



MODULE: LCDB701

QUANTITATIVE RESEARCH METHODS

ASSIGNMENT TITLE:

REPORT

STUDENT NAME : EMMANUEL OCHIENG

STUDENT NUMBER : 1807935

SUPERVISOR : DR. EBAD BANISI

WORD COUNT : 8,216

SUBMISSION DATE : 17/12/2024

RESEARCH TOPIC

Assessing the Role of Digital Twin Technology in enhancing the Resilience and Sustainability of Transport Infrastructure Projects in Developing Economies: *A Case Study of Sub-Saharan Africa.*

TABLE OF CONTENT

<i>ABSTRACT</i>	5
<i>CHAPTER 1: INTRODUCTION</i>	6
RESEARCH QUESTION	7
RESEARCH OBJECTIVES	8
<i>CHAPTER 2: LITERATURE REVIEW</i>	9
Overview of Digital Twin Technology (DTT)	9
Core components of Digital Twin Technology and enabling technologies	9
Applications of DTT in Transport Infrastructure	10
Sub-Saharan Africa Specific Challenges and Opportunities	11
Barriers to DTT Adoption	12
Lessons from Developed Economies.....	12
Research Gap	12
<i>CONCEPTUAL FRAMEWORK DIAGRAM</i>	13
THEORETICAL FRAMEWORKS UNDERPINNING THE STUDY	14
<i>CHAPTER 3: METHODOLOGY</i>	15
Hypothesis	15
Research Design and Paradigm.....	16
Sampling Strategy	16
Survey Instrument.....	17
Data Collection.....	17
Ethical Considerations.....	17
Inclusion and Exclusion Criteria	18
Data Analysis.....	18
<i>CHAPTER 4: RESULTS</i>	19
<i>CHAPTER 5: DISCUSSION</i>	27
Comparative Case Studies	38
<i>CHAPTER 6: CONCLUSION AND RECOMMENDATIONS</i>	44
Key Findings	44
Recommendation.....	44

<i>REFERENCES</i>	<i>46</i>
<i>APPENDICES.....</i>	<i>52</i>
Appendix A- Geographical focus of studies on Digital Twin Technology	52
Appendix B – Summary of articles used and their relevance.....	54
Appendix C – Geographical focus of articles.....	58
Appendix D – Summary of Key Findings.....	59
Appendix E – Summary of Case Studies.....	59
Appendix E- Comparative Analysis.....	60
Appendix F: Survey Questionnaire	61

ABSTRACT

This study investigates the potential of Digital Twin Technology (DTT) to enhance the resilience and sustainability of transport infrastructure in Sub-Saharan Africa (SSA). Employing a mixed-methods approach, the research examines DTT's capabilities in predictive maintenance, real-time monitoring, and disaster preparedness, while addressing key barriers to its adoption, including financial, technological, and institutional challenges.

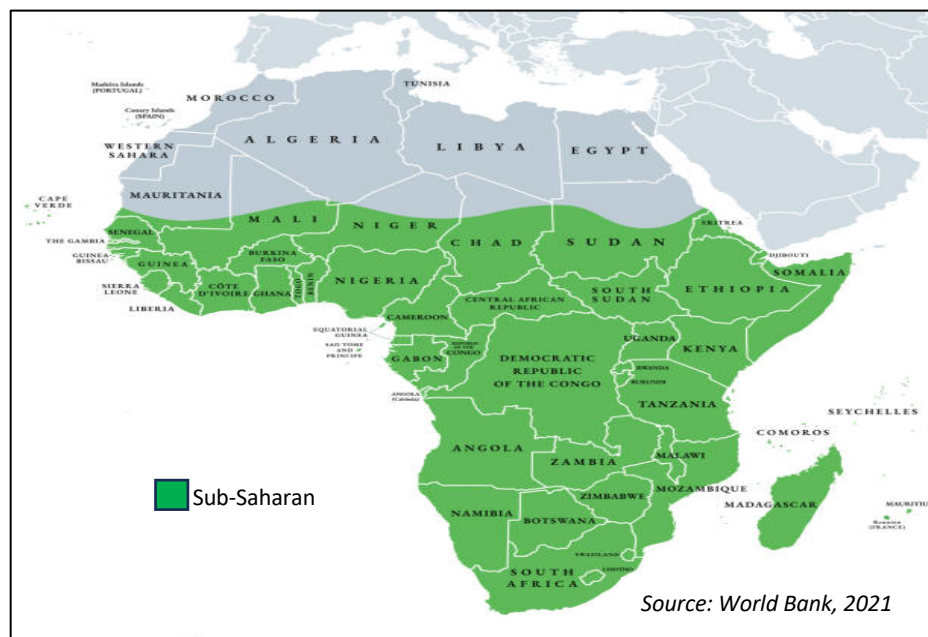
Findings reveal that DTT significantly enhances resilience by reducing infrastructure vulnerabilities and enabling proactive disaster response. It also supports sustainability through resource optimisation, carbon footprint reduction, and lifecycle management. However, adoption is constrained by limited awareness, inadequate digital infrastructure, and resistance to change. Lessons from developed economies emphasise the relevance of modular solutions, Public-Private Partnerships (PPPs), and scalable systems tailored to resource-constrained environments.

The study provides actionable recommendations, including strategic investments in digital infrastructure, capacity-building initiatives, and the implementation of clear policy frameworks to drive DTT adoption. Aligning DTT with United Nations Sustainable Development Goal 9a underscores its potential to transform SSA's transport systems into resilient and sustainable infrastructure networks, contributing to regional economic growth and global sustainability objectives. This research advances the discourse on digital innovation in infrastructure management, offering insights for policymakers, engineers, and stakeholders in SSA and beyond.

Keywords: Digital Twin Technology (DTT), Resilience, Sustainability, Transport Infrastructure, Sub-Saharan Africa (SSA), Quantitative method.

CHAPTER 1: INTRODUCTION

Transport infrastructure serves as the backbone of economic growth and societal connectivity, enabling commerce, mobility, and regional integration (World Bank, 2020; Hood, 2021) yet, in Sub-Saharan Africa, this vital sector faces a crisis. Millions of commuters across the region rely daily on ageing and underfunded transportation networks. As urban populations expand rapidly and climate change heightens vulnerabilities, the demand for innovative solutions has become increasingly critical (Banzhaf *et al.*, 2022; Ibrahim *et al.*, 2020).



World Bank defines Sub-Saharan Africa as all African countries located geographically south of the Sahara desert.

Figure 1 – Map of Africa showing the Sub-Saharan Africa

Digital Twin Technology (DTT), a ground-breaking innovation that creates dynamic virtual replicas of physical assets, has transformed infrastructure management in developed economies (Taherkhani *et al.*, 2024). It enables predictive maintenance, real-time monitoring, and resource optimisation (Franciosi *et al.*, 2024). However, its application in developing regions like Sub-Saharan Africa remains limited, hindered by financial, technological, and institutional barriers (Kosyakov *et al.*, 2023; Kelvin *et al.*, 2024). This gap exemplifies a critical opportunity to leverage

DTT for creating resilient and sustainable transport systems, particularly as the region grapples with rapid population growth and increasing climate risks (Bado et al., 2022).

This research aims to bridge this gap by addressing the following questions:

RESEARCH QUESTION

These questions are designed to guide the exploration of Digital Twin Technology's role in enhancing the resilience and sustainability of transport infrastructure in Sub-Saharan Africa.

Table 1- Research Questions organised in themes

Theme	Question
Resilience and Sustainability	1. How does Digital Twin Technology enhance resilience in transport systems by enabling predictive maintenance and disaster preparedness. 2. What is the potential of DTT to promote sustainability through resource optimisation and carbon footprint reduction in Sub-Saharan Africa.
Barriers and Challenges	3. What are the primary technical, financial, and institutional barriers to adopting DTT in transport infrastructure projects in Sub-Saharan Africa?
Policy and Implementation	4. What policy frameworks and governance strategies are necessary to support the integration of DTT in Sub-Saharan Africa's transport systems?
Alignment with Global Goals	5. To what extent can DTT contribute to achieving Sustainable Development Goal 9a (sustainable and resilient infrastructure) in the context of Sub-Saharan Africa?
Comparative Insights	6. What lessons from DTT implementation in developed economies can be adapted to address challenges in Sub-Saharan Africa?

RESEARCH OBJECTIVES

By exploring the potential of Digital Twin Technology, this research aims to identify actionable strategies to enhance resilience and sustainability in Sub-Saharan Africa's transport infrastructure.

- 1) To assess how Digital Twin Technology (DTT) can enhance the resilience of transport infrastructure through real-time monitoring, predictive maintenance, and disaster preparedness.
- 2) To evaluate DTT's potential in achieving sustainability by optimising resource use, reducing environmental impacts, and promoting lifecycle efficiency.
- 3) To identify and analyse key barriers, including technological, financial, and institutional challenges, to the adoption of DTT in transport infrastructure projects in Sub-Saharan Africa.
- 4) To provide actionable policy recommendations for enabling the integration of DTT into transport systems in Sub-Saharan Africa, addressing governance, regulatory, and stakeholder collaboration needs.
- 5) To align DTT applications with global sustainability goals, particularly Sustainable Development Goal 9a.
- 6) To draw and adapt insights from successful DTT implementations in other regions for application within the socio-economic and infrastructural context of Sub-Saharan Africa

CHAPTER 2: LITERATURE REVIEW

This review critically evaluates recent advancements in DTT and identifies gaps in the literature published in the last five years.

Overview of Digital Twin Technology (DTT)

Digital Twin Technology (DTT) is a transformative innovation enabling the creation of dynamic, virtual replicas of physical systems. Initially conceptualised in the early 2000s by Michael Grieves, DTT has evolved with advancements in IoT, AI, and cloud computing (Kosyakov et al., 2023). DTT integrates data collected from physical assets with advanced analytics to optimise operations and inform decision-making (Franciosi et al., 2024). While its adoption is prevalent in developed economies, its application in transport infrastructure in developing regions remains underexplored. *(For further details, please see Appendix A and B)*

Core components of Digital Twin Technology and enabling technologies

Digital twins rely on several key components to function effectively.

Table 2 - Components of Digital Twin Technology

Component	Description
Physical Entity	This includes the physical transport infrastructure or asset, such as roads, bridges, railways, or vehicles, that is being mirrored.
Digital Model	A virtual representation of the physical asset, created using advanced simulation tools and data collected from the physical system.
Data Integration Layer	Real-time data collected through IoT sensors, GPS devices, and other monitoring systems forms the backbone of the digital twin, ensuring synchronisation between the physical and virtual models.
Analytical Engine	AI and machine learning algorithms analyse the data, providing actionable insights for optimisation, predictive maintenance, and decision-making.

User Interface	A platform that allows stakeholders, including engineers, policymakers, and transport operators, to interact with and interpret the digital twin’s insights.
----------------	--

These components work together to enable continuous, bidirectional communication between the physical and digital systems, ensuring that the digital twin evolves alongside its real-world counterpart.

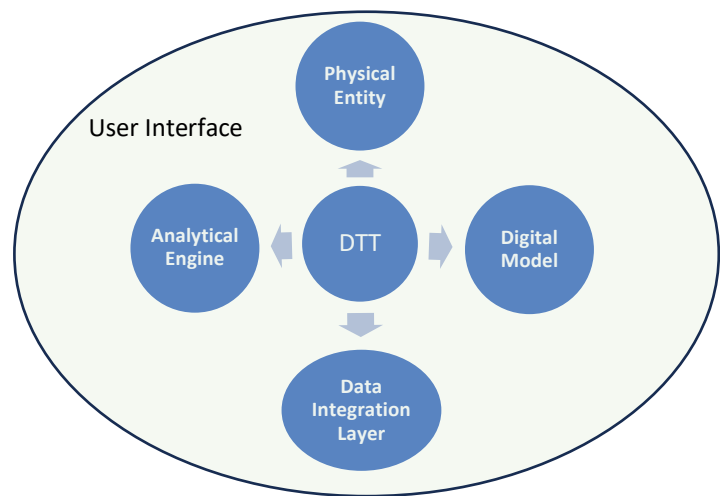


Figure 2- Components of Digital Twin Technology and enabling technologies

Applications of DTT in Transport Infrastructure

In developed economies, DTT has been applied to enhance operational efficiency, resilience, and sustainability. For example, London’s Underground employs DTT for predictive maintenance, reducing costs and increasing safety (Bado et al., 2022). Similarly, urban transport systems leverage DTT for dynamic traffic management and disaster response (Cheng et al., 2023). However, Sub-Saharan Africa faces unique challenges, such as limited digital infrastructure and technical expertise, which hinder large-scale DTT deployment (Shahzad et al., 2022).

Resilience and Sustainability

DTT significantly contributes to infrastructure resilience by enabling real-time monitoring, predictive maintenance, and disaster preparedness. For instance, digital twins simulate disaster impacts, allowing proactive planning and quicker recovery (Ariyachandra & Wedawatta, 2023). Sustainability is achieved through resource optimisation, lifecycle management, and emissions reduction (Jiao et al., 2023). In Sub-Saharan Africa, these capabilities are crucial for addressing climate-related vulnerabilities and promoting sustainable development (Franciosi et al., 2024). While DTT has revolutionised transport systems in developed economies, its application in resource-constrained contexts like SSA faces unique challenges, as discussed next.

