THE ROLE OF DIGITAL TWIN TECHNOLOGY IN SUPPORTING SUSTAINABLE TOURISM PRACTICES: DESTINATION PLANNING AND MANAGEMENT

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M23B63/019

A DISSERTATION SUBMITTED TO THE SCHOOL OF BUSINESS IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF A DEGREE OF BACHELOR OF TOURISM AND HOSPITALITY MANAGEMENT OF UGANDA CHRISTIAN UNIVERSITY

February, 2026

UGANDA CHRISTIAN UNIVERSITY

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DECLARATION

As per the university values of integrity and diligence, I have not received any unauthorized assistance while working on this paper. I declare that the work is authentically mine and to the best of my knowledge, it contains no trace of plagiarism or any other unethical practices. The only work used that has already been published by other persons has been purely for reference purposes and appropriate citations have been made.

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APPROVAL

This research report has been submitted for examination purposes with my approval as academic supervisor.

Signature. 

MR. JULIUS JJUUKO

Date. 28/02/2026

DEDICATION

I dedicate my work to my family who advised, supported and mentored me throughout my education up to university level. Above all, I thank God for guidance, protection and provision towards completion of this dissertation.

ACKNOWLEDGEMENT

I want to thank Almighty God for his grace, blessings, and the gift of life, which enabled me to complete this journey. I would also like to acknowledge my supervisor, for guiding me through the research project, through advice and lessons that made the project completion easier. My sincere gratitude goes to my parents, who also guided me and assisted me in this project in many ways. And my final gratitude goes to my colleagues and fellow classmates, I take this chance to thank them because they offered their help through brainstorming and spared their time to share what they could for this project to become a success, making the project completion a possibility.

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ABSTRACT

This dissertation explores the potential of digital twin (DT) technologies to aid the planning and management of sustainable tourism by applying the document-analysis method and concentrating on literature and policy material published in 201025, and a case study of the Bwindi Impenetrable National Park in the national context of Uganda. Based on the conceptual lineage of the DT back to Michael Grieves, and informed by the standards and practitioner guidance (including that of the Digital Twin Consortium), the study is a synthesis of peer-reviewed literature, technical white papers, policy documents and site management plans. Analysis with the aid of a structured codebook and thematic matrices revealed seven major themes, namely monitoring, simulation, conservation/heritage digitization, governance and ethics, interoperability and standards, cost and accessibility, and validation/evidence. Critical findings reveal a pragmatic approach of monitoring-first adoption trajectory of destination DTs, the primacy of governance (data-sharing, privacy, community co-design) in driving social legitimacy, lingering interoperability and cost barricades, and a desperate void on longitudinal validation of the links between DT interventions and quantifiable sustainability outcomes. The dissertation ends with the practical recommendations of staged, governance-based pilots, low-cost architecture, and stringent validation designs and research agenda to produce empirical evidence needed to implement the policy. The work places DTs as a facilitative, but not automatic, means to sustainable tourism- technical, institutional and ethical alignment has to happen to achieve conservation and community benefits.

ABREVIATION LIST

DT	Digital Twin
SLA	Service Level Agreement
GSTC	Global Sustainable Tourism Council
ETIS	Elephant Trade Information System
NGO	Non-Government Organization
IOT	Internet of Things
PLCs	Program Logic Controllers
AI	Artificial Intelligence
AR	Augmented Reality
VR	Virtual Reality
CAD	Computer Aided Design
BIM	Building Information Modeling
EHR	Electronic Health Record
ROI	Return on Investment
PLM	Product Lifecycle Management
GIS	Geographical Information System
LiDAR	Light Detection and Ranging

PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
GML	Geography Markup Language
RMSE	Root Mean Square Error
IFC	Industry Foundation Classes
CCTV	Closed-Circuit Television
UNWTO	United Nations World Tourism Organization
UNEP-WTO	United Nations Environment ProgrammeWorld Trade Organization
WWF	World Wide Fund for Nature
NEMA	National Environment Management Authority

CHAPTER ONE

1.0 Introduction

In this chapter the background of the study, problem statement, objectives of study, research questions, scopes of study, justification of study/ and structure of the study report are given.

1.1 The background

The UN World Tourism Organization defines tourism as a social cultural and economic phenomenal which entails the movement of people to countries or places outside their usual environment for personal or business/professional purposes. Jafari (1977), goes ahead to describe tourism is the study of man away from his usual habitat, of the industry which responds to his needs, and of the impacts that both he and the industry have on the hosts socio-cultural, economic and physical environments. Sustainable tourism is defined by UN Environment Program and the UN World Tourism Organization (2005), as tourism that takes full account of its current and future economic, social and environmental impacts, addressing the needs of visitors, the industry, the environment and the host communities. This is why it can be described as the control of tourist destinations to reduce adverse effects on the economical, environmental, and social components in accordance with sustainable development objectives (Kurniawan 2024). It seeks to strike a balance between tourism needs and sound management of resources with focus on economic, environmental and sociocultural factors. Sustainable tourism behavior refers to behaviors and consumption habits that encourage social, environmental and natural wellbeing whilst reducing adverse effects (Alazaizeh etal., 2019).

The major areas of concern are minimizing carbon footprints, increasing the preservation of biodiversity, and the fact that economic gains are fairly shared among the citizens of the area. Sustainable tourism is becoming more popular in the world since the World Tourism Organization indicated a substantial rise in destinations implementing sustainable tourism practices to meet the demands of the rising number of eco-friendly tourists (Maniktala & Sharma 2024).

The sustainable tourism practices are the environmental, economic and the socio-cultural components of tourism development and an appropriate balance needs to be struck among the three components to ensure the long term sustainability of tourism (UNEP-WTO, 2005). The aim of sustainable tourism is to develop and preserve the natural and cultural resources, decrease the emission of carbon, and help to sustain local economies and communities. It entails activities like eco-tourism, responsible tourism and community based tourism, which are aimed at encouraging sustainable and ethical tourism activities (Maniktala and Sharma 2024).

Although the focus has been on motivating tourists and other stakeholders engaged in the tourist business to engage in sustainable tourist behaviours, there are also a number of challenges that are likely to emerge as a result of several limitations. One of such problems is transparency, economic issues, culture and most importantly some of the adverse effects of the project exposure to the outside (Honey 2008).

WWF (2021) reports that environmental sustainability indicators are decreasing and a NEMA 2025 report reports continued deforestation, pollution and loss of biodiversity. ICG (2024) cautions that plastic waste is contaminating tourist spots. The concept of sustainable tourism is influenced by a combination of several factors that are linked and determine whether destinations can reconcile economic value with environmental and social health. The personal tourist variables like environmental awareness, values and attitudes influence the decision to make use of sustainable behaviors (Chen 2025). The psychological factors such as social norms and perceived control over behavior are also important psychological determinants of the intentions of tourists to adopt sustainable choice (Ballester & Esteve, 2025).

The involvement of communities and local support is essential because the perceived socio-economic and environmental effects of sustainable tourism development influence the readiness of the residents to endorse sustainable tourism development (Pohan et al., 2025). Moreover, governance and policy framework, such as environmental legislation and incentives offer structural support allowing the sustainable practice to be sustainable over the long term (Khan and Ahmed, 2021).

Lastly, economic and infrastructural factors like financial resources to support sustainable infrastructure and knowledge among the stakeholders have a direct impact on the implementation capacity (Islam et al., 2025). This paper will center on the digital twin technology and how it can contribute to the sustainable tourism practices.

