Integrating digital twin technology for dual goals: sustainable heritage management and environmental sustainability in Bangladesh to attain SDGs 11 and 13

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Abstract. ***Objective:*** *The main aim of this study is to go beyond digital replication and suggest a framework to create "dual-purpose" digital twins. These models are thus designed not only for visualisation and virtual access but also to optimise the efficiency of resources, minimise the environmental impact, and become an instrument for sustainable heritage capitalisation.* ***Method:*** *The study adopts qualitative thematic analysis using primary interviews with heritage experts and secondary sources on sustainable heritage management. It integrates best practices in green heritage management, digital twins, and environmental monitoring. IoT sensor data, including temperature, humidity, and structural stress, will support simulations for energy optimization and predictive maintenance.* ***Results:*** *The outcomes of this study led to a new practical framework for the implementation of a dual-purpose digital twin. The key findings show that this strategy may result in a quantifiable decrease in the environmental impact of heritage management through (1) energy-optimised preservation climate, (2) proactive conservation measures, which cut down on material waste, and (3) encouragement of high-fidelity virtual tours that contribute to over tourism, as an alternative to physical tourism. This shows a direct association between green outcomes and digital innovation.* ***Originality:*** *Novelty should be attributed to the fact that the study shows how digitalisation has become strategic and sustainable-oriented in approach to the management of heritage. Based on Public Goods Theory, it frames a digital twin as a tool for economy that can solve problems of underinvestment, optimise resource usage and can be beneficial for cultural infrastructure to tackle market failures. The plan for the project incorporates sustainable economic capitalisation and conservation science.*

Keywords: *sustainable heritage, digital twin, predictive maintenance, green transition, heritage capitalization, virtual tourism, energy efficiency.*
JEL Classification: O33, Q54, Z32.

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1. Introduction

The complex nature of the preservation of cultural resources and the satisfaction of the current needs of sustainability and technological absorption are becoming challenges in heritage management (Grey & Kuokkanen, 2020; Hou et al., 2024; Mihai et al., 2022). There are also good opportunities to enhance the efficiency and sustainability of heritage sites with newly developed technological advances, particularly with Digital Twin technology (Karatzas et al., 2024). To control heritage sites in a more proactive way, real objects can be monitored, simulated, and tuned using virtual models of real objects (digital twins) (Rasheed et al., 2020).

Over the past few years, a number of studies have seen the promise of Digital Twin technology in the conservation of cultural heritage, such as predictive maintenance, optimisation of energy use, and carbon emissions (Jouan & Hallot, 2020; Luther et al., 2023). The necessity to introduce innovative conservation technologies is justified by the fact that the number of cultural heritage sites under threat due to climate change and human activity reaches more than 100,000 globally, as a 2024 report by UNESCO explains (Meskell & Isakhan, 2024). Due to the nature of the two questions of cultural heritage conservation and addressing climate change, the concept of Digital Twin integration in heritage management can offer the opportunity to come up with sustainable solutions (Laohaviraphap & Waroonkun, 2024).

Nevertheless, even with such promising developments, there is a research gap regarding the practical implementation of Digital Twin technology in heritage management, especially regarding issues of policy enablement, capacity gaps, and barriers to capital expenditure (Mazzetto, 2024; Karunaratne et al., 2025). The available literature on it majorly concentrates on the technological facet and does not give the wider implications of the technology on the community impact and economic feasibility (Al-Emran, 2023; Maté-González et al., 2025). This study aims to fill this gap by discussing how Digital Twins can be applied to sustainable heritage management, particularly the incorporation of Internet of Things (IoT) sensors, predictive maintenance, and virtual tourism (Rahmadian et al., 2023; Shehata et al., 2024; Wang et al., 2025; Guo et al., 2024). Based on the research gaps mentioned above, the following research questions are addressed in this study:

-What are the possible ways of applying dual-purpose digital twin technology to heritage management to foster sustainability and reduce environmental footprints?

- What are the impediments to the implementation of digital twins in heritage sites for dual purposes?

Based on the research questions, the following research objectives were set:

- To investigate the applications of dual-purpose digital twin technology at heritage sites.

- To explore the impact of digital twin technology on sustainability and minimisation of environmental footprints.

To determine the barriers to and enablers of digital twin adoption in heritage management.

The current research has several contributions to heritage establishments such as from the standpoint of public economics, heritage assets (infrastructures) can be shown as quasi-public goods shaped by limited excludability, non-rivalry, and capacity to production of externalities related to positive culture. Conventional management related to heritage infrastructure in Bangladesh is marked by a mismatch among the required information, weak pricing mechanisms, and persistent underinvestment - challenges that are particularly frequent in developing economies. This study advances the uniqueness of adding digital twin technology as an economic and institutional instrument that helps mitigate asymmetries of information, strengthen efficiency in resource allocation, and sustainably promote heritage capitalisation development, considering a long-term development framework.

2. Literature review

The recent period has witnessed the emergence of Digital Twin (DT) technology that has become an important aspect of heritage management due to technological progress, artificial intelligence, and IoT sensors (Abdelalim et al., 2025). It has also become an inseparable part of heritage management through reinforcing and increasing efficiency, sustainability, and accessibility (Labadi et

al., 2021). A Digital Twin (DT) may be useful not only in the collection of data but also in the generation of accurate information, constant updates, and simulating and visualisation of data by combining 3D modelling with the Internet of Things (IoT) and real-time data sharing (Jiang et al., 2021). It has become among the most significant innovations in cultural heritage sites and landscapes. According to recent studies, the Digital Twin (DT) has been applied to energy optimisation, carbon emission, sustainable conservation, and virtual tourism, minimising the difficulty and limitations of heritage management (Arsecularatne et al., 2024; Sarigul & Gunaydin, 2025).