Sub-Saharan Africa Specific Challenges and Opportunities

Sub-Saharan Africa (SSA) faces unique challenges and opportunities in adopting Digital Twin Technology (DTT), particularly due to limited digital infrastructure and connectivity. Studies such as those by Kouladoun (2023) and Obonyo and Ouma (2022) highlight how basic infrastructural gaps hinder digital transformation in transport systems. However, case studies from SSA provide insights into potential applications. For example, Nairobi's Bus Rapid Transit (BRT) system demonstrates how DTT can optimise urban transport, reduce congestion, and improve access for underserved areas (Obonyo and Ouma, 2022). South Africa's use of digital twins in local road networks has enabled predictive maintenance, cutting costs and extending infrastructure lifespan (Steyn and Broekman, 2022) and Nigeria's integration of DTT with renewable energy microgrids for electric vehicle (EV) charging showcases scalable solutions for energy-dependent transport systems (Kelvin Edem Bassey et al., 2024). Tailoring global best practices, such as lifecycle optimisation in Europe's bridge infrastructure (Franciosi et al., 2024), to SSA's socio-economic and political contexts is crucial. However, existing literature reveals significant contradictions and gaps while DTT's scalability is often emphasised (Zhou et al., 2022), its cost-prohibitive nature in SSA remains underexplored (Shahzad et al., 2022). Additionally, research frequently overlooks policy integration and socio-economic factors critical for SSA's success (Montero and Finger, 2021; Kouladoun, 2023). Practical strategies for SSA include mitigating barriers through regulatory frameworks (Broo and Schooling, 2023), developing localized DTT solutions to address connectivity challenges, and leveraging digital infrastructure to foster

inclusive economic growth (Kouladoun, 2023), positioning DTT as a transformative tool for the region's development.

Barriers to DTT Adoption

Despite its potential, the adoption of Digital Twin Technology (DTT) in Sub-Saharan Africa faces significant barriers, including technological challenges such as inadequate digital infrastructure and interoperability issues (Kelvin et al., 2024), financial constraints like high implementation costs and limited funding opportunities (Ariyachandra & Wedawatta, 2023), institutional hurdles stemming from fragmented governance and regulatory gaps (Bassey et al., 2024), and socio-cultural factors such as resistance to change and limited stakeholder awareness (Singh et al., 2022).

Lessons from Developed Economies

Developed economies offer valuable insights into overcoming DTT adoption barriers. For instance, public-private partnerships (PPPs) in Europe have facilitated infrastructure funding and innovation (Kosyakov et al., 2023). Examples include the Dartford Crossing in London, the M5 motorway in Midlands-United Kingdom among others. Not only that, Modular and scalable solutions in Asia demonstrate cost-effective approaches suitable for resource-constrained regions (PwC, 2022; Shahzad et al., 2022).

Research Gap

Existing studies lack a focus on DTT's application in SSA's socio-economic context. This study addresses this gap by integrating empirical analysis and actionable strategies. *(For further details, please see Appendix A and B).*

CONCEPTUAL FRAMEWORK DIAGRAM

The conceptual framework illustrates the interplay between Digital Twin Technology (DTT) and its role in enhancing infrastructure resilience and sustainability in transport projects, while addressing barriers to adoption within the context of socio-technical systems theory.

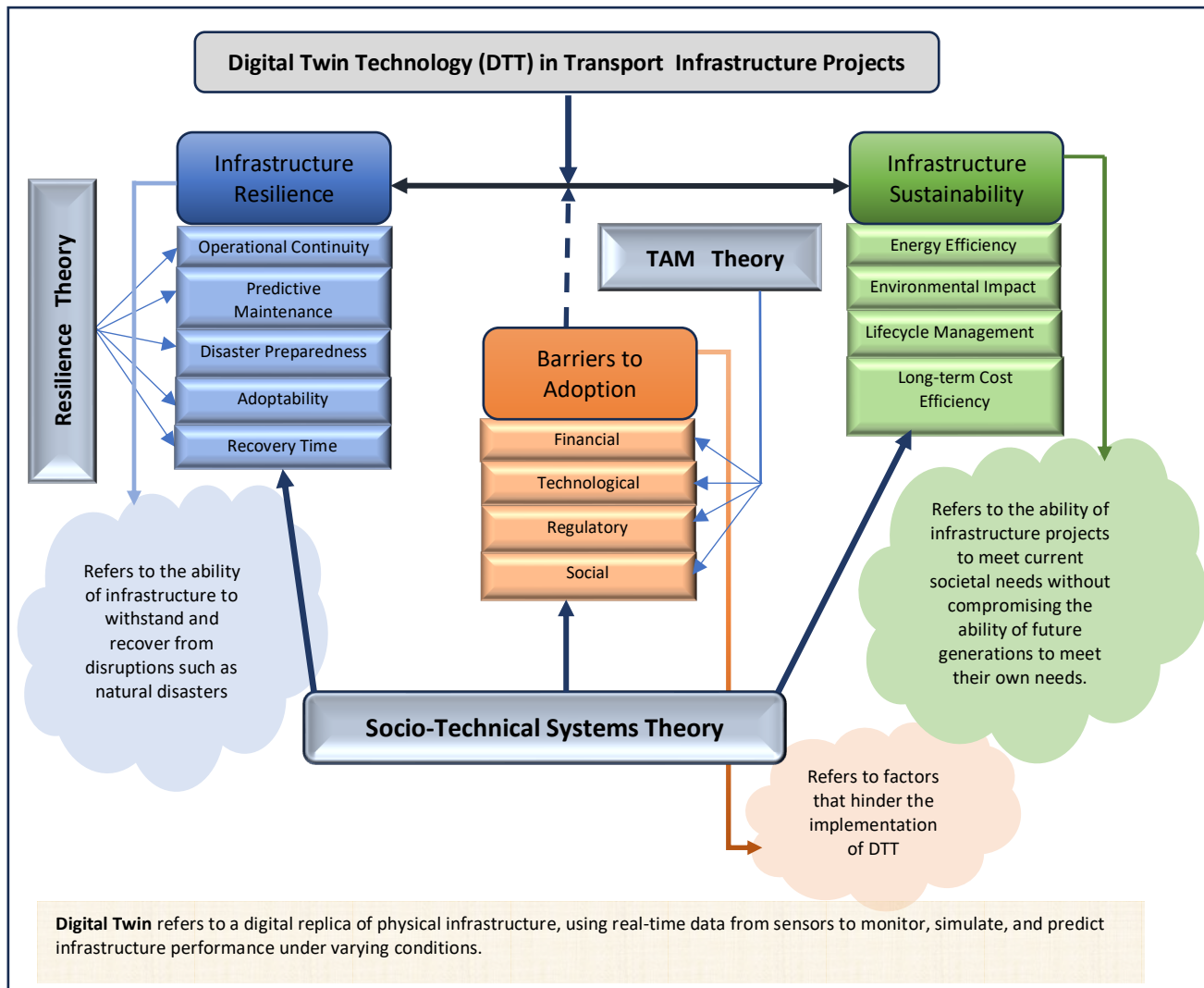


Figure 3 - Conceptual Framework Diagram

THEORETICAL FRAMEWORKS UNDERPINNING THE STUDY

The following theoretical foundations will guide the research, providing insights into the interaction between DTT, resilience, and sustainability.

1. Resilience Theory

Founded by C.S. Holling in 1973, it will guide the analysis of how DTT enhances infrastructure's ability to withstand disruptions, adapt to new conditions, and recover quickly from unforeseen events. The framework posits that DTT contributes to resilience through predictive maintenance, real-time monitoring, and disaster preparedness each of which reinforces the infrastructure's capacity to handle and bounce back from environmental or operational stresses.

2. Technology Acceptance Model (TAM)

Founded by Fred Davis in 1989, TAM will be instrumental in understanding how various stakeholders e.g., project managers, policymakers and engineers, perceive and accept DTT. This part of the framework will explore how perceived usefulness and ease of use influence the adoption of DTT, especially given the unique challenges in Sub-Saharan Africa such as financial constraints and limited technological infrastructure.

3. Socio-Technical Systems Theory

Established by Emery and Trist in 1960, this theory considers the interdependency between technology and social factors within complex systems. In this research, Socio-Technical Systems Theory will help examine how DTT interacts with organisational structures, stakeholder dynamics, and community needs, emphasising that successful DTT implementation requires alignment across technical and social components.

The literature review highlights the transformative potential of Digital Twin Technology in revolutionising the transport sector by addressing key challenges of resilience and sustainability.

CHAPTER 3: METHODOLOGY

This chapter outlines the methodological approach adopted for this study.

A positivist paradigm guides this cross-sectional quantitative study. Primary data was collected via structured surveys targeting professionals in SSA's transport sector. Non-parametric statistical analyses were conducted using SPSS to evaluate hypotheses.

Hypothesis

The following hypotheses are proposed to systematically explore the impact of DTT on transport infrastructure in Sub-Saharan Africa.

Table 3- Research Hypothesis organised in themes

Theme	Hypothesis
	H₀ - The adoption of DTT does not significantly contribute to the sustainability of transport infrastructure in Sub-Saharan Africa.
Resilience	H₁ - The adoption of Digital Twin Technology (DTT) significantly enhances the resilience of transport infrastructure in Sub-Saharan Africa through improved predictive maintenance and disaster preparedness.
Sustainability	H₂ - DTT adoption positively contributes to the sustainability of transport infrastructure in Sub-Saharan Africa by optimising resource use and reducing environmental impacts.
Barriers	H₃ - Technological, financial, and institutional barriers are significant impediments to the adoption of DTT in Sub-Saharan Africa's transport sector.
Policy and Regulation	H₄ - Effective policy frameworks and governance strategies significantly influence the successful integration of DTT into transport infrastructure systems in Sub-Saharan Africa.
Comparative Lessons	H₅ - Lessons from DTT implementation in developed economies can be adapted to overcome the challenges of DTT adoption in Sub-Saharan Africa.
Alignment	H₆ - DTT adoption contributes significantly to achieving SDG 9a by fostering sustainable and resilient infrastructure in Sub-Saharan Africa.

Research Design and Paradigm

This study adopts a positivist paradigm and employs a quantitative cross-sectional design to explore the role of DTT in enhancing resilience and sustainability in Sub-Saharan Africa's transport infrastructure. A quantitative approach was selected for its ability to systematically measure relationships between variables across a diverse sample.

Sampling Strategy

The table below details the strategy employed.

Table 4- Detail of sample strategy

Strata	Examples
Target Population	Transport engineers, policymakers, technology experts.
Geographic Focus	Kenya, Nigeria, South Africa, Ethiopia, Uganda, Rwanda.
Sampling Method	Purposive
Sample Size	50 respondents

Survey Instrument

A structured survey was developed and questions were validated for reliability using Cronbach's Alpha (0.86). ([See Appendix G for the questionnaire](#)).

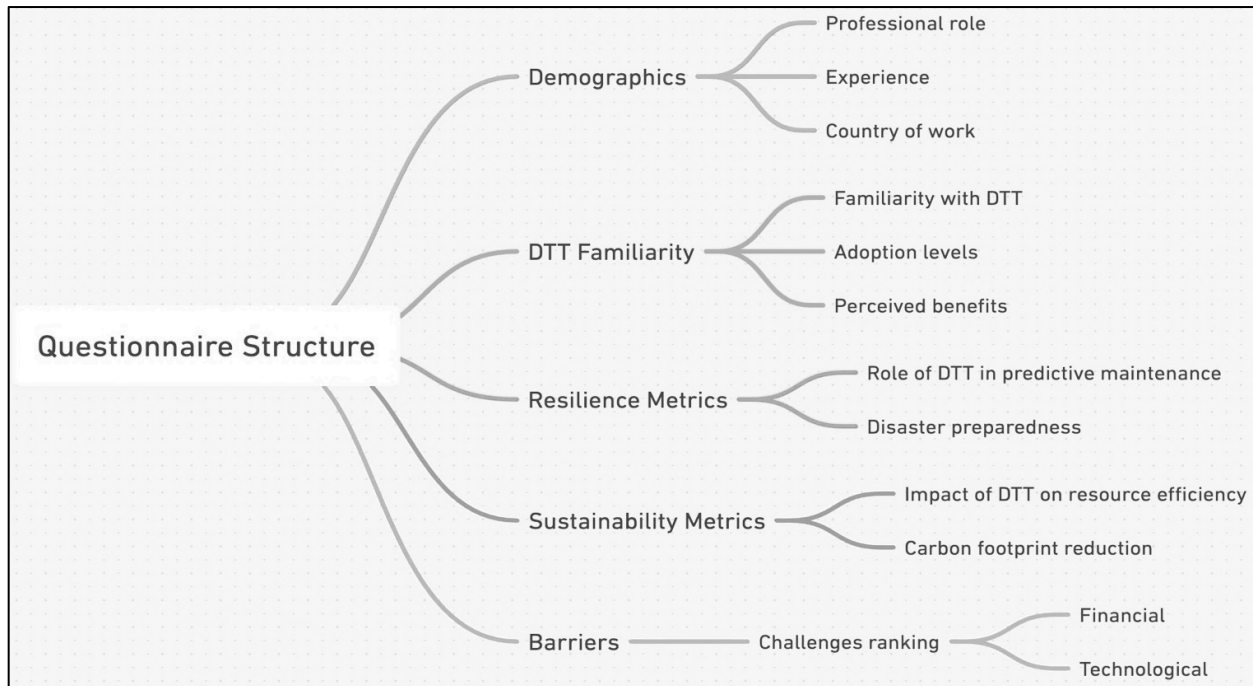


Figure 3 – Survey instrument structure

Data Collection

Primary data was assimilated due to time constraints. This was to enable me to demonstrate the data analysis skills expected of a doctoral scholar. Secondary data, including government reports and journal articles, provided contextual insights and benchmarks for analysis.