Technology refers to everything, tools, machines, utensils, weapons, instruments, houses, clothing, communicating and transporting devices and skills with which we make and use them (Read Bain 1937). Galbraith (1967) still goes ahead to give the definition of technology as the systematic use of scientific or other organized knowledge in practical tasks. Digital Twin (DT) is defined as the virtual representation or copy of any physical object (physical twin) all of which are tied together by exchanging data in real time (Singh 2021). In theory a DT replicates the state of its real-world counterpart in real time and vice versa. The use of DT encompasses real time monitoring, designing/planning, optimization, maintenance, remote access, etc. It is projected to expand exponentially in the next few decades (Singh 2021).

Digital twins enable organizations to simulate and predict what will happen in the real world by incorporating sensor data and advanced analytics, which results in enhanced operational performance, less downtime and smarter strategic decisions (McKinsey and Company 2024). In addition to efficiency benefits, digital twin technology aids in ongoing process and product optimization by allowing products to undergo virtual testing and rapid iteration, enabling companies to launch products in the market sooner and of higher quality (Almawave, 2023). As a result, digital twins not only drive competitive advantage through operational improvements but also contribute to broader organizational goals such as sustainability and risk mitigation, solidifying their importance in the current digital transformation landscape (McKinsey & Company, 2024).

1.2 Problem Statement

Although much interest has been in motivating tourists and other shareholders involved to engage in sustainable tourist activities, there are a number of issues as well that are likely to occur due to a number of constraints. Some of these problems include transparency, economic

issues, cultural dynamics and predominantly some of the adverse consequences of the exposure of the project to the outside (Honey 2008).

Tourism destination sites around the world are under growing pressure to maintain a sustainable economic development and environmental conservation. Popular destinations face the threat of overcrowding and waste management issues, as well as the depletion of resources (Gössling et al., 2020). WWF (2021) notes that the indicators of environmental sustainability are moving downwards and a 2025 NEMA report reports that there is continued deforestation, pollution and biodiversity loss. ICG (2024) cautions that plastic waste is polluting tourist spots.

The major challenge is the absence of strong policies and enforcement in which poor regulations and silos of the bureaucracy make coordinated responses difficult. Visitors are being used by many areas as measures of success, resulting in overcrowding and strain on infrastructure without the consideration of carrying capacities or the suppression of emissions. An example of this is where inadequate stakeholder cooperation between governments, businesses and communities worsens greenwashing where superficial assertions take the place of practices that can be verified. (Kuscer & Schonherr 2024).

1.3 Research Objectives

1.3.1 General Objective

To determine the role of the digital twin technology in sustaining tourism practices of destination planning and management.

1.3.2 Specific Research Objectives

To analyse sustainable tourism practices in planning and management of destinations.

To study digital twin technologies.

To determine the potential of digital twin technologies in sustainable tourism practices.

1.4 Research Questions

What are the sustainable tourism practices used in destination planning and management?

What are the digital twin technologies?

How can digital twin technologies help sustainable tourism practices?

1.5 Justification of the study.

The areas of concern such as over tourism, environmental degradation, and poor management of resources continue to pose a critical challenge to sustainable tourism practices as discussed in the above policy gaps and economic barriers. This paper supports the investigation of the digital twin technology as an independent variable affecting sustainable tourism practices as a dependent variable, particularly in destination planning and management. Illustrating real-world destinations on virtual models, digital twins can provide predictive analytics and scenario testing to overcome these obstacles that always arise, and instead, proactive instead of reactive strategies are possible.

The technology of digital twins, the dynamic, data-integrated models of physical assets, have revolutionized such industries as manufacturing and urban planning to streamline operations and minimize waste. Digital twins can predict carrying capacities, simulate environmental effects, and simulate the management of crowds in tourism without experimentation in the real world since destinations are sensitive to variability in visitor numbers and climate conditions. To provide an example, by incorporating IoT sensors, AI analytics, and geospatial data, planners can visualize the emission savings of the preferred transport routes, or hotel water consumption, which can directly help sustainability objectives, such as lower carbon footprints and biodiversity conservation. The urgency is due to the increasing global pressures, post-pandemic recovery has increased the pressure on mass tourism, and climate change increases threats to coastal and natural destinations. Conventional planning instruments are inadequate to deal with the real-time complexities, and this results in imbalance where economic benefits sacrifice ecological and social pillars.

The gap in this research is that it quantifies the benefits of digital twins in decision-making, such as virtual stress-testing of infrastructure during peak seasons that may reduce implementation barriers such as high costs and inter-stakeholder conflicts as highlighted in the sustainability challenges in tourism. This research is relevant and effective, and it coincides with 2030 Agenda

objectives on sustainable development and new tendencies on smart tourism in 2026. It offers practical policy implications to policymakers, destination managers, and technologists and promotes sustainable, low impact tourism frameworks that encompass a balance between growth and planetary constraints.

1.6 Scope of the study.

1.6.1 Subject Scope

The research is based on the implementation of digital twin technology in the tourism destination and specifically the sustainable practices in destination planning and management. Although the technology can be implemented in various industries, the study will focus on how it is used in tourism business, visitor management, and ecological sustainability.

1.6.2 Geographical Scope

The study can contain case studies of some chosen tourism destinations that might implement the digital twin technology. An example Bwindi Impenetrable National Park, where visitor volumes (gorilla trekking permits sell out) are high, places undue strain on the ecosystem, thus digital twins can simulate flows, forecast habitat effects and optimize planning, which is also aligned with emerging IoT/CCTV pilots in parks.

1.6.3 Time Scope

The time frame, in which the researcher plans to conduct this research, is three months, which starts in October and finishes in January.

1.7 Importance of the research.

This research will allow the researcher to meet the criteria of receiving the Bachelor Degree, promote Sustainable Tourism Practices and fills Technology Gap in Developing Contexts

1.8 Conceptual Framework

The research design of the present study is a conceptual framework that is founded on the correlation between digital twin technology (independent variable) and sustainable tourism practices (dependent variable). Simulation, monitoring, and predictive model applications are

digital twin applications that are likely to affect the outcome of sustainability like conservation of the environment, efficiency of resources and increased visitor satisfaction. Technological capacity, cost of implementation and stakeholder engagement are mediating factors.

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

One of the chapters upon which research is anchored is literature review, which puts the research into a broader context of existing knowledge. This chapter examines the existing literature on the digital twin technology and its application in sustaining tourism practice especially in destination planning and management. The review is a synthesis of conceptual definitions, theoretical understanding, worldwide practices, and national and regional insights. It also evaluates empirical evidence, determines critical research gaps and gives context to the ongoing research within the larger academic discourse on technology enabled sustainable tourism.

2.1 Definition of terms

World Tourism Organization defines tourism as encompassing the activity of individuals who travel and spend some time in locations other than their usual environment not longer than one full year consecutively with the aim of leisure, business, and other reasons. The definition encompasses different elements of the travelling and activities involved, which are based on the temporary nature of the residence and being outside the normal set-up.

UN Environment Program and the UN World Tourism Organization (2005) define sustainable tourism as tourism that considers all the current and future economic, social and environmental impacts of the tourism sector and it addresses the needs of the visitors, the industry, the environment and the host communities.

Sustainable tourism behavior involves the activities and consumption patterns that encourage social, environmental and natural gains and reduce adverse effects (Alazaizeh et al., 2019).

Technology is everything in the form of tools, machines, utensils, weapons, instruments, habitation, clothing, communicating and transporting equipment and the craft of how we make them and use them (Read Bain 1937).

Digital Twin (DT) refers to the virtual copy or model of any physical entity (physical twin) both of which are interconnected via exchange of data in real time (Singh 2021).

