STEM Students = INTEG (New STEM students - STEM Graduands - Student dropout)

Population with Basic Skills = INTEG (Basic skills acquisition - Advanced skills acquisition)

ICT Specialists = INTEG (Advanced skills acquisition + Workforce entry rate - ICT Skills migration

Workforce entry rate = STEM Graduates * ICT Graduate Employment rate

STEM Graduates = INTEG (STEM Graduands - Workforce entry rate)

ICT Skills migration = ICT Specialists * ICT skills migration rate

Matriculation rate = Grade 12 Students * Pass rate

Digital Infrastructure

Broadband decomm = Broadband Network Coverage*Broadband decomm rate

New broadband subscribers = (1/Broadband Network Coverage) +"Fixed Broadband Take-Up"*(1\ - Broadband unaffordability index)*Potential Broadband subscribers

Potential Broadband subscribers = Total households - Broadband Subscribers

Broadband Network Coverage= INTEG (Broadband infrastructure rollout-Broadband decomm,11000)

User Dissatisfaction factor = "5G data unaffordability index"*"5G QOS"

"5G subscriber Churn" = "5G data unaffordability index"*"5G Subscribers"*User Dissatisfaction factor

"5G QOS"="5G Decomm"*(1/"5G Subscribers")*Network congestion factor

"5G Decomm" = "5G Network Coverage"*"5G Decomm rate"

Broadband Subscriber churn = Broadband Subscribers*Broadband churn rate

"5G Network Coverage"= INTEG ("5G rollout rate"-"5G Decomm",2800)

New 5G Subscribers ="5G Network Coverage"*"5G Take-Up"*(1-"5G data unaffordability index")*Potential 5G Subscribers

"5G rollout rate" = Annual Mobile Investment/Cost Per Base station

Broadband infrastructure rollout = Annual Broadband Investment/Cost Per fiber per km

Potential 5G Subscribers = Total population-"5G Subscribers"

Broadband Subscribers= INTEG (New broadband subscribers-Broadband Subscriber churn, 1.48843e+06)

"5G Subscribers"= INTEG (New 5G Subscribers-"5G subscriber Churn",1.08e+07)

Technology Integration

New Tech adoption rate = (1 - (1/ICT investment))*Digital skills factor-Cost factor

New SMEs selling online = “Potential E-commerce SMEs"*"e-Commerce adoption rate"

"SMEs Engaged in E-Commerce" = INTEG (New SMEs selling online-"E-business churn", 20000)

"Potential E-commerce SMEs" = Total SMEs-"SMEs Engaged in E-Commerce"+"E-business churn"

"E-business churn" = "E-business churn rate"*"SMEs Engaged in E-Commerce"*(1 - New Tech adoption rate)

New SMEs adopting advanced technologies = Potential SMEs Leveraging Advanced Technologies*New Tech adoption rate

Potential SMEs Leveraging Advanced Technologies = Total SMEs-SMEs Leveraging Advanced Technologies

SMEs Leveraging Advanced Technologies = INTEG (New SMEs adopting advanced technologies - Advanced tech decomm, 10000)

"SMEs Engaged in Cross-Border e-commerce" = INTEG ("New SMEs doing Cross-Border e-commerce" -"Cross-border e-commerce churn", 1000)

Advanced tech decomm = SMEs Leveraging Advanced Technologies*Advanced tech decomm rate

"Cross-border adoption rate" = "Cross-border Market demand factor" * (1 - "Cross-border barrier factors")

"e-Commerce adoption rate" = Market Demand factor*(1 - Adoption barrier factors)

"New SMEs doing Cross-Border e-commerce"=("SMEs Engaged in E-Commerce)*"Cross-border adoption rate"

Digital Public Services

"e-government user churn"="e-Government users"*"e-government user churn rate"

Awareness of digital public services=Digitalised Public Services/Total public services

Rate of Digitalisation=(1 - (1/ICT Investment))*Digital skills factor-Cost factor

"New e-Government users" = "Potential e-Government users"*(Awareness of digital public services\
* (1 - Digital literacy factor))

Digital services decomm = Digitalised Public Services*Rate of service decomm

Service digitalisation = Manual public services*Rate of Digitalisation

Digitalised Public Services= INTEG (Service digitalisation - Digital services decomm, 134)

"e-Government users"= INTEG ("New e-Government users"-"e-government user churn", 5e+06)

Manual public services = Total public services-Digitalised Public Services

"Potential e-Government users" = Population-"e-Government users"