Ethical Considerations

- Informed Consent: Participants will be briefed on the study's objectives and their rights.
- Confidentiality: No person-identifiable data will be collected.
- Ethical Approval: Approval by the relevant authority will be sought.

Inclusion and Exclusion Criteria

To ensure the quality of responses, the following inclusion and exclusion criteria were applied.

Table 5 How inclusion and Exclusion criteria were applied

Criteria	Details
Inclusion	→ Professionals directly involved in transport infrastructure projects. → Individuals with knowledge or experience in DTT or related digital technologies. → Participants located in Sub-Saharan Africa or with direct involvement in projects within the region.
Exclusion	→ Respondents with no professional background in transport infrastructure or DTT. → Incomplete survey responses will be excluded from the analysis.

Data Analysis

- ⇒ Quantitative data were statistically analysed using various strategies.
- ⇒ Given that the data did not meet the assumptions of normality, non-parametric statistical methods were employed to analyse the dataset.

Table 6– Strategy for Data Analysis

Techniques	Method
Descriptive Statistics	Non-parametric measures, such as medians and interquartile ranges, were calculated to summarise adoption levels and barriers.
Inferential Statistics	◆ Kruskal-Wallis Test: Assessed variations in resilience/sustainability metrics based on DTT familiarity. ◆ Mann-Whitney U Test: Compared differences in perceptions on effectiveness of DTT. ◆ Spearman’s Rank Correlation: Explored relationships between adoption levels and outcomes.

CHAPTER 4: RESULTS

The results presented in this chapter address the study's questions and objectives.

Descriptive Statistics

The tables below presents the descriptive statistics for demographics.

Table 7- Descriptive Statistics for Demographics

Descriptive Statistics					
	N	Minimum	Maximum	Mean	Std. Deviation
Title held in the industry	50	1	5	2.96	1.384
Number of years working in the management of infrastructure project	50	1	4	3.02	1.000
Are you familiar with DTT	50	1	2	1.24	.431
Was DTT implemented in the project you worked in	50	1	3	1.84	.584
Valid N (listwise)	50				

Reliability Test

The table below presents the results of the reliability test of the survey data.

Table 8- Reliability Test of all variables

Reliability Statistics		
Cronbach's Alpha	Cronbach's Alpha Based on Standardised Items	N of Items
.162	.469	15

Normality Test

The table below presents the results of the normality test of the survey data.

Table 9- Normality Test of all variables

Tests of Normality						
	Kolmogorov-Smirnov ^a			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Title held in the industry	.136	50	.022	.896	50	<.001
Number of years working in the management of infrastructure project	.257	50	<.001	.823	50	<.001
Are you familiar with DTT	.471	50	<.001	.530	50	<.001
Was DTT implemented in the project you worked in	.348	50	<.001	.749	50	<.001
DTT helps with Early identification of structural vulnerabilities	.477	50	<.001	.512	50	<.001
DTT helps with Disaster preparedness	.477	50	<.001	.512	50	<.001
DTT helps with Real-time monitoring and predictive maintenance of infrastructures	.437	50	<.001	.605	50	<.001
DTT helps with Risk assessment and management of infrastructures	.405	50	<.001	.657	50	<.001
Belief that DTT can significantly reduce vulnerabilities in infrastructures	.499	50	<.001	.467	50	<.001
Suggestive main barriers to DTT adoption in Sub-Saharan Africa	.157	50	.004	.883	50	<.001
Government policies and regulations are supportive of integrating advanced technologies like DTT	.349	50	<.001	.710	50	<.001
DTT helps with Reducing carbon footprint of construction projects	.528	50	<.001	.304	50	<.001
DTT helps with improving the efficiency of resource use	.535	50	<.001	.303	50	<.001
DTT helps in reducing long-term costs of infrastructure maintenance	.535	50	<.001	.303	50	<.001
This study supports the achievement of UN SDG 9a	.497	50	<.001	.400	50	<.001
a. Lilliefors Significance Correction						

Results addressing Research Questions, Objectives and Hypotheses

a) Research Question 1 & Objective 1 - Enhancing Resilience through DTT

- ⇒ How does Digital Twin Technology (DTT) enhance resilience in transport systems?
- ⇒ To assess how Digital Twin Technology (DTT) can enhance the resilience of transport infrastructure through real-time monitoring, predictive maintenance, and disaster preparedness.
- ⇒ **H₁**: DTT enhances resilience through predictive maintenance and disaster preparedness.

- ◆ This objective examines how DTT enables transport infrastructure to withstand disruptions and recover efficiently.

Table 10 -Nonparametric Correlations of Resilience metrics

Correlations					
			DTT helps with Real-time monitoring and predictive maintenance of infrastructures	DTT helps with Early identification of structural vulnerabilities	DTT helps with Disaster preparedness
Spearman's rho	DTT helps with Real-time monitoring and predictive maintenance of infrastructures	Correlation Coefficient	1.000	.733**	.733**
		Sig. (2-tailed)	.	<.001	<.001
		N	50	50	50
	DTT helps with Early identification of structural vulnerabilities	Correlation Coefficient	.733**	1.000	1.000**
		Sig. (2-tailed)	<.001	.	.
		N	50	50	50
	DTT helps with Disaster preparedness	Correlation Coefficient	.733**	1.000**	1.000
		Sig. (2-tailed)	<.001	.	.
		N	50	50	50
** . Correlation is significant at the 0.01 level (2-tailed).					

b) Research Question 2 & Objective 2 - Promoting Sustainability

- ⇒ What is the potential of DTT to promote sustainability?
- ⇒ To evaluate DTT's potential in achieving sustainability by optimising resource use, reducing environmental impacts, and promoting lifecycle efficiency.
- ⇒ **H₂**: DTT contributes to sustainability by optimising resources and reducing environmental impact.

◆ This objective focuses on the environmental and resource-based benefits of DTT.

Table 12 -Nonparametric Correlations of Sustainability metrics

Correlations					
			DTT helps with Reducing carbon footprint of construction projects	DTT helps with improving the efficiency of resource use	DTT helps with Risk assessment and management of infrastructures
Spearman's rho	DTT helps with Reducing carbon footprint of construction projects	Correlation Coefficient	1.000	.733**	.125
		Sig. (2-tailed)	.	<.001	.386
		N	50	50	50
	DTT helps with improving the efficiency of resource use	Correlation Coefficient	.733**	1.000	.132
		Sig. (2-tailed)	<.001	.	.360
		N	50	50	50
	DTT helps with Risk assessment and management of infrastructures	Correlation Coefficient	.125	.132	1.000
		Sig. (2-tailed)	.386	.360	.
		N	50	50	50
**. Correlation is significant at the 0.01 level (2-tailed).					

c) Research Question 3 & Objective 3 - Identifying Barriers to DTT Adoption

- ⇒ What barriers exist to adopting DTT in Sub-Saharan Africa?
- ⇒ To identify and analyse key barriers, including technological, financial, and institutional challenges, to the adoption of DTT in transport infrastructure projects in Sub-Saharan Africa.
- ⇒ **H₃**: Technological, financial, and institutional barriers significantly impede DTT adoption.

◆ This objective explores why DTT adoption is limited in the region.

Table 13 -Descriptive Statistics of Adaptation Barriers in Sub-Saharan Africa

Suggestive main barriers to DTT adoption in Sub-Saharan Africa		
	Frequency	Percent
Lack of financial resources	9	18.0
Lack of technological expertise	10	20.0
Poor infrastructure for data connectivity	10	20.0
Resistance to change within organizations	9	18.0
Lack of awareness and knowledge about DTT	12	24.0
Total	50	100.0

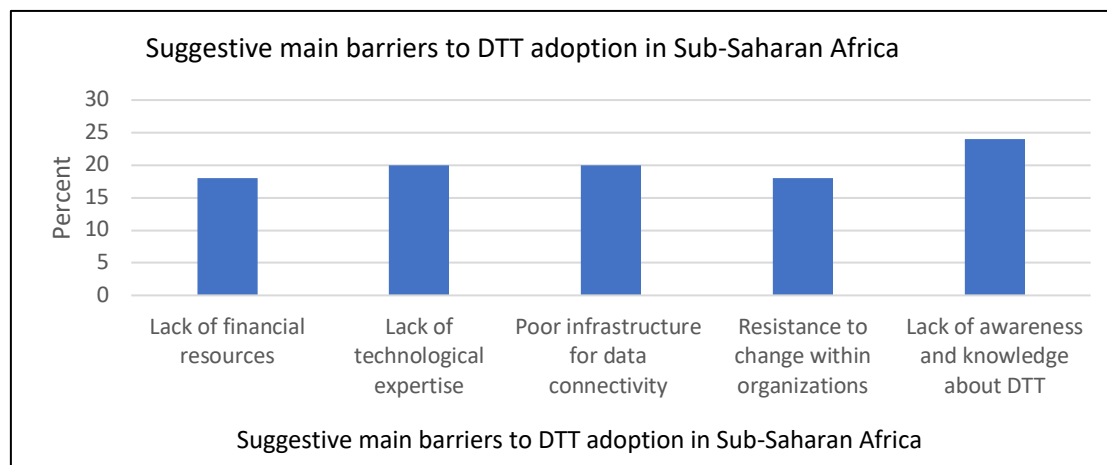


Figure 4 – Bar Chart of Adaptation Barriers

d) Research Question 4 & Objective 4- Policy Frameworks and Governance Strategies

⇒ What policy frameworks support the integration of DTT?

⇒ To provide actionable policy recommendations for enabling the integration of DTT into transport systems in Sub-Saharan Africa, addressing governance, regulatory, and stakeholder collaboration needs.

⇒ **H₄**: Effective policy frameworks significantly influence DTT integration.

◆ This objective investigates how governance and policy can facilitate DTT adoption.

Table 14 -Descriptive Statistics of perceptions on the effectiveness of Regulations and Policies

Government policies and regulations are supportive of integrating advanced technologies like DTT		
	Frequency	Percent
Disagree	1	2.0
Neutral	3	6.0
Agree	17	34.0
Strongly agree	29	58.0
Total	50	100.0

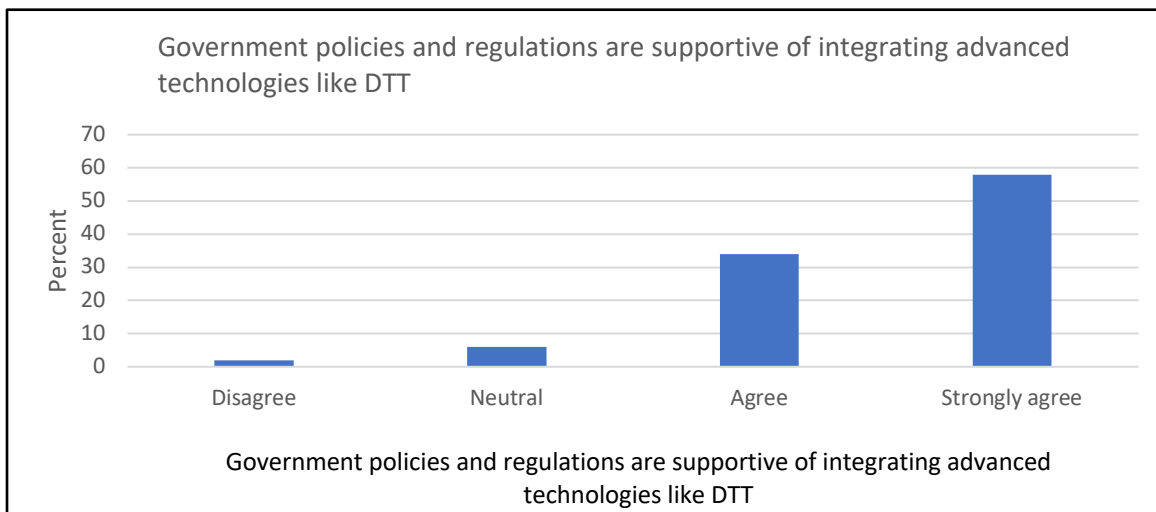


Figure 5 – Bar Chart of Perceptions on Regulations and Policies

e) Research Question 5 & Objective 5 - Lessons from Developed Economies

- ⇒ What lessons from developed economies can be adapted?
- ⇒ To draw and adapt insights from successful DTT implementations in other regions for application within the socio-economic and infrastructural context of Sub-Saharan Africa.
- ⇒ **H₅**: Lessons from developed economies can address adoption challenges in SSA.

- ◆ This objective focuses on adapting best practices from developed economies to the Sub-Saharan African context.