2.2 Sustainable tourism in destination management and planning

Sustainable tourism, or tourism that balances economic gains with the preservation of natural and cultural resources and fair gains to the host society, has become the key to destination planning and management around the globe (Matiku, Zuwarimwe, and Tshipala, 2020). Sustainable tourism has become a critical paradigm in destination planning and management, which aims to balance economic viability, environmental integrity and sociocultural preservation. It is also an emerging trend as it has focused on the pitfalls of mass tourism such as over tourism and depletion of resources since the 1980s Brundtland Report. This review integrates major themes, frames, and empirical findings, based on systematic reviews and studies of cases to highlight ongoing gaps and new strategies (Fuchs 2022). Sustainable Livelihoods Approach (SLA) frameworks go further by considering destinations as capital assets, such as natural, human, social, financial, and need to be co-managed to address community wellbeing. GSTC Criteria offer international standards, giving priority to good planning, minimization of waste, and local advantages. Nevertheless, there is ambiguity in the concepts; the terms such as carrying capacity are different, which complicates the application of the concept in uniform (Pardo-López & Pardo-López 2024).

Destination planning incorporates sustainability through such tools as carrying capacity assessment and scenario modeling. Such indicators as ETIS (European Tourism Indicators System) allow tracking such pressures as the number of visitors per resident tolerance (Font et al., 2021). Participatory planning is promoted in literature, with local wisdom. Sustainable tourism is an opportunity and need in Uganda, where nature-based and cultural tourism (especially primate- and park-based tourism) are significant sources of foreign exchange (Mwaura, 2012). The themes that are recurrent in the literature on Uganda are the significance of governance and policy frameworks, central role of protected-area management and revenue-sharing, community involvement and benefit-sharing, carrying-capacity and visitor-management issues, and market diversification.

(domestic and regional) to build resilience (Sarkar et al., 2022). This review is a synthesis of academic, government and NGO publications (2010–2025) to define the current understanding of sustainable tourism practices in destination planning and management in Uganda and to determine gaps to guide future research and policy. The tripartite sustainable development framing, i.e., economic, socio-cultural and environmental sustainability, is taken as the paradigm of most studies and applied to tourism systems (i.e., destination as a human-environment system) (Miller & Delgado, 2023). In order to evaluate the results of sustainability, authors often refer to the notions of carrying capacity, stakeholder participation, adaptive governance, benefit-sharing (especially regarding the so-called protected areas), and community-based natural resource management (Blair, 2014; Mugyenyi et al., 2014). This theoretical agreement offers practical pointers (income diversification, perceptions of local benefit, ecological indicators, visitor impacts, governance transparency) applied throughout Uganda case studies (Snyman & Bricker, 2019).

2.2.1 Policy, institutional arrangements and governance

The planning tools and sector plans of Uganda directly refer to sustainability. Contribution of tourism to Vision 2040 and the need to have integrated planning, infrastructure and community engagement are described in the national Tourism Sector Development Plan (2015) and other government and donor publications (Republic of Uganda, Tourism Sector Development Plan). At operational level, the Uganda Wildlife Authority (UWA) oversees majority of the protected areas and has introduced projects providing a combination of conservation finance, visitor management, and community revenue sharing (e.g., Bwindi VMGP and related projects) (Sarkar et al., 2022). However, issues of governance such as fragmentation within ministries, low enforcement, and the lack of capacity on the local government level emerge again and again in reviews of policy implementation (McQuide et al., 2023).

2.2.2 Protected-area management and revenue-sharing: The Bwindi model

The most common site in literature on Uganda is the Bwindi Impenetrable National Park owing to its mountain gorilla tourism model (Laudati, 2010). Trade-offs have been noted within research and NGO reports of how high-value, low-volume gorilla permits, restrictive visitation policies, and revenuesharing agreements have facilitated conservation benefits along with community projects--yet not without trade-offs (Sabuhoro et al., 2017). Research indicates that permit income has been used to finance park management and community initiatives, yet distribution systems, benefit equity (between and within communities), as well as social effects (e.g., the loss of access to traditional resources) are controversial (Kegamba et al., 2023). The policy briefs and recent project documents highlight that better governance of revenue sharing and enhancing transparency of benefits is crucial to retain local support of conservation and sustainable destination management (Kegamba et al., 2023).

2.2.3 Impacts on livelihood and community participation

The literature emphasizes that sustainable destination management in Uganda needs to involve significant community involvement and have real livelihood gains. Bwindi, Lake Mburo and Mount Elgon case studies record activities like community tourism ventures, working as porters/guides, social welfare funded by revenues, and alternative livelihoods (beekeeping, coffee cooperatives) (Laudati, 2010). Empirical assessments have shown positive results, such as reduced poaching, support of conservation locally, and income growth in the household in certain settings, but also have shown a mix of unequal benefits, elite capture, and shorter sustainability of the enterprises when the enterprises lack markets or technical assistance (Lesorogol & Lesorogol, 2024). This leads to authors proposing the incorporation of enterprise development, capacity building, and market linkages in destination planning (Surmeier, 2020).

2.2.4 Visitor management, carrying capacity and environmental impacts

The management of visitors is an ongoing topic: unregulated visitation may damage trails, enhance human-wildlife interactions, and transmit disease (especially in the case of great apes) . The gorilla-tourism literature emphasizes group-size restrictions, health check-ups and

spatial zoning as controls- yet also cites the pressures of increasing demand (signals of permit prices and the general growth of tourism). According to a few studies, the ecological carrying-capacity assessment, monitoring plans, and contingency plans (zoning, seasonal restrictions, infrastructure criteria) should be part of destination plans to avoid irreversible effects (Costa et al., 2022). The recent news and conservation media replicate the conflict between the high population of gorillas and their low habitat, which explains the necessity of spatial planning outside the park (Plumptre et al., 2021).

2.2.5 Market diversification and economic sustainability

Literature highlights two interconnected concerns: dependence on a set of high-value products (gorilla trekking, safari circuits) introduces the risk of being vulnerable to shocks (COVID-19, travel restrictions), and domestic/regional tourism are not developed (Okello & Novelli, 2014). According to reports commissioned by business forums and tourism board, stimulus to domestic tourism, business-enabling reforms, better access to finance by small tourism enterprises, and investment in low impact infrastructure (roads, sanitation, waste management), as part of destination planning, are recommended to expand economic resilience (World Bank, 2025). Authors suggest pricing and allow policies that strike a balance between conservation finance and fair access and other income sources (e.g., community ecotourism products, cultural tourism) (Hodbod et al., 2019).

2.2.6 Cultural heritage, rights and inclusion

Cultural heritage and indigenous rights should also be taken care of in sustainable destination planning in Uganda. Groups (e.g., Batwa around Bwindi) displacement and disputed land use are popular topics of discussion in the literature. Participatory heritage management, restitution strategies, and benefit frameworks are among the concepts proposed by authors to put cultural restoration and inclusion in tourist narratives and businesses at the center of tourism (Kokunda et al., 2023). The lack of proper social protection also poses a risk of cultural commodification and social exclusion of tourism development.

2.2.7 Institutional partnerships, private sector and donor roles

NGOs, donors, and private operators have a role in the implementation of sustainable practices, which is documented in multiple studies through public- private partnership (ecolodges, community projects), conservation funding and technical assistance. Although these partnerships have delivered successful pilot projects, the literature raises concerns about sustainability risks when they are donormade and have no exit strategies or transfer of local capacity. Sustainability will need institutionalized processes, such as policy alignment, local capacity, and transparent financial flows, to entrench sustainability not just during pilot phases, but also on long-term destination management.

2.3 Digital twin technologies

Digital twin technology (DT) is a digital recreation of real-world systems that reflects the real time status, dynamics, and performance of a real world through data stream of sensors, IOT devices, artificial intelligence and cloud computing (Tao, Zhang, Liu, and Nee, 2019). The DT concept has its origin in the early product-life cycle work; Dr. Michael Grieves described the original manufacturing-based framing (physical product, virtual model, information linkage) which was subsequently generalized to cities, infrastructure and cultural assets. Modern models highlight three attributes that make DTs not a simple digital model, constant or regular connection with real-world information, analytic and simulation skills, and two-way feedback (virtual to physical) to control operations or make informed decisions. Research and practice summaries offer uniform taxonomies of DT components (sensors/IoT, data pipelines, simulation engines, visualization interfaces) that constitute the technical foundation of destination applications (Greives, 2014).

Digital twins offer a cyber-physical system in which data indicate real-life conditions and the stakeholders are able to monitor the operation, simulate, and assess possible situations without necessarily touching the physical aspect (Uhlemann, Lehmann, and Steinhilper, 2017). Digital twins, first created to improve product lifecycle and operational efficiency in the fields of manufacturing and engineering, are currently used in environmental monitoring, urban planning, and healthcare (Bruynseels, Santoni de Sio, and van den Hoven, 2018). DT

models can be used in tourism to model destinations virtually, such as their infrastructure, tourist flows, environmental factors, and cultural attractions, which allows the study of complex interactions between tourism subsystems (Zhang, Wang, and Li, 2021). It is not a static simulation since this living model is updated (in (near) real time) and may provide decisions or control signals back to the physical asset. The theoretical origins can be traced back to early product-lifecycle and simulation research. The model of physical space, virtual space and the information connection between the two developed by Grieves (2014) has become the basis of further literature.

With constantly connecting sensors, models, analytics and visualization, digital twins enable engineers and managers to observe systems in real time, simulate what-if, forecast failures, and close feedback loops between the virtual and the real world. This essay defines digital twins, their origin, key elements and functionalities, offers an overview of the primary applications in the industry, assesses their advantages and obstacles to implementation, and provides an overview of current trends and future projections. Michael Grieves (2014) is credited with formalising the concept, which has since been generalised by manufacturing, aerospace and health care researchers.

2.3.1 How Digital Twins Work and Components

The following layers are typically included in digital twin systems:

Physical asset and sensors include PLCs and measurement systems, IoT sensors, measure operational state.

Data and communication layer include Edge/cloud infrastructure passes and stores telemetry.

Modeling and simulation involves Physics based models, reduced-order models or learned models are reproducive of behavior.

Analytics and AI involves Machine learning and statistical analytics identify anomaly, forecast failure and optimize operation.

Visual and interfaces include Dashboards, 3-D visuals or AR/VR enable users to interact with the twin.

Control/feedback loop involves the outputs of the twin can cause controls or alarms in the physical system.

Sensors broadcast measurements into the data layer in operation, the virtual model is updated and analytics are run to generate diagnoses, forecasts or optimization suggestions; results are visualized and may be fed-back to the asset (closed-loop control) to take corrective action (Elias et al., 2022). Strong twins integrate various sources of data (CAD/BIM, historical logs, sensor telemetry) and often use edge processing to minimize latency on time-sensitive applications (Hasan and Crawford, 2025).

2.3.2 Key Applications Across Sectors

In manufacturing, Product-lifecycle management, virtual commissioning of production lines, and predictive maintenance are some of the uses of the digital twins. Researchers and practitioners present twin-based product design and service models that combine big data and lifecycle data to achieve manufacturing that is less wasteful and more sustainable (examples and models) (Machacek et al., 2025).

Aerospace and Transportation involves Fleet-scale twins are used by aircraft manufacturers and operators to monitor conditions, do prognostics and optimize operations. To illustrate, modern aerospace initiatives are integrating thousands of aircraft with analytics platforms in such a way that in-service information feeds personalised aircraft twins that aid in maintaining schedules and analysing the lifecycle (Moenck et al., 2024).

Healthcare and Biomedicine includes individualized diagnosis, surgical planning and continuous monitoring (through wearables and EHR data) are under investigation using patient-level digital twins, which are virtual models of whole-body physiology or organs. Despite the potential, clinical twins also increase the data-privacy and validation criteria to be met prior to common utilization (Rudsari et al., 2025).

In Infrastructure and Smart Cities, City-scale twins mimic the buildings, utilities, traffic, and environmental data to aid planning, emergency response, and energy optimization. High-resolution urban twins and other programs allow planners to model interventions virtually and enhance resilience and sustainability, prior to physical implementation (Hossain et al., 2026).

Active areas of adoption include energy grids, maritime operations, construction (digital building twins), agriculture and consumer products personalization, the literature indicates a wide cross-sector interest and numerous domain-specific architectures and pilot projects (Hasan & Crawford, 2025).

The adoption of digital twins provides various quantifiable benefits in operations, cost, decision-making and sustainability: by allowing continuous monitoring and predictive analytics, digital twins provide resiliency and uptime in operation and help extend the life of assets through reducing unplanned failures; virtual testing in the digital environment reduces prototyping and testing costs and speeds up time-to-market, allowing faster innovation; stakeholders can run scenarios and optimize These advantages are confirmed by academic reviews and case studies in the industry, which claim quantifiable ROI in manufacturing and fleet operations with the introduction of twins on a large scale (Gulewicz, 2022).

2.3.3 Challenges and Limitations

In spite of its promise, digital twins have a number of continuing obstacles: they require highquality, fully-integrated sensor and enterprise data poor data degrades model fidelity and causes mistrust in twin results (Zhang, 2022). Twin constructions and operations may also be expensive and technically challenging--software license, sensor deployment, storage, and continuous engineering and maintenance make them unaffordable to many small and medium enterprises (Fett et al., 2025). Connected twins serve as additional attack points on the cyberattacks and expand the privacy risk in sensitive areas, and it is vital to have an effective security infrastructure and compliance (Larmelina, Silva, and Risso, 2025). A multiplicity of proprietary platforms continues to limit interoperability, and standardization has been underway at organizations like Digital Twin Consortium and international standards bodies

like ISO, but cross-vendor integration has yet to be standardized to ensure universal standards (David et al., 2024). Lastly, successful twin programmes require interdisciplinary capabilities (domain professionals, data scientists, simulation and systems engineers) and organizational change in processes and governance-ability and cultural gaps that habitually slow adoption (Xames et al., 2025).

2.3.4 Trend and Future Prospect

Existing trends suggest a growing pace of maturation and wider application of digital twins spurred by four converging trends, increased integration of AI, where advanced machine learning and generative models enhance twins to allow autonomous optimization, more scenario generation, and adaptive decision support (Rudsari et al., 2025). Edge computing and pervasive low-latency connectivity (e.g. 5G) that moves computation and analytics nearer to assets to provide near-real-time feedback and control to critical systems. Increasing standardization and open systems, such as interoperable 3-D scene formats, shared data schemas that minimize vendor lock-in and make ecosystem expansion and broader domain dissemination easier (Petropoulos et al., 2025). With the reduction in tooling and compute costs, twins will likely expand outside manufacturing to buildings, power grids, health care and urban planning, and provide operational value to more and more diverse areas (Patel et al., 2025). In case of such trends, digital twins will become more of an infrastructure than a high-value pilot, as familiar as CAD and PLM systems.

Digital twin technologies combine sensing, modeling, analytics and visualization to generate living digital models of physical systems (Hasan & Crawford, 2025). Since their first conceptualization by Grieves (2014), twins have been demonstrated to be useful in the optimization of design, predictive maintenance and operational decision support. However, to achieve their full potential, data governance, security, standards and organizational capability must be paid attention to. To undergraduate researchers, as well as practitioners, digital twins can be viewed as an enabling architecture: carefully designed and managed, they provide an effective, data-driven route to safer, more efficient and more sustainable systems.