Digital Twin Technology has been extensively adopted in developed countries, showcasing its transformative potential. Key examples highlight DTT's ability to enhance operational efficiency, predictive maintenance, and disaster resilience. *(See Appendix C for a Comprehensive Summary)*

The comparative analysis of DTT in developed economies highlights its transformative potential for resilience and sustainability. Scalability insights emphasise the importance of modular, cost-effective solutions that align with resource-constrained environments. Lastly, localised implementation strategies for SSA focusing on data integration, affordability, capacity building, and governance can bridge existing gaps and ensure sustainable infrastructure development tailored to the region's unique challenges.

f) Research Question 6 & Objective 6- Alignment with Global Sustainability Goals

- ⇒ To align DTT applications with global sustainability goals, particularly Sustainable Development Goal (SDG) 9a.
- ⇒ This objective evaluates how DTT contributes to global development objectives, such as Sustainable Infrastructure Development (SDG 9a) by Measuring how DTT supports building resilient and sustainable infrastructure.
- ⇒ **H₆**: DTT adoption contributes significantly to achieving SDG 9a by fostering sustainable and resilient infrastructure in Sub-Saharan Africa.

- ◆ This objective evaluates how DTT contributes to global development objectives, such as Sustainable Infrastructure Development (SDG 9a) by Measuring how DTT supports building resilient and sustainable infrastructure.

Table 15 -Alignment of DTT applications with global sustainability goals

This study supports the achievement of UN SDG 9a		
	Frequency	Percent
Not helpful	2	4.0
Somewhat helpful	1	2.0
Moderately helpful	4	8.0
Very helpful	43	86.0
Total	50	100.0

Digital Twin Technology (DTT) plays a pivotal role in supporting Sustainable Development Goal 9a (SDG 9a), which emphasises the development of resilient and sustainable infrastructure to foster inclusive and sustainable industrialisation.

CHAPTER 5: DISCUSSION

This chapter interprets the findings of this study on DTT and its role in enhancing resilience and sustainability.

a) Research Question 1 & Objective 1- Enhancing Resilience through DTT

- ⇒ How does Digital Twin Technology (DTT) enhance resilience in transport systems?
- ⇒ To assess how Digital Twin Technology (DTT) can enhance the resilience of transport infrastructure through real-time monitoring, predictive maintenance, and disaster preparedness.
- ⇒ **H₁**: DTT enhances resilience through predictive maintenance and disaster preparedness.

Findings and Interpretation

The study findings demonstrate a strong statistical association between the key metrics of DTT adoption and the enhancement of resilience in transport systems. Spearman's correlation coefficients indicate significant relationships between:

- ⇒ Real-time monitoring and predictive maintenance and early identification of structural vulnerabilities (0.733, $p < 0.001$),
- ⇒ Real-time monitoring and disaster preparedness (0.733, $p < 0.001$),
- ⇒ Early identification of structural vulnerabilities and disaster preparedness, which exhibit a perfect correlation (1.000).

These findings not only validate the hypothesis but also align with insights from the literature, establishing a scholarly foundation for the critical role of DTT in resilience-building.

Theoretical and Practical Implications of Findings

The findings underscore the interplay between predictive maintenance, real-time monitoring, and disaster preparedness as core enablers of resilience. This is consistent with the *Resilience Theory* (Holling, 1973), which frames resilience as the capacity of systems to absorb disruptions, adapt to challenges, and recover effectively. DTT operationalises these principles by enabling:

- ⇒ Real-time data analytics that provide actionable insights for pre-emptive action.
- ⇒ Predictive maintenance capabilities that mitigate risks before failures occur.
- ⇒ Simulated disaster scenarios that support proactive disaster preparedness.

For instance, Franciosi et al. (2024) highlight that in bridge infrastructure, real-time monitoring facilitated by DTT allows for early detection of structural vulnerabilities, reducing downtime and minimising the risk of catastrophic failures. This is mirrored in the perfect correlation found in this study between vulnerability identification and disaster preparedness, underscoring DTT's potential to avert disaster through predictive modelling. In Sub-Saharan Africa (SSA), the unique vulnerabilities of transport systems such as aging infrastructure, climate variability, and limited resources intensify the need for such proactive approaches. Nairobi's Bus Rapid Transit (BRT) system, for example, has demonstrated how localised DTT applications can optimise traffic management and mitigate congestion (Obonyo & Ouma, 2022). The synergy between real-time data and predictive maintenance in this case aligns with the correlation between these metrics found in the current study.

Bridging Knowledge Gaps

While the present literature predominantly emphasises the efficacy of DTT in developed economies, this study contributes insights specific to SSA's socio-economic and infrastructural context. As noted by Zhou et al. (2022), real-time monitoring and predictive analytics are cornerstone features of DTT, yet their implementation in resource-constrained environments has

been limited due to financial and technical barriers. The current study's findings advance this discourse by providing empirical evidence of how these features directly support resilience in SSA. Moreover, the findings extend the conceptual understanding of DTT's role in disaster preparedness. Ariyachandra and Wedawatta (2023) found that urban transport systems equipped with DTT could simulate flood scenarios and mitigate potential impacts. This aligns with the strong correlation found in this study between disaster preparedness and early identification of vulnerabilities, affirming DTT as an essential tool for resilience in disaster-prone regions of SSA.

Policy and Practice Implications

- **Strategic Investments in DTT**

The data highlight the urgent need for strategic investments in DTT infrastructure to ensure that transport systems in SSA are equipped with robust real-time monitoring and predictive maintenance capabilities. Public-private partnerships (PPPs), as successfully employed in European contexts (Kosyakov et al., 2023), could offer a model for financing such investments in SSA.

- **Localised Implementation Strategies**

Drawing from Shahzad et al. (2022) and PwC (2022), scalable DTT solutions tailored to SSA's unique needs should be prioritised. Incremental deployment, focusing on high-impact urban transit systems, could optimise resource utilisation while addressing infrastructural constraints.

- **Capacity Building and Stakeholder Engagement**

To overcome the barriers noted by Singh et al. (2022), capacity-building initiatives targeting engineers, policymakers, and local communities are essential. Effective training programs will ensure that DTT systems are not only adopted but also sustained.

- **Policy Frameworks for Resilience**

The perfect correlation between vulnerability identification and disaster preparedness calls for regulatory frameworks that mandate the integration of predictive analytics into transport system governance. As noted by Broo and Schooling (2023), clear policies are instrumental in aligning DTT initiatives with national resilience goals.

These findings of reinforce the transformative potential of DTT in enhancing transport system resilience and sustainability.

b) Research Question 2 & Objective 2- Promoting Sustainability

- ⇒ What is the potential of DTT to promote sustainability?
- ⇒ To evaluate DTT's potential in achieving sustainability by optimising resource use, reducing environmental impacts, and promoting lifecycle efficiency.
- ⇒ **H₂**: DTT contributes to sustainability by optimizing resources and reducing environmental impact.

Findings and Interpretation

The correlation analysis reveals significant relationships between key sustainability metrics associated with DTT adoption.

a) Reducing Carbon Footprint and Improving Resource Efficiency

The correlation coefficient of 0.733 ($p < 0.001$) demonstrates a strong positive relationship between *DTT's role in reducing the carbon footprint of construction projects* and *improving the efficiency of resource use*. This finding underscores the symbiotic nature of these sustainability goals, where resource efficiency directly contributes to lower environmental impacts.

▪ Reducing Carbon Footprint and Risk Assessment

A weak correlation of 0.125 ($p = 0.386$) indicates that while risk assessment and management are vital aspects of infrastructure sustainability, their direct impact on reducing carbon emissions is limited.

▪ Improving Resource Efficiency and Risk Assessment

A similarly weak correlation of 0.132 ($p = 0.360$) suggests that while resource efficiency and risk management are essential for long-term sustainability, their relationship is not as pronounced in this dataset.

The findings align with existing scholarship that highlights DTT's role in driving sustainability through resource optimisation and lifecycle management. For example, Jiao et al. (2023) emphasise that DTT enables energy-efficient operations by providing actionable insights into resource use, which directly contributes to carbon footprint reduction. This is mirrored in the strong correlation between resource efficiency and carbon footprint reduction identified in this study.

Resource Optimisation and Carbon Reduction

In developed economies, lifecycle models using DTT have demonstrated reductions in material waste and environmental impact. Franciosi et al. (2024) report significant gains in bridge maintenance efficiency in Europe, where DTT reduced unnecessary repairs and optimised resource allocation. These insights are directly transferable to Sub-Saharan Africa (SSA), where resource constraints heighten the need for sustainable practices.

Addressing Gaps in Risk Assessment

The weak correlations between risk assessment and other sustainability metrics indicate that the integration of risk management into broader sustainability goals remains underdeveloped in the current dataset. This finding echoes Zhou et al. (2022), who noted that DTT's potential for holistic risk assessment in transport systems is often underutilised in resource-constrained settings. Further efforts to align risk management with sustainability objectives are necessary for maximising DTT's impact.

Promoting Lifecycle Efficiency

The emphasis on lifecycle efficiency in the literature aligns with the potential observed in this study. Steyn and Broekman (2022) demonstrated how predictive maintenance, enabled by DTT,

extends infrastructure lifespans while minimising costs and environmental impacts. For SSA, where aging transport networks contribute to inefficiency, lifecycle-focused approaches could be transformative.

In the context of SSA, the findings provide actionable insights into leveraging DTT for sustainability.

1. Carbon Reduction in Climate-Sensitive Regions

The correlation between carbon reduction and resource efficiency highlights an opportunity for SSA to address its disproportionate vulnerability to climate change. DTT can enable transport systems to transition to low-carbon models, aligning with global climate goals.

2. Localised Resource Optimization

The strong relationship between resource efficiency and carbon reduction supports the adoption of modular DTT solutions, as noted by Shahzad et al. (2022). By focusing on high-impact areas, such as urban transit systems, SSA can achieve substantial sustainability gains with limited resources.

3. Bridging the Gap in Risk Assessment:

While risk management appears underexplored in this study, its integration into sustainability frameworks is critical. Lessons from disaster-prone regions like Sri Lanka (Ariyachandra & Wedawatta, 2023) demonstrate that DTT can bridge this gap by simulating and mitigating risks that threaten both infrastructure resilience and sustainability.

Policy and Practice Implications

Governments in Sub-Saharan Africa (SSA) must prioritise the adoption of green policy frameworks that incentivize low-carbon initiatives, particularly those supported by Digital Twin Technology (DTT), such as renewable energy integration and lifecycle management practices. Public-private partnerships (PPPs) offer a viable model to address the financial and technical

requirements of deploying DTT in transport systems, as demonstrated by successful cases in Europe (Kosyakov et al., 2023). Stakeholders should also make targeted investments in resource efficiency by implementing DTT in areas with immediate sustainability impacts, such as reducing energy consumption in urban transit networks. Moreover, training and capacity-building initiatives are critical; policymakers, engineers, and transport operators must be equipped with the skills to leverage DTT for sustainable infrastructure development, as emphasized by Kouladoun (2023).

The findings strongly support Hypothesis H2, demonstrating that DTT adoption enhances sustainability in transport systems by optimising resource use and reducing environmental impacts. This provides a compelling case for integrating DTT into SSA's transport sector as a means of achieving global sustainability goals and objectives such as UNSDG 9a.

c) Research Question 3 & Objective 3- Identifying Barriers to DTT Adoption

- ⇒ What barriers exist to adopting DTT in Sub-Saharan Africa?
- ⇒ To identify and analyse key barriers, including technological, financial, and institutional challenges, to the adoption of DTT in transport infrastructure projects in Sub-Saharan Africa.
- ⇒ **H₃**: Technological, financial, and institutional barriers significantly impede DTT adoption.

Findings and Interpretation

The data reveal several significant barriers to the adoption of Digital Twin Technology (DTT) in Sub-Saharan Africa (SSA), distributed as follows:

- a) **Lack of awareness and knowledge about DTT**: 24% of respondents identified this as the primary barrier, highlighting the critical need for education and capacity-building initiatives.

- b) **Lack of technological expertise:** Reported by 20% of respondents, this reflects the skills gap in SSA for implementing and managing advanced digital systems like DTT.
- c) **Poor infrastructure for data connectivity:** Cited by another 20%, this emphasises the infrastructural limitations in SSA, such as unreliable internet and inadequate digital infrastructure.
- d) **Lack of financial resources:** Identified by 18%, financial constraints remain a major challenge, given the high costs of implementing and scaling DTT systems.
- e) **Resistance to change within organisations:** Also at 18.0%, this suggests cultural and institutional inertia that hampers the adoption of innovative technologies.

These findings align with the existing literature, which underscores similar barriers in resource-constrained contexts. For instance, Singh et al. (2022) emphasise the interplay between technological, financial, and organisational challenges in hindering DTT adoption. The distribution of responses in this study mirrors global trends while also contextualising the unique challenges in SSA.

Lack of Awareness and Knowledge

The lack of awareness and knowledge about DTT, cited by the highest proportion of respondents (24.0%), is consistent with findings by Broo and Schooling (2023), who stress that insufficient stakeholder education slows innovation adoption. In SSA, this barrier is compounded by limited access to training resources and professional development programs, making it imperative to prioritise awareness-building initiatives.

Technological Expertise and Infrastructure Deficits

The lack of technological expertise (20%) and poor infrastructure (20%) further reflect systemic challenges in SSA. As highlighted by Zhou et al. (2022), inadequate digital infrastructure, such as low internet penetration and limited IoT sensor deployment, severely constrains the scalability of DTT. This barrier is particularly critical for transport systems, where real-time data collection and processing are essential.

Financial Barriers

Financial constraints, identified by 18% of respondents, echo the findings of Kosyakov et al. (2023), who argue that the high upfront costs of DTT systems deter adoption in low-income regions. Public-private partnerships (PPPs) have been proposed as a viable model to address this gap, facilitating cost-sharing between governments and private entities.