2.4 How digital twins technologies can help to facilitate sustainable tourism practices

Dynamic, data-driven virtual replicas of physical locations, assets or systems known as digital twin (DT) technologies are gaining interest as one of the means to assist in sustainable destination planning and management (Ali et al., 2025). A DT with tourism in mind can combine the geospatial models, sensor streams, visitor data and simulation engines to track carrying capacity, manage test management interventions (e.g., time-slotting, rerouting) and present the results to stakeholders (Vogklis, 2025). This review of literature combines peer-reviewed articles, practitioner reports and current case studies to demonstrate what is known about DTs as a tourism sustainability tool, (Alhaddar and Kummitha, 2025).

2.4.1 The role of digital twins in destination planning and management in terms of sustainability

The DTs are integrative surveillance solutions, combining environmental sensors (air quality, noise, structural strain), visitor tracking (ticket purchases, anonymized mobile users, turnstile data), and geospatial overlay (GIS/BIM/3-D scans) (Mao et al., 2026). It is this coupled perspective that allows managers to view spatially explicit cues of carrying capacity, environmental exposure, and infrastructure stress in near real time - a precondition to adaptive management and evidence-based policy. Empirical reviews dedicated to tourism indicate that monitoring is the most developed DT activity in the destination uses cases (Zuniga-Teran et al., 2019).

DTs with agent-based and discrete-event simulations enable managers to experiment with interventions (time-slot allocation, dynamic pricing, one-way routing) prior to making physical modifications (Karakra et al., 2025). The literature highlights the usefulness of DTs in what-if testing at site and city scales, allowing planners to measure potential densities of peak reductions, predict infrastructure bottlenecks, and trade-offs between social, environmental and economic goals (Bittencourt et al., 2026). Megacity twins are setting precedents of multi-agency scenario work that can (and must) include tourism as a sectoral contribution to transport and resource planning (Cohen, 2021).

Visitors and the conservation of heritage. Photogrammetry (high-fidelity digitization, LiDAR) facilitates conservation management and provides virtual access options that may ease the pressure on vulnerable sites posed by physical visits. Recent high-profile projects show how digitization both aids preservation and extends access — but also spark debate about governance, cultural ownership and commercialization of cultural data (Singh & Yadav, 2026).

2.4.2 Benefits observed

The literature reviewed can be summed up into a list of uniform advantages in the properly designed and regulated digital twins of sustainable tourism. They enhance situational awareness based on fine-grained, spatial-temporal monitoring of visitor pressure and environmental indicators, facilitate evidence-based intervention by enabling managers to simulate options and prevent the expensive trial and error, encourage conservation outcomes through early detection of structural degradation and provide virtual access to sensitive collections; and enhance cross-sector coordination through connecting tourism with transport, utilities and emergency planning to enhance resilience and resource efficiency. (Rahmadian, Feitosa, & Virantina, 2023).

A combination of conceptual arguments, practitioner case studies, and gradually but steadily increasing number of empirical pilots underpin these benefits (Sayles et al., 2019). The lack of quantitative, longitudinal evidence of better sustainability outcomes is a warning about these benefits (Sayles et al., 2019).

One of the key themes of the studies is that technological capacity is not an assurance of sustainable results. Governance policies, such as data-sharing contracts, open access policies, community engagement, and anti-privatization of cultural data, determine whether DTs can fulfill social sustainability objectives or cater to commercial agendas (Kukutai, 2023). The practitioner literature identifies the requirement of multi-agency governance frameworks of the city scale twins; tourism-specific reviews emphasize community acceptance, visitor privacy (anonymization and consent), and ethical stewardship of cultural digital doubles. Empirical studies of the public acceptance indicate mixed results but are rather skeptical:

tourists and residents favor DT-enabled interventions when advantages and protection are evident (Rahmadian, Feitosa, and Virantina, 2023).

The technical limitations that are often reported are: heterogeneous data formats (BIM, GIS, sensor streams), bandwidth/latency challenges to operate in real-time, tradeoffs between model fidelity and computational cost, and lack of universally adopted DT standards (Uslu, Okay, and Dursun, 2020). These concerns usually compel tourism projects to start with simplified site-level prototypes (offline or near-real-time synchronization) as opposed to fully continuous twins. Priority enablers of scalable destination DTs are reported to be standardization and open-data initiatives (Rahmadian, Feitosa, and Virantina, 2023).

2.5 Research gaps and implications

According to the literature, there are a number of gaps that can be realistically filled by an undergraduate study as providing new empirical evidence:

Measured sustainability performance. There are very limited studies that measure the effect of DT interventions on environmental indicators (erosion, noise, waste), or visitor behavior; a site-level study that simulates and (where possible) pilot an intervention can fill this gap (Settina, Marion, and Schwartz, 2020).

Short- to medium-term validation of outputs of simulation. Simulation of scenarios and comparison to measured post-intervention values (even small-scale) are rare and useful (Scrieciu et al., 2022).

Governance case studies. Recording the preferences of the stakeholders, data-sharing limitations and ethical requirements in a particular destination provide convenient policy recommendations (Acev et al., 2025).

Low-cost DT architectures of resource-constrained destinations. This is an engineering-social research undertaking that is traceable to develop and review lightweight DT prototypes (GIS + simple agent model + environmental sensors) with high applied significance (Karunaratne, 2025).

The literature presents digital twins as the potential, but still developing, set of tools to plan and manage a destination sustainably. The most significant direct tourism benefit of DTs is integrative monitoring, simulation-driven policy testing and conservation support (Rahmadian, Feitosa, and Virantina, 2023). Nevertheless, to achieve such value, it is important to note that efforts to governance, privacy, interoperability and resource constraints should be considered, and therefore, contributions to the field, such as prototype assessment of DT-enabled interventions at site scale and empirical recording of governance and stakeholder acceptance, are feasible and impactful steps that would bring the field beyond conceptual promise to tested practice (Veronese et al., 2023).

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Research Design

This paper is a qualitative and descriptive research study that utilizes systematic document analysis as the only source of data-collection technique. The kind of analysis that should be employed is the document analysis since the research purpose is to synthesize existing knowledge, policies and practice relating to digital twin technologies and their relevance to sustainable tourism planning and management. The design is a synthesis of a systematic literature survey (peer-reviewed journals and conference papers), and a systematic analysis of grey literature (policy documents, management plans, NGO and donor reports, technical white papers and industry case studies). The method focuses on the clear choice and replicable analytic methods to the extent that the results can be critically evaluated and, in case of necessity, revised by the future researchers.

3.2 Study Area

The study documents were chosen to provide international context as well as practical application to the issue of protected-area tourism management with special emphasis upon practice at the site level in the field site, Bwindi Impenetrable National Park and the national policy environment of Uganda. This two-fold focus enables the study to compare global

conceptual and technical advances in digital twins with locally pertinent governance, management and community involvement issues that inform sustainable tourism outcomes.

3.3 Search and data sources

Three complementary streams were used as sources; Academic literature which includes electronic databases were searched (e.g., Scopus, Web of Science, and Google Scholar), Policy and institutional documents which includes national tourism and environment strategies, plans to manage the protected areas, and public reports by the authorities of the parks and government agencies, Practitioner and industry material including technical white papers, consultancy reports and case studies of industry and non-governmental organisations (grey literature), Search terms and selection criteria involving publications in the last 10-25 years to reflect recent developments and policies in English language with combinations of keywords including digital twin, virtual replica, sustainable tourism, destination management, carrying capacity, visitor management, protected area, and the name of the research location. It was enlarged using a broader coverage with the help of the Boolean logic and wildcard (e.g., digital twin and tourism).

The Inclusion criteria involves the papers that clearly discuss the topic of the digital twin technologies (conceptual, technical or applied), papers that discuss the topic of sustainable tourism practice or destination management, and site-level management plans or monitoring reports concerning the study area are included.

The Exclusion criteria includes documents out of the date range, documents only on the purely commercial product brochures without the methodological detail, sources lacking sufficient methodological transparency.

The selection process involved application of the PRISMA style of flow; identification (database and web search), screening (title and abstract/summary), eligibility (full-text review in compliance with inclusion criteria), and inclusion. Each stage had a log of reasons why an individual had been excluded in order to achieve transparency and reproducibility.

3.4 Data sampling and dataset

A final dataset was generated as a result of a purposive sampling strategy that consisted of Core scholarly articles that constitute conceptual and empirical foundation (systematic and narrative reviews, empirical pilots, methodological papers), National and local policy documents and management plans pertaining to tourism and protected-area management, Representative grey literature (industry case studies, technical notes and donor evaluations) outlining applied digital twins initiatives or similar monitoring/simulation solutions.

The following metadata was recorded in a study register for each of the included documents: author(s), year, document type, source, geographic focus, stated aims, methods (when empirical), key findings, and relevance to the research questions of the study.

3.5 Procedure of data extraction and analysis

Similar information in each document was obtained through a structured extraction template. Key topics; document provenance, conceptual definitions, reported elements of digital twins, reported use-cases in tourism or other related industries, methodological specifics of the empirical research, governance and ethical commentary, reported advantages and drawbacks, and research gaps.

The analysis was a mix of directed content analysis and thematic analysis in two connected steps:

The research questions and categories of concepts were conceptualized in Chapter 2 provided a first codebook (e.g., monitoring, simulation, conservation outcomes, governance, interoperability, costs).

In the process of review, new themes not reflected in the original codebook were incorporated (e.g., particular local governance bottlenecks, community consent mechanisms, low-cost sensor architectures).

Coding was carried out with the help of qualitative analysis software (where software was not accessible, systematic manual coding with the help of spreadsheets).

The coded data were synthesized into thematic matrices, which cross-tabulated document type and theme (e.g., policy vs empirical study on governance issues).

Where feasible, quantitative measures of the content were elicited (frequency of themes, geographic distribution of case studies) to give a descriptive background to the qualitative synthesis.

Two validation steps were used to increase analytic rigor: (a) an intra-coder consistency check where a sample (≈20%) of coded documents was re-coded after a two-week interval to test stability of coding; and (b) peer debriefing with a supervisor or colleague to review emerging themes and interpretations. In case of having a number of coders, inter-coder agreement statistics (Cohen kappa) were computed to measure reliability.

3.6 Trustworthiness, reliability and validity

The study uses conventional qualitative protective measures to make it credible and dependable. Triangulation was done by Fusing academic, policy and practitioner data to cross-check assertions and minimize bias to single sources. A detailed log of search requests, inclusion/exclusion decisions and coding alterations was created so that it can be reproduced. Recording what the researcher assumes and the ways they might have impacted document interpretation and transparency to allow assessment of transferability by readers by reporting criteria in selection, coding framework and limitations in Chapter 3.

3.7 Ethical considerations

This study solely depends on the secondary and publicly available sources. The areas of concern revolving around ethical concerns are proper usage and presentation of source material, proper citation and proper paraphrasing of all documents referred to, respecting copyright, and handling sensitive information (e.g., community data presented in donor evaluations). A process of granting permission and acknowledgement is followed when unpublished or restricted documents are consulted.

3.8 Limitations of the method

Document analysis has its strengths (breadth, access to policy and historical records) as well as limitations like Pilot projects that find positive effects will be more commonly reported and perceived efficacy will be distorted. Practice can have changed over time, so the results represent the publication evidence up to 2025. The limitation to English documents can exclude any local reports that are in other languages. Changeable quality of grey literature where variable methodological transparency of industry and donor reports should be interpreted with caution and as such quality appraisal criteria are employed in the selection and synthesis phases.

3.9 Deliverables from Chapter 3 procedures

Using the above procedure, the result is a reproducible document register (appendix) of all sources and extraction fields included, a document (codebook and thematic matrices (appendix)) of the way data were categorized and an analytic narrative (Chapters 4 and 5) where synthesized results are presented using exemplary quotations, summary tables, and in visibly suitable cases, a conceptual framework that would connect the functions of DT to the results of sustainable tourism.

3.10 Conclusion

Chapter 3 outlined a clear systematic and repeatable methodology that had a focus on document analysis. The systematic search and purposive sampling, followed by the systematic extraction and integrated deductive-inductive analysis, provide the study with the capability to credibly chart the conceptual landscape, evaluate the empirical evidence and outline actionable research gaps applicable to the application of digital twin technologies in sustainable destination planning and management.

CHAPTER FOUR

ANALYSIS AND INTERPRETATION OF DATA-PRESENTATION

4.1 Introduction

The analysis of the documents resulted in a purposive dataset that was a combination of peer-reviewed articles, technical white papers, industry reports, policy documents and management plans (see Appendix A). The selection of materials was given priority to those that directly covered the concept of digital twins or those that outlined monitoring and simulation systems that could be used in destination management. Throughout the corpus, three general orientations were clear: (1) conceptual and taxonomic literature defining the components and architectures of the system; (2) technical/engineering commentaries and pilot reports defining the design of the system and prototypes; (3) policy, management and conservation literature that situates technological choices within the framework of governance and community. These orientations influenced the literature in which the benefits, limitations, and challenges to implementation were framed and influenced the coding and synthesis to be reported below.

4.2 Document analysis as thematic results

The analysis grouped results into seven major themes that directly correspond to research questions and categories of the codebook of the study: monitoring, simulation, conservation/heritage, governance and ethics, interoperability and standards, cost and accessibility and validation and evidence. Below, each theme is summarized and evidence synthesized to support it based on the register.

4.3 Scenario and simulation testing

The most common suggestions on how DTs assist policy testing include simulation capabilities, agent-based models, discrete-event simulations and system-dynamics formulations. The time-slot allocations, routing options, and dynamic pricing experiments are examples of exercises that are described in pilot documents and methodological papers (A2, A11). Simulations are most commonly applied in the literature to short-term visitor-flow

management and infrastructure stress testing. Less documentation provides city level, multi-agency scenario exercises involving utilities and transport together.

4.4 Conservation, heritage digitization and visitor substitution

High-fidelity digitization (LiDAR, photogrammetry) is offered as a two-fold conservation and access approach: it allows tracking of the structure and offers virtual alternatives that can take the burden of visitation on sensitive sources (A12). Case studies demonstrate that digitization facilitates condition assessment (crack growth, surface erosion), and provides avenues to engage with the public remotely. Nonetheless, there are also a number of sources that question cultural ownership, commodification of digital heritage, and the necessity of community consent frameworks.

4.5 Governance, ethics and stakeholder acceptance

Policy and practitioner sources reveal governance and ethics as decisional factors in whether DT deployments contribute to sustainability objectives. Themes in governance relate to data-sharing contracts, visibility of access and revenue sharing, anonymity and privacy of visitor telemetry, and ways of involving the community in design and benefit distribution. Policies and conservation sector reports consistently warn that even technological capacity is not the panacea to fair results; social protection and institutionalized governance frameworks are needed to guarantee local acceptance and legitimacy (see A6, A7).