Organisational Resistance

Resistance to change within organisations (18%) highlights the cultural and institutional inertia that often accompanies technological innovation. Singh et al. (2022) suggest that this barrier can be mitigated through leadership-driven change management strategies and stakeholder engagement to foster a culture of innovation.

Implications for Policy and Practice

To overcome the barriers to Digital Twin Technology (DTT) adoption in Sub-Saharan Africa, a multifaceted strategy is essential. Capacity-building initiatives should target engineers, policymakers, and transport operators, focusing on the practical benefits of DTT and its alignment with global sustainability goals. Simultaneously, investment in digital infrastructure, such as reliable internet connectivity and IoT device deployment, is crucial. Modular DTT applications can serve as scalable solutions to address infrastructure deficits incrementally. Financial constraints can be mitigated through public-private partnerships, which leverage subsidies, tax breaks, and grants to incentivise investments. Organisational resistance, another significant barrier, requires structured change management approaches, including stakeholder engagement, demonstrative pilot projects, and clear communication of DTT's value. Lastly, awareness campaigns tailored to the SSA context can bridge knowledge gaps by highlighting successful DTT implementations and their transformative impact. Collaborative efforts between academic institutions and industry stakeholders will be vital to amplifying these initiatives.

The barriers identified in this study are consistent with global challenges but take on unique dimensions in the SSA context due to the region's resource constraints and infrastructural deficits. By tackling these issues, SSA can unlock the transformative potential of DTT in creating resilient and sustainable transport systems.

g) Research Question 4 & Objective 4- Policy Frameworks and Governance Strategies

- ⇒ What policy frameworks support the integration of DTT?
- ⇒ To provide actionable policy recommendations for enabling the integration of DTT into transport systems in Sub-Saharan Africa, addressing governance, regulatory, and stakeholder collaboration needs.
- ⇒ **H₄**: Effective policy frameworks significantly influence DTT integration.

Findings and Interpretation

The data reveal that most respondents perceive government policies and regulations as supportive of integrating advanced technologies like DTT. 58% strongly agree that policies are conducive to DTT integration, 34% agree, 6% are neutral, and only 2% disagree. These results indicate a predominantly favourable policy environment, suggesting that foundational regulatory frameworks for DTT adoption are in place. However, the minority perceptions of neutrality or disagreement highlight areas for further refinement and alignment of policies with on-ground realities.

The findings align with global insights emphasising the critical role of policy frameworks in facilitating advanced technology integration. Broo and Schooling (2023) stress the importance of clear, supportive regulations for fostering innovation and collaboration.

The Role of Policy Frameworks

Effective policies must create an enabling environment for DTT adoption, as evidenced in developed regions. For instance, Europe's emphasis on data governance and interoperability

standards (Kosyakov et al., 2023) has accelerated DTT deployment. In SSA, replicating such frameworks can help overcome technical and organisational barriers.

Governance and Stakeholder Collaboration

The findings also underscore the need for strong governance structures that promote multi-stakeholder collaboration. Public-private partnerships (PPPs), as highlighted by Montero and Finger (2021), can address funding and expertise gaps while ensuring the alignment of DTT initiatives with national development goals.

Addressing Perception Gaps

The 8% of respondents who were neutral or disagreed with the statement highlight the disconnect between policy intentions and their perceived effectiveness. Singh et al. (2022) attribute such gaps to inconsistent enforcement, lack of stakeholder involvement, and inadequate communication about policy benefits.

Policy and Practice Implications

Establishing robust data governance frameworks is essential for ensuring interoperability, security, and privacy, which are critical to building stakeholder trust and accelerating the adoption of Digital Twin Technology (DTT). To further incentivise innovation, governments should implement regulations that offer tax breaks, subsidies, and grants tailored to the unique challenges of different transport sectors. Public-private partnerships (PPPs) can serve as a vital mechanism for securing funding, technical expertise, and strategic implementation, with successful European models, such as the UK's Dartford Crossing project, providing valuable blueprints for Sub-Saharan Africa (SSA). Capacity-building programs for policymakers and regulatory authorities are equally crucial, enabling governance structures to remain responsive and adaptive to technological advancements. Additionally, early stakeholder engagement, involving engineers, transport operators, and community leaders, is necessary to bridge perception gaps, ensure inclusivity, and foster broad acceptance of DTT policies and initiatives.

The findings indicate that a favourable policy environment exists for DTT integration in SSA, with significant opportunities to enhance its effectiveness. By strengthening governance frameworks, promoting stakeholder collaboration, and addressing perception gaps, policymakers can ensure that DTT initiatives are well-aligned with regional development goals.

d) Research Question 5 & Objective 5- Lessons from Developed Economies

- ⇒ What lessons from developed economies can be adapted?
- ⇒ To draw and adapt insights from successful DTT implementations in other regions for application within the socio-economic and infrastructural context of Sub-Saharan Africa.
- ⇒ **H₅**: Lessons from developed economies can address adoption challenges in SSA.

Comparative Case Studies

a) Europe - Bridge Maintenance

In Europe, DTT has been employed to optimise lifecycle management and structural health monitoring for critical infrastructure such as bridges. Studies, such as those by Franciosi et al. (2024), have demonstrated significant cost reductions and extended asset lifespans through sensor-based monitoring. For SSA, where aging infrastructure is a persistent issue, adopting sensor-driven DTT solutions could enable efficient resource allocation and proactive maintenance, mitigating the risk of catastrophic failures.

b) United Kingdom - Urban Transit

London's Underground system leverages DTT for predictive maintenance, which has been instrumental in reducing delays and enhancing operational efficiency (Bado et al., 2022; Cheng et al., 2023). In SSA's rapidly urbanising cities, real-time monitoring and predictive analytics could similarly optimise urban transit systems, alleviating congestion and improving service reliability.

c) Asia - Modular DTT

Asian countries have adopted modular DTT systems to improve traffic flow, reduce emissions, and optimise resource use (PwC, 2022; Shahzad et al., 2022). These scalable solutions are particularly relevant for SSA, where modular approaches could prioritise high-impact urban transit systems, allowing for gradual expansion as funding becomes available. *(For further details, please see Appendix D).*

Scalability Insights

a) Public-Private Partnerships (PPPs)

In Europe, PPPs, such as the Dartford Crossing project (Kosyakov et al. 2023), have been pivotal in financing DTT implementations, ensuring cost-effectiveness and operational gains. For SSA, fostering PPPs could address financial barriers by pooling resources from government, private sector, and international development agencies to fund large-scale DTT projects.

b) Open-Source Platforms

The Netherlands' use of open-source platforms to lower costs and ensure interoperability (Montero and Finger, 2021; Broo and Schooling, 2023) offers a valuable model for SSA. Adopting similar platforms can reduce costs while addressing compatibility challenges across diverse transport infrastructure projects.

c) Cloud and IoT Solutions

Australia's integration of cloud-based DTT with IoT for real-time data analysis (Gurdur Broo et al., 2023) provides scalability and flexibility. SSA could combine cloud and IoT solutions to overcome infrastructure deficits and deliver actionable insights for decision-makers, particularly in remote and resource-constrained regions.

Transferable Lessons

a) Localised Data Integration

Developed economies rely on robust data systems, which often do not account for SSA's bandwidth and connectivity challenges (Zhou et al., 2022; Obonyo and Ouma, 2022). Hybrid data models integrating offline and online capabilities can address these gaps, ensuring reliable data flow even in regions with intermittent connectivity.

b) Community Engagement

Public acceptance has been a critical driver of DTT success in Europe's transit systems (Singh et al., 2022; Obonyo and Ouma, 2022). In SSA, involving local communities in DTT projects can build trust and ensure that the technology addresses their specific needs, particularly in rural and underserved areas.

c) Incremental Deployment

Asian models emphasise starting with high-impact areas and gradually expanding DTT systems (PwC, 2022). For SSA, focusing initial efforts on urban transit systems could demonstrate tangible benefits, fostering broader acceptance and enabling incremental scaling as resources permit.

d) Capacity Building

Training programs in developed economies have enhanced the expertise of engineers, policymakers, and stakeholders (Montero and Finger, 2021; Kouladoun, 2023). Investing in similar capacity-building initiatives in SSA is critical to developing local expertise for managing and maintaining DTT systems.

e) Policy Frameworks

Clear and supportive regulations in developed economies have facilitated collaboration and innovation (Broo and Schooling, 2023; Montero and Finger, 2021). SSA must create policies

fostering government, private sector, and academic collaboration, ensuring a cohesive approach to DTT adoption.

Implications for Sub-Saharan Africa

To effectively adopt Digital Twin Technology in Sub-Saharan Africa, leveraging proven models from developed economies is critical. Lessons from successful public-private partnerships, open-source platforms, and modular DTT implementations can provide practical solutions to the region's unique challenges. Prioritising community-centric approaches by engaging local stakeholders early will build trust and ensure the technology meets the specific needs of both urban and rural communities. Scalability should also be a focus, starting with high-impact sectors like urban transit and gradually expanding as resources and infrastructure improve. Additionally, investing in human capital through targeted training programs for policymakers and engineers will bridge the skills gap, ensuring the sustainability of DTT initiatives. Finally, strengthening governance by developing regulatory frameworks that incentivise innovation, resolve interoperability challenges, and align DTT initiatives with broader developmental objectives will create a supportive environment for successful implementation.

The insights from developed economies underscore the transformative potential of DTT for SSA's transport infrastructure.

e) Research Question 6 & Objective 6- Alignment with Global Sustainability Goals

- ⇒ To align DTT applications with global sustainability goals, particularly Sustainable Development Goal (SDG) 9a.
- ⇒ This objective evaluates how DTT contributes to global development objectives, such as Sustainable Infrastructure Development (SDG 9a) by Measuring how DTT supports building resilient and sustainable infrastructure.

⇒ **H6:** DTT adoption contributes significantly to achieving SDG 9a by fostering sustainable and resilient infrastructure in Sub-Saharan Africa.

Findings and Interpretation

The results demonstrate overwhelming support for DTT's alignment with the achievement of SDG 9a with 86% of respondents rating DTT as "very helpful" in supporting SDG 9a and additional 8% as "moderately helpful", while only 6% rated it as "somewhat helpful" or "not helpful." These findings underscore the consensus among respondents that DTT significantly contributes to the development of resilient and sustainable infrastructure, a core tenet of SDG 9a. This finding resonates strongly with global research, highlighting DTT's transformative potential for sustainability and resilience in infrastructure systems. According to Franciosi et al. (2024), DTT optimises resource use, reduces waste, and extends the lifecycle of transport assets, directly supporting the goals of SDG 9a. Similarly, Zhou et al. (2022) emphasise that predictive maintenance and real-time monitoring facilitated by DTT reduce infrastructure vulnerabilities, ensuring continuity and reliability.

Contributions to Resilience

DTT enhances infrastructure resilience by enabling real-time monitoring, predictive analytics, and disaster preparedness. For example, in developed regions, DTT applications in urban transit systems have reduced downtime and minimised the impact of disruptions (Cheng et al., 2023). These capabilities are vital for SSA, where infrastructure is often exposed to climate-related risks and resource constraints.

Contributions to Sustainability

The lifecycle management features of DTT allow for more efficient use of resources and a significant reduction in carbon footprints, as evidenced in Europe's transport systems (Franciosi et al., 2024). In SSA, adopting DTT can directly support sustainability goals by improving energy

efficiency and integrating renewable energy systems into transport networks, as seen in Netherland's elective vehicle renewable energy charging systems.

Policy and Practice Implications

The strong alignment of Digital Twin Technology (DTT) with Sustainable Development Goal 9a (SDG 9a) underscores its critical role in sustainable development. Policymakers in Sub-Saharan Africa (SSA) should prioritise DTT in national and regional infrastructure strategies to maximise its contributions to resilience and sustainability. Collaboration with international agencies and developed economies can further support this effort by providing access to technical expertise and funding, enabling SSA to leverage successful models of DTT adoption. Integrating renewable energy systems with DTT, as exemplified by initiatives in Netherlands, can enhance the sustainability of transport projects by reducing reliance on fossil fuels and promoting cleaner energy solutions. To ensure effective implementation, governments and stakeholders must establish measurable indicators to evaluate DTT's impact on SDG 9a, fostering accountability and enabling data-driven strategies for continuous improvement. The findings demonstrate that DTT is a powerful tool for advancing SDG 9a by fostering resilient and sustainable infrastructure development.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

This study demonstrated the transformative potential of Digital Twin Technology (DTT) in enhancing the resilience and sustainability of transport infrastructure in Sub-Saharan Africa (SSA).

Key Findings

Table 16 -Summary of Key Findings

Theme	Explanation
Resilience	DTT enhances resilience through real-time monitoring, predictive maintenance, and disaster preparedness, reducing structural vulnerabilities and enabling faster recovery.
Sustainability	By optimising resources and reducing carbon footprints, DTT promotes lifecycle efficiency, addressing SSA's critical environmental challenges.
Barriers	Key impediments include limited awareness (24%), inadequate digital infrastructure (20%), financial constraints (18%), and organisational resistance (18%).
Policy and Governance	While policy support exists, implementation gaps, enforcement challenges, and limited stakeholder engagement remain critical issues.
Lessons from Developed Economies	Insights from Europe, Asia, and Australia emphasise the value of modular solutions, Public-Private Partnerships (PPPs), and open-source platforms in overcoming SSA's constraints.