4.6 Interoperability, standards and vendor lock in

Repeated technical limitations are interoperability and standards. A number of technical white papers and consortium outputs emphasize the importance of having common data schemas and 3-D scene standards to prevent vendor lock-in and to be able to cross-platform integrate (such as the Digital Twin Consortium guidance). In practice, simplified or proprietary stacks are used by a large number of pilots to provide functionality in the near term; this expedient decision, though, poses longer-term scaling and maintainability challenges.

4.7 Costs, business case and low resource access

Prices and affordability are the most eminent barriers to adoption. Case studies and industry reports (e.g., A4, A10) give opposing views: big-scale manufacturing and fleet twins report a quantifiable ROI in large-scale deployment, whereas low-resource destinations have high initial sensor and data storage and human resource requirements. A number of documents suggest low-cost architectures (Raspberry Pi-class edge nodes, simplified agent models) as a plausible option to resource-constrained sites, although they highlight trade-offs of fidelity and real-time capability.

4.8 validation, evidence of impact and methodological gaps

One uniformity is the lack of strong, longitudinal validation studies that measure the impact of DT interventions on sustainability outcomes (environmental indicators, visitor behavior, community wellbeing). Systematic reviews of the corpus (A9) and selected field-based studies (A11) indicate that although pilots report an improvement in operations (enhanced situational awareness, decreased response times), not many of them compare the predicted simulation outputs and post intervention observations rigorously. This puts confidence in scale-up as well as in assertions regarding better conservation or socio-economic performance in doubt. 4.9 Site-level and national contextual discoveries: Bwindi Impenetrable National Park.

The national policy materials and site-level documents in the register (management plans, national sector strategies and conservation reports) show that there are an apparent set of priorities and constraints that are applicable to DT adoption at the study site:

Park management focuses on high-value, low-volume, and controlled tourism; health screening and group-size regulation in gorilla trekking; and a system of revenue sharing to maintain community support. Monitoring (visitor flows, health indicators, trail conditions) is an urgent, high-value application of DT concepts, as these operational priorities.

Current revenue-sharing schemes and community projects form institutional avenues of reinvesting technology dividends, yet documents also reveal persistent governance failures:

local inability to conduct technical maintenance, unequal distribution of benefits, and laxity at sub-national tiers.

Connection, power availability and cost containment are mentioned multiple times; these constraints are conducive to lightweight, offline-capable DT architectures, and incremental pilots, as opposed to full continuous twins.

biological and cultural sensitivities of the park further support the concept of non-intrusive monitoring, high levels of privacy, and co-design with communities, especially where the digitization of cultural objects is suggested.

Combined, the evidence of the site and the nation suggests a stepwise adoption pathway of DT, starting with monitoring pilots, which respond to immediate operational demands, matching pilots with governance systems, which formalize data stewardship and benefit-flow, and iterating to small simulation capability, which is verified through observed results.

4.10 Practical and research implications

The implication on the findings can be of particular value to the destination managers and researchers based on the findings.

Practical implications (to site managers and policymakers)

Priorities monitor pilots with low risks that answer well-known management questions (e.g. maximum visitor numbers, areas of trail erosion), and that pilots contain straightforward maintenance plans and local capacity elements.

Couple technology pilots with data-sharing agreements and transparent benefit distribution plans in such a way that community stakeholders realize visible benefits.

Where possible, use open or documented data schema to minimize future vendor lock-in, and enable gradual integration with transport or utility systems.

4.11 Summary

Chapter 4 summarizes the analysis of the documents into practical findings. The most developed and directly applicable DT features in implementing sustainability practices in destination management and planning are monitoring functions. The possibilities of simulation and digitization are high but need to be validated and carefully governed. The binding constraints and evidence that connects DTs to long-term sustainability outcomes are limited, and interoperability and cost. In the case of a site like the one under study, an incremental and governance-based strategy that emphasizes pilots monitoring with integrated assessment is the most feasible route to go through the concept-to-practice continuum.

CHAPTER FIVE

DISCUSSIONS, CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

The analysis of the documents (Chapter 4) shows that there is a definite and regular pattern. The concepts and pilots of digital-twin (DT) generate the most reliable operational value when they are initially founded on specific monitoring capabilities and coupled with specific governance mechanisms. Monitoring represents the least risky, most valuable entry point since it directly aligns with current management activities (visitor counts, trail condition, structural monitoring) and involves relatively small modelling and integration work. Simulation and high-fidelity digitization offer systemic benefits (scenario testing, visitor substitution, heritage conservation) but the corpus reveals that these functions are conditional on three conditions. Data quality and integration, governance structures that cover privacy, data sharing and benefit distribution, and rigorous validation which connects model output and observed results.

There are two tensions that are distinguished and determine trade-offs in practice. First, fidelity vs. cost. High-resolution twins (LiDAR, continuous streams) have greater analytical capability, but require high initial and ongoing investment and maintenance overheads that many protected-area managers cannot afford without external assistance. Second, technology vs. legitimacy. Even technically high-quality pilots may fail, or deliver perverse results when communities, regulators or other stakeholders are not part of data governance and benefit-sharing deals. Such tensions justify why a lot of tourism-relevant DT work in the corpus will use pragmatic, site-level prototypes or hybrid architectures (edge preprocessing + periodic cloud sync) and not try to go to full continuous, city-scale twins.

Lastly, there is a methodological gap in the corpus. The scarcity of longitudinal validation studies and dearth of quantitative studies indicating that the DT interventions lead to quantifiable effects on environmental, socio-economic or cultural outcomes. There are numerous accounts of operational efficiencies or increased situational awareness. Much fewer document sustained decreases in erosion, quantifiable changes in visitor behavior or

long-term changes in local livelihoods attributable to DT-enabling interventions. That is the gap that limits the uptake of policies and investor confidence.

5.2 Conclusions

In the case of resource-constrained destinations and/or protected areas (including the study site), the sensor-based monitoring is the most viable route to early value capture to address particular management questions.

Governance defines whether DTs can be used to meet public sustainability purposes. Critical enablers are data-sharing agreements, transparency, community co-design and benefit distribution mechanisms; technology in the absence of governance may become an entrenchment of inequality or yield contested results.

Interoperability and low-cost architectures are important scaling requirements. Schemas Open data schema and a documented system design minimizes vendor lock-in and enables incremental integration with transport, utilities and emergency services.

The literature pinpoints viable empirical methods (pre-intervention, pilot-validation procedures) that can generate the unavailable causal proof of the connection between DT interventions and sustainability results.

5.3 Practical suggestions (to practitioners and policymakers)

Start with tightly focused monitoring pilots answering operationally significant questions (e.g., peak-hour visitor density, trail erosion triggers, basic health-screening compliance). Ensure pilots specify success metrics up front. Make intermittent connectivity and local maintenance capacity with modular, documented stacks (edge nodes + periodic cloud sync). Prefer open data formats and document APIs to minimize future vendor lock-in.

Write down clear data-sharing contracts prior to sensor deployment specifying ownership, anonymization will be imposed, and access requests will be processed.

Integrate community co-design and benefit contracts within project governance where local representatives would be involved in the choice of indicators, data-access policies, and investment options to reinvest revenue.

Institute open reporting systems to enable management, communities, and donors to evaluate outcomes and budget associated with DT activities.

Pair technology deployment with capacity-building (local technician training, simple maintenance manuals, basic data-literacy workshops for managers).

Build simple maintenance budgets into project proposals (sensor replacement, power, connectivity) and explore pooled procurement or regional maintenance hubs with neighboring sites.

Provide validation plans during pilot design: provide reserves to gather independent groundtruth data and calculate standard validation measures (e.g., RMSE, precision/recall on detection tasks, percent deviation in predicted and observed peak density).

Seek multi-stakeholder collaboration (park authorities, local government, universities, NGOs and private vendors) to share costs and technical risk.

Explore the hybrid financing options: small-scale donor grants to pilot projects; small amounts of user fees; and conservation levy or permit revenue reinvestment.

5.4 Recommendations for research

Design before/after or stepped-wedge assessments that compare the results of the simulation to actual results (e.g., predicted vs. observed visitor flows or erosion measures). Report measures of standard error as well as effect sizes in order to develop similar evidences.

Create and release engineering analyses of lightweight DT stacks (Raspberry-class edge nodes, power-saving LoRa sensors, simplified agent models) that explicitly quantify fidelity-cost trade-offs and maintenance overhead.

Carry out a qualitative study of data governance, consent of stakeholders, distribution of benefits and cultural ownership of digital heritage resources in particular destinations.

Introduce and record pilots with open schemas (e.g., CityGML/IFC or similar tourism-relevant formats) and quantify integration work and payoffs in terms of linking transport, utilities and emergency services.

Integrate the quantitative measures of performance with qualitative inquiry of community acceptance and institutional preparedness to learn how technical results can be converted to social impact.

Suggested indicators for empirical work can include reducing Erosion rate (m 3/year or relative trail degradation index), change in vegetation cover (percent), water quality indicators where appropriate, observing peak density (visitors/hour per hotspot), average time at hotspot, route/health rule compliance, sharing of permit revenues to community projects (%), household income alters to those involved in tourism enterprises and using RMSE or MAE on continuous predictions, precision/recall on event detection tasks, percentage reduction in predicted and observed peak density post intervention.

5.5 Limitations of the study

The research is based on purposive document analysis (20102025) and thus represents the reporting and availability of documented projects. Pilots or local project reports, which are in non-English languages and are not published, could be underrepresented.

The document-analysis approach offers a breadth and policy context but does not directly quantify on-site results; therefore, allegations regarding local viability ought to be experimented with site pilots.

The corpus combines peer-reviewed articles, industry reports and white papers. Grey literature in terms of variable methodological transparency must be carefully interpreted and constrains the simple aggregation of meta-analytic aggregation.

5.6 Directions for implementation at the study site

In the case of Bwindi Impenetrable National Park, a practical program which is incremental and governance conscious would comprise three practical steps:

Pilot monitoring which would involve choosing 1-2 high-priority operation questions (e.g., distribution of visitor arrivals by time; hot-spots of trail erosion). Deploy low-cost sensors and a simple dashboard. Co-design local stakeholder's data access and reuse guidelines.

Operate the pilot until you have ground-truth data and you have validated the model outputs, and tuned the sensors/algorithms based on the observed behavior. Post transparency (short note on method and validation metrics).

On validation of value, increase monitoring to more locations, introduce specific simulation (e.g., agent-based routing during peak hours), and institutionalize multi-party governance systems to long-term data stewardship.

(Capacity-building, maintenance budgeting and a written governance tool should be entrenched with each phase)

5.7 Final remarks

The digital twins are an enabler architecture and not a solution in itself. In the case of such destinations as the study site, their immediate usefulness is in enhanced situational awareness and low risk simulation that facilitates superior operational decisions. The practitioners should combine small, highly tested technical pilots with transparent governance, engagement with communities and the dedication to open and interoperable design of the system to achieve sustainability benefits at scale. Such a move will transform theoretical potential into quantifiable conservation, social and economic results and yield the empirical data base (validation measures, cost-effectiveness data and governance case studies) to promptly transition DTs out of pilots into the wider practice.

APPENDIX

Appendix A - Codebook for document analysis (draft)

The aim of the codebook operationalizes deductive themes of the research questions and the inductive ones that occurred during scoping. It directed uniform extraction and coding of documents.

Code	Definition	Inclusion Criteria	Exclusion Criteria	Examples	Value Type	Notes
MONITORING	Sensor-based or telemetry monitoring for visitor, environmental, or infrastructure indicators.	Sensors, dashboards, real-time monitoring, telemetry frequency.	Generic phrases without data/process detail.	visitor counts; air quality sensors; real-time dashboard	Categorical	Capture instrument types (CCTV, Bluetooth, sensors).
SIMULATION	Simulation or modelling functions for policy or scenario analysis.	Agent-based, discrete event, system dynamics models.	High-level scenarios without modelling methods.	agent-based model; time-slotting simulation	Categorical + Free text	Record model scale if stated.
CONSERVATIO	Digital	Structural	Generic	LiDAR	Categori	Note

N	twin support for conservation and heritage protection.	monitoring, LiDAR, erosion tracking.	sustainability language.	scan; structural strain detection	cal + Free text	ethical/ownership concerns.
INTEROPERABILITY	Standards, formats, and cross-platform data exchange.	ISO, APIs, CityGML, IFC, vendor lock-in.	Unapplied mentions of standards.	Digital Twin Consortium; open API	Categorical + Free text	Record standards used.
COST & ACCESSIBILITY	Costs and affordability in resource-constrained contexts.	Cost figures, SMEs, low-cost architectures.	Unsupported claims of expense.	TCO; Raspberry Pi sensors	Categorical + Numeric	Record currency and year.
GOVERNANCE & ETHICS	Data ownership, privacy, consent, and participation.	Data-sharing, consent, governance models.	Vague governance mentions.	data-sharing agreement; benefit-sharing	Categorical + Free text	Note stakeholders and power dynamics.
VALIDATION &	Validation	Pilot	No	validated	Categori	Note time

EVIDENCE	comparing model outputs to real data.	studies, error metrics, cross-validation	empirical validation.	results; RMSE reported	cal + Numeric	scope.
DOMAIN / SECTOR	Primary sector focus.	Explicit or implied sector.	No sectoral anchor.	tourism; protected area	Categorical	Multiple sectors allowed.
METHODOLOGY	Research method used.	Case studies, policy reviews, evaluations.	No methodology detail.	case study; policy review	Categorical	Used for synthesis grouping.

Coding protocol and quality control where all the documents are read and coded with the complete codebook. On long documents, section level code and document level flags.

Take out a brief quotation (not more than 40 words) and page/section on each coded theme. Extraction table: store quotations. Inter-coder reliability, a second coder is used to code a 20% random sample of the codes independently; calculate Cohens kappa with primary binary codes. (monitoring, simulation, conservation, interoperability, governance). target kappa $\geq$ 0.70.

Appendix B - Methods flowchart (brief)

Below is a concise, dissertation-ready methods flow representation suitable for inclusion as a one-panel figure or slide. Use this as a blueprint for a simple flowchart graphic (e.g., to be redrawn in PowerPoint or drawing software).

Define scope & research questions

Develop search strategy (databases, grey literature, keywords, timeframe 2010–2025)

Identification (database + web searches)

Screening (title/abstract/summary filtering)

Eligibility (full-text review against inclusion/exclusion criteria)

Inclusion (final document set)

Data extraction (structured template: bibliographic metadata, methods, findings, codes)

Coding & analysis (deductive codebook, inductive theme addition; thematic matrices)

Validation & QA (intra-coder check; peer debriefing; inter-coder reliability where applicable)

Synthesis & reporting (narrative synthesis, tables, conceptual linkages, identified gaps).

Figure caption (suggested): Methods flowchart for systematic document analysis showing the sequence from scoping and search through screening, coding and synthesis (2010–2025 coverage).

Deliverables produced in this appendix

Formatted document register (summary table above). The full register with all extraction fields can be exported into a spreadsheet for Annex 1 on request.

Draft codebook (operationalized table above) ready for application and reproducibility checks.

Compact methods flowchart (text blueprint above) suitable for conversion into a onepanel figure.

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