(For further details, please see Appendix C).

Recommendation

- **Regulatory Frameworks:** Enforce standards and interoperability protocols for DTT implementation to ensure uniformity and effectiveness across SSA.
- **Capacity Building:** Develop region-specific training programs to equip engineers, policymakers, and technicians with practical knowledge of DTT systems.

- **Localised Solutions:** Focus on modular, cost-effective DTT systems tailored to SSA's infrastructure needs and financial constraints, leveraging scalable models from developed economies.
- **Incentivised Partnerships:** Establish public-private partnerships (PPPs) to mitigate financial barriers and encourage investment in digital infrastructure projects.
- **Awareness Campaigns:** Launch targeted awareness programs to educate stakeholders about DTT's benefits and application in transport resilience and sustainability.

REFERENCES

- Akinshipe, O., Aigbavboa, C. and Anumba, C. (2024) 'Digital Twin Technology as a Paradigm for Smart Management in the Built Environment', in S. Skatulla and H. Beushausen (eds) *Advances in Information Technology in Civil and Building Engineering*. Cham: Springer International Publishing (Lecture Notes in Civil Engineering), pp. 417–430. Available at: https://doi.org/10.1007/978-3-031-35399-4_31.
- Ariyachandra, M.R.M.F. and Wedawatta, G. (2023) 'Digital Twin Smart Cities for Disaster Risk Management: A Review of Evolving Concepts', *Sustainability*, 15(15), p. 11910. Available at: <https://doi.org/10.3390/su151511910>.
- Astarita, V. *et al.* (2024) 'Risk Reduction in Transportation Systems: The Role of Digital Twins According to a Bibliometric-Based Literature Review', *Sustainability*, 16(8), p. 3212. Available at: <https://doi.org/10.3390/su16083212>.
- Bado, M.F. *et al.* (2022) 'Digital Twin for Civil Engineering Systems: An Exploratory Review for Distributed Sensing Updating', *Sensors*, 22(9), p. 3168. Available at: <https://doi.org/10.3390/s22093168>.
- Banzhaf, E. *et al.* (2022) 'Mapping Open Data and Big Data to Address Climate Resilience of Urban Informal Settlements in Sub-Saharan Africa', *Climate*, 10(12), p. 186. Available at: <https://doi.org/10.3390/cli10120186>.
- Bello, A.O. *et al.* (2024) 'Exploring the barriers to digital twin adoption in the Nigerian construction industry: a structural equation modelling approach', *Journal of Engineering, Design and Technology* [Preprint]. Available at: <https://doi.org/10.1108/JEDT-01-2024-0012>.
- Botin-Sanabria, D.M. *et al.* (2022) 'Digital Twin Technology Challenges and Applications: A Comprehensive Review', *Remote Sensing*, 14(6), p. 1335. Available at: <https://doi.org/10.3390/rs14061335>.
- Broo, D.G. and Schooling, J. (2023) 'Digital twins in infrastructure: definitions, current practices, challenges and strategies', *International Journal of Construction Management*, 23(7), pp. 1254–1263. Available at: <https://doi.org/10.1080/15623599.2021.1966980>.
- Callcut, M. *et al.* (2021) 'Digital Twins in Civil Infrastructure Systems', *Sustainability*, 13(20), p. 11549. Available at: <https://doi.org/10.3390/su132011549>.
- Chakraborty, R.K. *et al.* (2019) 'Digital Twin-based Cyber Physical System for Sustainable Project Scheduling', in *2019 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*. 2019 IEEE International Conference

on *Industrial Engineering and Engineering Management (IEEM)*, Macao, Macao: IEEE, pp. 820–824. Available at: <https://doi.org/10.1109/IEEM44572.2019.8978712>.

- Cheng, R., Hou, L. and Xu, S. (2023) 'A Review of Digital Twin Applications in Civil and Infrastructure Emergency Management', *Buildings*, 13(5), p. 1143. Available at: <https://doi.org/10.3390/buildings13051143>.
- Doubell, G.C. *et al.* (2022) 'The Potential for Digital Twin Applications in Railway Infrastructure Management', in J.O.P. Pinto *et al.* (eds) *15th WCEAM Proceedings*. Cham: Springer International Publishing (Lecture Notes in Mechanical Engineering), pp. 241–249. Available at: https://doi.org/10.1007/978-3-030-96794-9_22.
- Franciosi, M., Kasser, M. and Viviani, M. (2024) 'Digital Twins in Bridge Engineering: Streamlining Maintenance and Enhancing Sustainability'. Available at: <https://doi.org/10.2139/ssrn.4791521>.
- Gurdur Broo, D., Bravo-Haro, M. and Schooling, J. (2022) 'Design and implementation of a smart infrastructure digital twin', *Automation in Construction*, 136, p. 104171. Available at: <https://doi.org/10.1016/j.autcon.2022.104171>.
- Hakimi, O. *et al.* (2023) 'Data Fusion for Smart Civil Infrastructure Management: A Conceptual Digital Twin Framework', *Buildings*, 13(11), p. 2725. Available at: <https://doi.org/10.3390/buildings13112725>.
- Hood, R. (2021) *The Digitisation of Transport Think Different*. Available at: https://trl.co.uk/uploads/trl/documents/Digitisation-of-Transport---Think-Different_v1.pdf.
- Irena.org (2022) *Power to mobility: Status*. Available at: <https://www.irena.org/Innovation-landscape-for-smart-electrification/Power-to-mobility/Status#:~:text=Norway%20is%20uniquely%20positioned%20to,with%20Chinese%20and%20US%20markets>.
- Jiao, Z. *et al.* (2023) 'Sustainable Operation and Maintenance Modelling and Application of Building Infrastructures Combined with Digital Twin Framework', *Sensors*, 23(9), p. 4182. Available at: <https://doi.org/10.3390/s23094182>.
- Kelvin Edem Bassey *et al.* (2024) 'Digital twin technology for renewable energy microgrids', *Engineering Science & Technology Journal*, 5(7), pp. 2248–2272. Available at: <https://doi.org/10.51594/estj.v5i7.1319>.
- Korus, K., Salamak, M. and Winkler, J. (2023) 'Digital Twins as the Next Step in the Design and Management of Bridge Structures', in A. Ilki, D. Çavunt, and Y.S. Çavunt (eds) *Building for the Future: Durable, Sustainable, Resilient*. Cham: Springer Nature

Switzerland (Lecture Notes in Civil Engineering), pp. 1586–1593. Available at: https://doi.org/10.1007/978-3-031-32511-3_162.

- Kosyakov, D.V. and Marchenko, M.A. (2023) 'Digital Twins in Large-Scale Scientific Infrastructure Projects', *Supercomputing Frontiers and Innovations*, 10(3). Available at: <https://doi.org/10.14529/jsfi230308>.
- Kouladoum, J.-C. (2023) 'Digital infrastructural development and inclusive growth in Sub-Saharan Africa', *Journal of Social and Economic Development*, 25(2), pp. 403–427. Available at: <https://doi.org/10.1007/s40847-023-00240-5>.
- Liu, C., Zhang, P. and Xu, X. (2023) 'Literature review of digital twin technologies for civil infrastructure', *Journal of Infrastructure Intelligence and Resilience*, 2(3), p. 100050. Available at: <https://doi.org/10.1016/j.iintel.2023.100050>.
- Lu, M. and Antwi-Afari, M.F. (2024) 'A Scientometric analysis and critical review of digital twin applications in project operation and maintenance', *Engineering, Construction and Architectural Management* [Preprint]. Available at: <https://doi.org/10.1108/ECAM-03-2024-0304>.
- Madubuike, O., Anumba, C. and Papadonikolaki, E. (2024) 'Leveraging Digital Twins for Enhanced Construction Project Delivery', in: *2024 European Conference on Computing in Construction*. Available at: <https://doi.org/10.35490/EC3.2024.305>.
- Madubuike, O.C., Anumba, C.J. and Khallaf, R. (2022) 'A review of digital twin applications in construction', *Journal of Information Technology in Construction*, 27, pp. 145–172. Available at: <https://doi.org/10.36680/j.itcon.2022.008>.
- Montero, J. and Finger, M. (2021) 'Digitalizing infrastructure: active management for smarter networks', in J. Montero and M. Finger (eds) *A Modern Guide to the Digitalization of Infrastructure*. Edward Elgar Publishing. Available at: <https://doi.org/10.4337/9781839106057.00007>.
- Moshood, T.D. et al. (2024) 'Infrastructure digital twin technology: A new paradigm for future construction industry', *Technology in Society*, 77, p. 102519. Available at: <https://doi.org/10.1016/j.techsoc.2024.102519>.
- Napolitano, A. et al. (2023) 'Implementation of a Digital Twin integrating remote sensing information for network-level infrastructure monitoring', 15 May. Available at: <https://doi.org/10.5194/egusphere-egu23-14981>.
- Obonyo, E.A. and Ouma, L.A. (2022) 'Enhancing the resilience of low-income housing using emerging digital technologies', *IOP Conference Series: Earth and Environmental*

Science, 1101(9), p. 092013. Available at: <https://doi.org/10.1088/1755-1315/1101/9/092013>.

- Oditallah, M., Alam, M.M. and Ekambaram, P. (2023) 'Digital Twins in AEC Infrastructure and Building Management Systems', in. *The 2nd International Conference on Civil Infrastructure and Construction*, pp. 717–726. Available at: <https://doi.org/10.29117/cic.2023.0094>.
- Omrany, H. *et al.* (2023) 'Digital Twins in the Construction Industry: A Comprehensive Review of Current Implementations, Enabling Technologies, and Future Directions', *Sustainability*, 15(14), p. 10908. Available at: <https://doi.org/10.3390/su151410908>.
- Opoku, D.-G.J. *et al.* (2022) 'Drivers for Digital Twin Adoption in the Construction Industry: A Systematic Literature Review', *Buildings*, 12(2), p. 113. Available at: <https://doi.org/10.3390/buildings12020113>.
- Pot, W., De Ridder, Y. and Dewulf, A. (2024) 'Avoiding future surprises after acute shocks: long-term flood risk lessons catalysed by the 2021 summer flood in the Netherlands', *Environmental Sciences Europe*, 36(1), p. 138. Available at: <https://doi.org/10.1186/s12302-024-00960-3>.
- PwC (2022) *Energy transition in Southeast Asia*. Available at: https://www.siew.gov.sg/docs/default-source/downloads/2022/energy-transition-thought-leadership-short-presentation_june-2022.pdf.
- Rashidi, A. *et al.* (2024) 'A systematic taxonomic review of the application of BIM and digital twins technologies in the construction industry', *Engineering, Construction and Architectural Management* [Preprint]. Available at: <https://doi.org/10.1108/ECAM-02-2024-0239>.
- Rotilio, M., Villa, V. and Corneli, A. (2023) 'Digital Twin for a resilient management of the built environment', in *2023 IEEE International Workshop on Metrology for Living Environment (MetroLivEnv)*. *2023 IEEE International Workshop on Metrology for Living Environment (MetroLivEnv)*, Milano, Italy: IEEE, pp. 113–117. Available at: <https://doi.org/10.1109/MetroLivEnv56897.2023.10164033>.
- Rudskoy, A., Ilin, I. and Prokhorov, A. (2021) 'Digital Twins in the Intelligent Transport Systems', *Transportation Research Procedia*, 54, pp. 927–935. Available at: <https://doi.org/10.1016/j.trpro.2021.02.152>.
- Sacks, R. *et al.* (2020) 'Construction with digital twin information systems', *Data-Centric Engineering*, 1, p. e14. Available at: <https://doi.org/10.1017/dce.2020.16>.

- Salem, T. and Dragomir, M. (2022) 'Options for and Challenges of Employing Digital Twins in Construction Management', *Applied Sciences*, 12(6), p. 2928. Available at: <https://doi.org/10.3390/app12062928>.
- Shahzad, M. *et al.* (2022) 'Digital Twins in Built Environments: An Investigation of the Characteristics, Applications, and Challenges', *Buildings*, 12(2), p. 120. Available at: <https://doi.org/10.3390/buildings12020120>.
- Singh, M. *et al.* (2022) 'Applications of Digital Twin across Industries: A Review', *Applied Sciences*, 12(11), p. 5727. Available at: <https://doi.org/10.3390/app12115727>.
- Sofia, H., Anas, E. and Faiz, O. (2020) 'Mobile Mapping, Machine Learning and Digital Twin for Road Infrastructure Monitoring and Maintenance: Case Study of Mohammed VI Bridge in Morocco', in *2020 IEEE International conference of Moroccan Geomatics (Morgeo)*. *2020 International conference of Moroccan Geomatics (Morgeo)*, Casablanca, Morocco: IEEE, pp. 1–6. Available at: <https://doi.org/10.1109/Morgeo49228.2020.9121882>.
- Sohal, K. *et al.* (2023) 'The uptake of digital twins in delivering infrastructure sector projects', *Smart and Sustainable Built Environment* [Preprint]. Available at: <https://doi.org/10.1108/SASBE-03-2023-0046>.
- Steyn, W.J. and Broekman, A. (2022) 'Development of a Digital Twin of a Local Road Network: A Case Study', *Journal of Testing and Evaluation*, 50(6), pp. 2901–2915. Available at: <https://doi.org/10.1520/JTE20210043>.
- Taherkhani, R., Ashtari, M.A. and Aziminezhad, M. (2024) 'Digital Twin-Enabled Infrastructures: A Bibliometric Analysis-Based Review', *Journal of Infrastructure Systems*, 30(1), p. 03123001. Available at: <https://doi.org/10.1061/JITSE4.ISENG-2323>.
- Tchana, Y., Ducellier, G. and Remy, S. (2019) 'Designing a unique Digital Twin for linear infrastructures lifecycle management', *Procedia CIRP*, 84, pp. 545–549. Available at: <https://doi.org/10.1016/j.procir.2019.04.176>.
- Teng, S.Y. *et al.* (2021) 'Recent advances on industrial data-driven energy savings: Digital twins and infrastructures', *Renewable and Sustainable Energy Reviews*, 135, p. 110208. Available at: <https://doi.org/10.1016/j.rser.2020.110208>.
- Van Der Veen, S., Meusburger, E. and Meusburger, M. (2023) 'Digital Twin as enabler of Business Model Innovation for Infrastructure Construction Projects', in. *40th International Symposium on Automation and Robotics in Construction*, Chennai, India. Available at: <https://doi.org/10.22260/ISARC2023/0092>.

- Vieira, J. *et al.* (2022) 'Towards Resilient and Sustainable Rail and Road Networks: A Systematic Literature Review on Digital Twins', *Sustainability*, 14(12), p. 7060. Available at: <https://doi.org/10.3390/su14127060>.
- World Bank (2019) *Case Studies in Integrated Urban Flood Risk Management in Japan*. Japan. Available at: <https://documents1.worldbank.org/curated/en/915131601460271575/pdf/Appendix-Case-Studies-in-Integrated-Urban-Flood-Risk-Management-in-Japan.pdf>.
- Yan, B. *et al.* (2023) 'Digital twin in transportation infrastructure management: a systematic review', *Intelligent Transportation Infrastructure*, 2, p. liad024. Available at: <https://doi.org/10.1093/iti/liad024>.
- Ye, X. *et al.* (2023) 'Developing Human-Centered Urban Digital Twins for Community Infrastructure Resilience: A Research Agenda', *Journal of Planning Literature*, 38(2), pp. 187–199. Available at: <https://doi.org/10.1177/08854122221137861>.
- Yiran, G.A.B. *et al.* (2020) 'Urban Sprawl in sub-Saharan Africa: A review of the literature in selected countries', *Ghana Journal of Geography*, 12(1), pp. 1–28. Available at: <https://doi.org/10.4314/gjg.v12i1.1>.
- Zhou, S. *et al.* (2022) 'A Conceptual Model-based Digital Twin Platform for Holistic Large-scale Railway Infrastructure Systems', *Procedia CIRP*, 109, pp. 362–367. Available at: <https://doi.org/10.1016/j.procir.2022.05.263>.

APPENDICES

Appendix A- Geographical focus of studies on Digital Twin Technology

Table 4- Geographical Focus of DTT Studies

Author	Title of the Study	Geographical Location	Economic Status
Zhou et al.	A Conceptual Model-based Digital Twin Platform for Holistic Large-scale Railway Infrastructure Systems	Global	Developed regions
Teng et al.	Recent Advances on Industrial Data-Driven Energy Savings: Digital Twins and Infrastructures	China	Developed
Salem and Dragomir	Options for and Challenges of Employing Digital Twins in Construction Management	Europe	Developed
Van Der Veen et al.	Digital Twin as Enabler of Business Model Innovation for Infrastructure Construction Projects	Netherlands	Developed
Sacks et al.	Construction with Digital Twin Information Systems	Europe	Developed
Rudskoy et al.	Digital Twins in the Intelligent Transport Systems	Russia	Developed
Sohal et al.	The Uptake of Digital Twins in Delivering Infrastructure Sector Projects	United Kingdom	Developed
Obonyo and Ouma	Enhancing the Resilience of Low-Income Housing Using Emerging Digital Technologies	Kenya	Developing
Montero and Finger	Digitalizing Infrastructure: Active Management for Smarter Networks	Europe	Developed
Callcut et al.	Digital Twins in Civil Infrastructure Systems	United Kingdom	Developed
Steyn and Broekman	Development of a Digital Twin of a Local Road Network: A Case Study	South Africa	Developing
Franciosi et al.	Digital Twins in Bridge Engineering: Streamlining Maintenance and Enhancing Sustainability	Europe	Developed
Kosyakov et al.	Digital Twins in Large-Scale Scientific Infrastructure Projects	Russia	Developed
Ye et al.	Developing Human-Centered Urban Digital Twins for Community Infrastructure Resilience	Global	Developed Regions
Bassey et al.	Digital Twin Technology for Renewable Energy Microgrids	Nigeria	Developing
Kouladoum	Digital Infrastructural Development and Inclusive Growth in Sub-Saharan Africa	Sub-Saharan Africa	Developing
Vieira et al.	Towards Resilient and Sustainable Rail and Road Networks: A Systematic Literature Review on Digital Twins	Global	Developed Regions
Broo and Schooling	Digital Twins in Infrastructure: Definitions, Current Practices, Challenges and Strategies	United Kingdom	Developed
Ariyachandra and Wedawatta	Digital Twin Smart Cities for Disaster Risk Management: A Review of Evolving Concepts	Sri Lanka	Developing
Botin-Sanabria et al.	Digital Twin Technology Challenges and Applications: A Comprehensive Review	Global	Developed Regions
Bado et al.	Digital Twin for Civil Engineering Systems: An Exploratory Review for Distributed Sensing Updating	Global	Not Specific

Astarita et al.	Risk Reduction in Transportation Systems: The Role of Digital Twins	Global	Not Specific
Opoku et al.	Drivers for Digital Twin Adoption in the Construction Industry: A Systematic Literature Review	Global	Not Specific

Appendix B – Summary of articles used and their relevance

Author	Title	Methodology	Findings	Relevance to Study
Bado et al.	Digital Twin for Civil Engineering Systems: An Exploratory Review for Distributed Sensing Updating	Exploratory review of DTT applications in distributed sensing	Explored the application of distributed sensors integrated with DTT for structural monitoring.	Highly relevant for distributed monitoring in rail and road networks.
Astarita et al.	Risk Reduction in Transportation Systems: The Role of Digital Twins	Bibliometric-based literature review	Highlighted DTT's capacity for proactive risk reduction through predictive analytics and simulation.	Applicable for proactive risk reduction in transport systems.
Ariyachandra and Wedawatta	Digital Twin Smart Cities for Disaster Risk Management: A Review of Evolving Concepts	Systematic review of DTT in smart city disaster risk management applications	Emphasized the role of DTT in disaster planning and management. Found applicability in urban contexts.	Relevant for urban mobility resilience
Kosyakov et al.	Digital Twins in Large-Scale Scientific Infrastructure Projects	Exploratory review of large-scale digital twin implementations	Identified optimization strategies for scientific infrastructure using DTT, including operational efficiency and resource allocation.	Offers scalability insights.
Shahzad et al.	Digital Twins in Built Environments: An Investigation of the Characteristics, Applications, and Challenges	Literature review and expert interviews	Discussed integration with BIM and IoT. Identified challenges in standardization and adaptation.	Relevant for understanding adaptation issues in urban and rural transport systems.
Tchana et al.	Designing a Unique Digital Twin for Linear Infrastructures Lifecycle Management	Case study and theoretical analysis	Proposed DTT-BIM integration for infrastructure lifecycle management.	Useful for infrastructure lifecycle strategies leveraging DTT and BIM integration.
Singh et al.	Applications of Digital Twin Across Industries: A Review	Cross-industry application review	Found DTT benefits for predictive maintenance and real-time optimization across sectors.	Provides cross-sector DTT insights, some applicable to SSA's transport challenges.
Obonyo and Ouma	Enhancing the Resilience of Low-Income Housing Using	Case studies on disaster risk reduction using DTT	Found DTT effective in improving resilience through early warning systems and disaster	Highly relevant for resilience-focused transport infrastructure.

	Emerging Digital Technologies		preparedness planning.	
Montero and Finger	Digitalizing Infrastructure: Active Management for Smarter Networks	Exploratory conceptual analysis of digital infrastructure management	Demonstrated the role of DTT in active management for network optimization. Found limitations in data standardization.	Relevant for analysing transport network optimisation challenges.
Madubuike et al.	Leveraging Digital Twins for Enhanced Construction Project Delivery	Literature review and framework development targeting DT integration in construction	Outlined how DTT supports lifecycle efficiency in construction, reducing costs and project timelines.	Relevance for DTT lifecycle management insights in transport.
Zhou et al.	A Conceptual Model-based Digital Twin Platform for Holistic Large-scale Railway Infrastructure Systems	Conceptual model development and use-case implementation	Identified gaps in subsystem integration within railways. Emphasized potential for performance enhancement.	Highly relevant for identifying transport resilience challenges and gaps in DTT for SSA rail infrastructure.
an et al.	Digital Twin in Transportation Infrastructure Management: A Systematic Review	Systematic review of DTT applications in transportation	Identified benefits in lifecycle management and challenges like data integration and security.	Relevant for understanding key DTT transport applications and challenges.
Vieira et al.	Towards Resilient and Sustainable Rail and Road Networks: A Systematic Literature Review on Digital Twins	Systematic literature review	Mapped rail and road DTT applications. Emphasized operational and maintenance benefits.	Useful for linking DTT to sustainability and resilience.
Van Der Veen et al.	Digital Twin as Enabler of Business Model Innovation for Infrastructure Construction Projects	Conceptual proposal of DTT-driven business model innovations	Highlighted inefficiencies in construction. Identified need for business-model-focused research.	Relevant for exploring SSA transport project inefficiencies using DTT insights.
Teng et al.	Recent Advances on Industrial Data-Driven Energy Savings: Digital Twins and Infrastructures	Literature review and framework proposal	Proposed DTT for energy optimization. Highlighted IoT and AI in improving infrastructure energy use.	Relevant for renewable energy integration into SSA transport infrastructure.
Ye et al.	Developing Human-Centered Urban Digital Twins for Community Infrastructure Resilience	Scoping review, framework proposal	Highlighted urban DTT role in resilience. Proposed physical-cyber-social integration framework.	Relevant for analysing urban mobility solutions in SSA's growing cities.
Zhou et al.	A Conceptual Model-based Digital Twin Platform for Holistic	Conceptual model development and	Identified gaps in subsystem integration within railways.	Highly relevant for identifying transport

	Large-scale Railway Infrastructure Systems	use-case implementation	Emphasized potential for performance enhancement.	resilience challenges and gaps in DTT for SSA rail infrastructure.
Lu and Antwi-Afari	A Scientometric Analysis and Critical Review of Digital Twin Applications in Renewable Energy	Scientometric analysis and critical review	Explored DTT's role in optimizing microgrid operations and renewable energy integration. Identified gaps in widespread adoption.	Relevant for integrating renewable energy systems in SSA transport projects.
Liu et al.	Literature Review of Digital Twin Technologies for Civil Infrastructure	Literature review summarizing DT methods	Reviewed diverse civil infrastructure applications of DTT, finding significant sustainability benefits but challenges in scaling.	Useful for understanding DTT's impact on SSA transport sustainability.
Steyn and Broekman	Development of a Digital Twin of a Local Road Network: A Case Study	Case study focusing on road network development	Demonstrated predictive maintenance benefits and cost-effective monitoring.	Highly relevant as a case study in South Africa, transferable to other SSA countries.
Sohal et al.	The Uptake of Digital Twins in Delivering Infrastructure Sector Projects	Literature review on barriers and adoption strategies	Found low adoption rates due to technical, cultural, and funding barriers.	Highlights gaps in adoption strategies relevant to SSA transport challenges.
Salem and Dragomir	Options for and Challenges of Employing Digital Twins in Construction Management	Systematic literature review	Proposed a framework for construction-focused DTT. Found significant ROI potential in advanced applications.	Indirect relevance for ROI arguments supporting DTT adoption in SSA.
Sacks et al.	Construction with Digital Twin Information Systems	Conceptual analysis of data-driven workflows	Highlighted the importance of real-time monitoring. Identified limited real-world implementation.	Highlights implementation challenges that SSA transport systems would also face.
Rudskoy et al.	Digital Twins in the Intelligent Transport Systems	Case study and reference model	Proposed traffic optimization strategies using DTT. Highlighted scalability challenges.	Relevant for improving SSA urban traffic flow and system scalability with DTT.
Opoku et al.	Drivers for Digital Twin Adoption in the Construction Industry: A	Systematic literature review	Identified adoption drivers and challenges globally. Emphasized	Useful for policy recommendations in SSA transport

	Systematic Literature Review		awareness-building for DTT.	adoption strategies.
Omran et al.	Digital Twins in the Construction Industry: A Comprehensive Review	Comprehensive literature review	Identified enabling technologies and adoption trends. Highlighted governance challenges.	Relevant for understanding governance issues in SSA transport adoption.
Kouladoun	Digital Infrastructural Development and Inclusive Growth in Sub-Saharan Africa	Quantitative analysis using Driscoll-Kraay standard errors	Showed the positive correlation between digital infrastructure development and inclusive economic growth in SSA.	Critical for understanding SSA-specific infrastructure growth challenges.
Bassey et al.	Digital Twin Technology for Renewable Energy Microgrids	Case study on integrating renewable energy systems with DTT	Highlighted the role of DTT in optimizing energy use for microgrids, enhancing resilience, and reducing reliance on fossil fuels.	Directly relevant to Nigeria's renewable energy-driven transport systems.
Jiao et al.	Sustainable Operation and Maintenance Modelling and Application of Building Infrastructures Combined with Digital Twin Framework	Development of digital twin models	Developed a novel framework (SDTOM-BI) to streamline energy management in public buildings.	Applicable to energy-intensive transport operations in SSA.
Gurdur Broo et al.	Design and Implementation of a Smart Infrastructure Digital Twin	Case study and literature review	Proposed an architecture for scalable DTT systems in infrastructure projects, emphasizing design flexibility.	Relevant for scalability insights in SSA transport system implementation.
Franciosi et al.	Digital Twins in Bridge Engineering: Streamlining Maintenance and Enhancing Sustainability	Case studies of bridge maintenance and lifecycle management	Demonstrated how DTT models enhance maintenance scheduling, reducing costs and extending asset life.	Highly relevant for extending lifecycle and reducing costs of SSA transport infrastructure.
Cheng et al.	A Review of Digital Twin Applications in Civil and Infrastructure Emergency Management	Systematic literature review and framework development	Proposed a DTT-based emergency management framework. Found potential in resilience enhancement but noted data challenges.	Useful for SSA's disaster-prone transport network resilience strategies.
Callcut et al.	Digital Twins in Civil Infrastructure Systems	Literature review and expert interviews	Mapped barriers to adoption in civil systems and identified opportunities for	Indirectly relevant for identifying adoption barriers

			technology integration.	in SSA's transport systems.
Broo and Schooling	Digital Twins in Infrastructure: Definitions, Current Practices, Challenges and Strategies	Literature review and semi-structured interviews	Identified key operational and governance challenges limiting DTT implementation in large infrastructure projects.	Relevant for governance and operational challenges in SSA transport projects.
Botin-Sanabria et al.	Digital Twin Technology Challenges and Applications: A Comprehensive Review	Systematic literature review identifying global DTT challenges	Reviewed global challenges in DTT, including interoperability and cost barriers, with limited solutions for SSA.	Applicable for global DTT challenges, indirectly relevant to SSA.

Appendix C – Geographical focus of articles

Omrany et al.	Digital Twins in the Construction Industry: A Comprehensive Review of Current Implementations, Enabling Technologies, and Future Directions	Global	Not Specific
Oditallah et al.	Digital Twins in AEC Infrastructure and Building Management Systems	Global	Not Specific
Madubuike et al.	Leveraging Digital Twins for Enhanced Construction Project Delivery	Global	Not Specific
Lu and Antwi-Afari	A Scientometric Analysis and Critical Review of Digital Twin Applications in Renewable Energy	Global	Not Specific
Liu et al.	Literature Review of Digital Twin Technologies for Civil Infrastructure	Global	Not Specific
Yan et al.	Digital Twin in Transportation Infrastructure Management: A Systematic Review	Global	Not Specific
Tchana et al.	Designing a Unique Digital Twin for Linear Infrastructures Lifecycle Management	Global	Not Specific
Singh et al.	Applications of Digital Twin Across Industries: A Review	Global	Not Specific
Shahzad et al.	Digital Twins in Built Environments: An Investigation of the Characteristics, Applications, and Challenges	Global	Not Specific
Jiao et al.	Sustainable Operation and Maintenance Modelling and Application of Building Infrastructures Combined with Digital Twin Framework	Global	Not Specific
Gurdur Broo et al.	Design and Implementation of a Smart Infrastructure Digital Twin	Global	Not Specific
Cheng et al.	A Review of Digital Twin Applications in Civil and Infrastructure Emergency Management	Global	Not Specific

Appendix D – Summary of Key Findings

Table 5- Summary of Key Findings from the Literature Review

Key Finding	Summary
Enhanced Resilience	DTT supports proactive risk management through real-time monitoring and predictive analytics. Applications include rail, road, and urban transport systems.
Sustainability and Efficiency	DTT optimises resource use, reduces material waste, and enables lifecycle efficiency. Facilitates integration of renewable energy in transport systems.
Geographical Bias	Most research focuses on developed economies, leaving a gap in understanding DTT's role in resource-constrained settings like SSA.
Scalability Challenges	High costs and technical requirements hinder large-scale DTT adoption in SSA. Scalable, cost-effective models are needed.
Limited Case Studies	Few in-depth case studies explore DTT applications in SSA, limiting insights into its practical impact on the region.
Lack of Regulatory Frameworks	The absence of clear regulatory standards creates ambiguity, slowing DTT adoption in transport systems.
Data Security and Privacy	Weak data governance and cybersecurity frameworks hinder trust and adoption of DTT in SSA.
Emerging Technologies	AI and blockchain can enhance DTT's predictive and data management capabilities, but their application remains underexplored in SSA.
Public-Private Partnerships (PPPs)	PPPs can address financial and technical gaps, fostering broader adoption of DTT in SSA transport systems.
Urban and Rural Mobility	DTT can optimize urban transport and improve connectivity in underserved rural areas, ensuring equitable mobility access.
Localized Applications	Case studies in SSA demonstrate the potential of DTT to address unique regional challenges, such as climate resilience.
Economic Growth Potential	DTT adoption correlates with economic development, fostering inclusive growth through improved transport systems.
Renewable Energy Integration	Integration of renewable energy systems with DTT supports sustainable and resilient transport infrastructure in SSA.

Appendix E – Summary of Case Studies

Table 6- Summary of Case Studies in Digital Twin Technology Applications

Case Study Context	Source	Findings	Relevance to SSA
Road Infrastructure Maintenance: South Africa	Steyn and Broekman (2022)	DTT enabled proactive identification of road deterioration patterns, reducing maintenance costs and extending infrastructure lifespan.	Highly relevant for addressing road maintenance inefficiencies in resource-constrained settings.
Rail System Optimization: Europe	Zhou et al. (2022)	Enhanced operational efficiency and reduced delays through train schedule optimization. Improved predictive maintenance minimized downtime.	Demonstrates applicability of DTT for improving SSA rail systems' operational efficiency and maintenance.

Urban Transit Optimization: Nairobi, Kenya	Obonyo and Ouma (2022)	Reduced passenger waiting times and congestion in Nairobi's BRT system via dynamic scheduling and traffic flow simulations.	Directly applicable for optimizing urban transit in SSA cities experiencing rapid urbanization.
Bridge Maintenance and Lifecycle Management: Europe	Franciosi et al. (2024)	Improved maintenance scheduling and extended asset life through structural health monitoring. Optimized resource use reduced environmental impact.	Transferable to SSA for improving bridge maintenance and addressing resource limitations.
Disaster Resilience in Urban Transport: Sri Lanka	Ariyachandra and Wedawatta (2023)	Enhanced disaster preparedness and recovery for urban transport systems by simulating flood scenarios and visualizing mitigation strategies.	Provides a model for disaster-prone regions in SSA to enhance transport system resilience.
Lifecycle Management for Linear Infrastructure: Global	Tchana et al. (2019)	Improved efficiency in infrastructure design, construction, and operation by integrating BIM and PLM with DTT.	Transferable to SSA for managing lifecycle efficiency of large-scale highway and linear infrastructure projects.

Appendix F- Comparative Analysis

Table 17– Comparative Case Studies, Scalability Insights, and Transferable Lessons for Digital Twin Technology Adoption in Sub-Saharan Africa

Theme	Case/Insight	Details	Supporting References	Relevance to Sub-Saharan Africa(SSA)
Comparative Case Studies	Europe- Bridge Maintenance	DTT enables lifecycle management and structural health monitoring, reducing costs and extending asset life.	Franciosi et al. (2024)	Implement sensor-based monitoring for critical infrastructure in SSA to manage aging bridges and roads efficiently.
	United Kingdom- Urban Transit	London's Underground uses DTT for predictive maintenance, reducing delays and increasing operational efficiency.	Bado et al. (2022); Cheng et al. (2023)	Adopt real-time monitoring and predictive analytics for urban transit systems to address inefficiencies in SSA's cities.
	Asia- Modular DTT	Modular DTT solutions improve traffic flow, reduce emissions, and optimise resource use.	PwC (2022); Shahzad et al. (2022)	Prioritise modular and scalable DTT solutions for transport systems in SSA's growing urban areas.
Scalability Insights	Public-Private Partnerships (PPPs)	European PPPs (e.g., Dartford Crossing) finance DTT projects, ensuring cost-effectiveness and operational gains.	Kosyakov et al. (2023)	Use PPPs to secure funding and technical expertise for large-scale DTT adoption in SSA.

	Open-Source Platforms	Netherlands' open-source platforms lower costs and ensure interoperability.	Montero and Finger (2021); Broo and Schooling (2023)	Promote open-source solutions to reduce costs and address compatibility issues across infrastructure projects in SSA.
	Cloud and IoT Solutions	Australia's cloud-based DTT uses IoT for real-time data analysis, ensuring scalability.	Gurdur Broo et al. (2023)	Combine cloud and IoT to overcome infrastructure deficits and provide actionable insights for SSA decision-makers.
Transferable Lessons	Localised Data Integration	Developed economies rely on robust data systems; SSA faces connectivity issues.	Zhou et al. (2022); Obonyo and Ouma (2022)	Implement hybrid models with offline and online data integration to address bandwidth and connectivity challenges.
	Community Engagement	Public acceptance has driven DTT success in Europe's transit systems.	Singh et al. (2022); Obonyo and Ouma (2022)	Involve local communities to build trust and ensure DTT addresses their specific needs, especially in rural areas.
	Affordable Modular Deployment	Incremental DTT adoption in Asia starts with high-impact areas before expanding.	PwC (2022)	Deploy DTT incrementally in SSA, focusing on urban transit systems and expanding as funding allows.
	Capacity Building	Developed economies invest in training for stakeholders and engineers.	Montero and Finger (2021); Kouladoum (2023)	Train SSA engineers, policymakers, and stakeholders to develop local expertise in managing and maintaining DTT systems.
	Policy Frameworks	Clear regulations in developed economies facilitate DTT collaboration.	Broo and Schooling (2023); Montero and Finger (2021)	SSA must create policies that foster collaboration between governments, private sectors, and academia to drive DTT adoption.

Appendix G: Survey Questionnaire

Section 1: General Information

- What is your role in the infrastructure sector?
 - Project Manager

- Government Official
 - Infrastructure Consultant
 - Technology Expert
 - Engineer
- How many years of experience do you have in managing infrastructure projects?
 - Less than 5 years
 - 5-10 years
 - 11-15 years
 - More than 15 years
 - Which country are you currently working in?
 - Kenya
 - Uganda
 - Tanzania
 - Rwanda
 - Ethiopia

Section 2: Understanding of Digital Twin Technology (DTT)

- Are you familiar with Digital Twin Technology?
 - Yes
 - No
- Has DTT been implemented in any infrastructure projects you have been involved in?
 - Yes
 - No
 - Not sure

Section 3: Potential for Digital Twin Technology in Enhancing Infrastructure Resilience

- To what extent do you believe Digital Twin Technology can improve the following aspects of infrastructure resilience?
 - a) Early identification of structural vulnerabilities
 - Not helpful
 - Somewhat helpful
 - Moderately helpful
 - Very helpful
 - b) Disaster preparedness (e.g., earthquakes, floods)
 - Not helpful
 - Somewhat helpful
 - Moderately helpful
 - Very helpful
 - c) Real-time monitoring and predictive maintenance
 - Not helpful
 - Somewhat helpful

- Moderately helpful
 - Very helpful
- d) Risk assessment and management
 - Not helpful
 - Somewhat helpful
 - Moderately helpful
 - Very helpful
- Do you believe that DTT can significantly reduce these vulnerabilities?
 - Yes
 - No
 - Not Sure
- In your experience, what are the primary vulnerabilities that infrastructure projects face in Sub-Saharan Africa?

Section 4: Barriers to Implementing Digital Twin Technology

- What do you think are the main barriers to adopting Digital Twin Technology in Sub-Saharan Africa? *(Please rank the following in order of significance, from 1 being the most significant to 5 being the least significant)*
 - Lack of financial resources
 - Lack of technological expertise
 - Poor infrastructure for data connectivity (e.g., limited access to high-speed internet)
 - Resistance to change within organizations
 - Lack of awareness and knowledge about DTT
- To what extent do you agree with the following statement: "Government policies and regulations in my country are supportive of integrating advanced technologies like Digital Twin Technology in infrastructure projects."
 - Strongly disagree
 - Disagree
 - Neutral
 - Agree
 - Strongly agree
- What support mechanisms do you think are needed to overcome the barriers to DTT implementation

Section 5: Contribution of DTT to Sustainable Infrastructure

- To what extent do you believe Digital Twin Technology can contribute to the following aspects of sustainable infrastructure?
 - a) Reducing the carbon footprint of construction projects:
 - Not helpful
 - Somewhat helpful
 - Moderately helpful
 - Very helpful
 - b) Improving the efficiency of resource use (e.g., water, energy):

- Not helpful
- Somewhat helpful
- Moderately helpful
- Very helpful

c) Reducing the costs of long-term infrastructure maintenance:

- Not helpful
- Somewhat helpful
- Moderately helpful
- Very helpful

d) Supporting the achievement of UN SDG 9a (*sustainable infrastructure for economic development and human well-being*).

- Not helpful
- Somewhat helpful
- Moderately helpful
- Very helpful