2.1 Energy optimization and carbon reduction

Numerous studies have advanced the capability of decreasing the amount of energy utilised by Digital Twin (DT) technology (Barenji et al., 2021; Fathy et al., 2021). Iqbal & Mirzabeigi (2025) justified that Building Information Modelling (BIM) and the Internet of Things (IoT) can help to optimise the control over the inner world and to save on energy usage in heritage buildings, and these prospects have been fulfilled with Digital Twin (DT) technology. Their research study produced an insight that through the observation of the humidity, temperature, and lighting of the interior environment, IoT sensors and a real-time sharing model can be used to analyze the information and control the total environment within cultural heritage locations (Akter, 2026a; Iqbal & Mirzabeigi, 2025). In this respect, Kavousi-Fard et al. (2024) clarified that Digital Twin is energy-saving because it monitors the HVAC system, predicts data, and interacts with renewable energetic resources (solar, wind, or other sustainable resources). This may be emphasized because the participants of this study could identify that predictive maintenance and intelligent climate control allow Digital Twin to save energy (Falekas & Karlis, 2021; Hu et al., 2023; Ohueri et al., 2025).

Another significant benefit of employing a Digital Twin is that it assists in the reduction of carbon emissions. As explained by Chen et al. (2024); Liu and Zhang (2024); Wang & Wang (2024) to minimize carbon emissions in heritage sites or landscapes means reducing wastages and using more green or renewable energy Digital Twin is helping to cut the carbon emissions. With the implementation of digital twins, it will be possible to pursue the goals of Sustainable Development Goals (SDG-12) by integrating them with renewable sources (Mahbub & Akter, 2026; Omrany et al., 2024; Patel et al., 2024). The results of the present study suggest that a Digital Twin can be used to minimize the carbon footprint of heritage buildings with the help of efficient resource management (Kaewunruen et al., 2025).

2.2 Predictive maintenance and structural integrity

Digital Twin (DT) technology in predictive maintenance is a proactive solution that can be used to preserve the structural integrity of historic buildings (Kong & Hucks, 2023; Salzano et al., 2025; Wang et al., 2025). Gbadamosi et al., (2021) have established that since it is a proactive strategy it predicts the degradation, breakage or any sort of early indicators and aids in undertaking maintenance in due time. The problem can be proactively analysed with the help of IoT sensors and a real-time model (Villegas et al., 2024). This strategy is also enlightening because it can help solve the problems of any form of environmental deterioration of heritage sites (Coombes & Viles, 2021).

One of the key benefits of Digital Twin technology was discovered in this study, and this is predictive maintenance. The participants also observed that it can undertake proactive steps that to assist the managers of heritage sites to avoid the expenses (Mihai et al., 2022). Yu & He (2022) elaborated that it is not possible to survive all forms of natural disasters through many buildings or structures, and that is where the predictive maintenance of a Digital Twin comes in to overcome any form of damage to such locations. The sustainability, stability, and safety of cultural heritage are guaranteed by the capacity for proactive measures.

2.3 Virtual tourism and community engagement

Another use of the Digital Twin (DT) in heritage management is the concept of virtual tourism. This idea gives tourists an opportunity to visit historical locations virtually via Virtual or Augmented Reality (Guo et al., 2024; Yu & He, 2022). It minimises accidents and pedestrian traffic in these

destinations because tourists can explore sites using 3D visualisation devices (Bilim, 2025; Huang et al., 2024). According to Bec et al. (2021), virtual tourism enables tourists to take part in the global culture and heritage buildings and eliminates the unwanted effects of mass people on these delicate sites.

Rahmadian et al. (2023) found that the Digital Twin fosters sustainable digital tourism which facilitates global connections to tourists, which again is consistent with the past research. Digital twins assist in the formulation of new business models and introduce opportunities for sites that are not large and not frequently visited (Fukawa & Rindfleisch, 2023).

In addition to technological and economic advantages, it has another advantage: community engagement. As Tzachor et al. (2022) described, it is impossible to implement a Digital Twin without the presence of active participation of the local community. Their other argument was that this digital preservation process cannot be achieved without engaging local people to access the global community (Saner et al., 2020). In a bid to defend the sites and preserve the knowledge and value of the heritage, there is need to be connections between the local and global communities (Ginzarly & Teller, 2021). Similarly, Luther et al. (2023) established that local communities also play a role in the adoption of Digital Twin technology to preserve and maintain cultural heritage.

2.4 Challenges and barriers to adoption

Digital Twin (DT) has come with numerous opportunities in the field of heritage management; however, it has a number of challenges and barriers to the adoption of this technology (Opoku et al., 2023). Mansuri et al. (2022) noted that the overall cost is reduced, but the initial cost of implementing this technology is high in the field of heritage management despite the technology reducing the cost. Small organisations that do not have sufficient funds experience issues with the implementation of IoT sensors and BIM infrastructure (Singh & Kumar, 2024).

Besides financial issues, institutions are blocked because of a lack of expertise to handle artificial intelligence and advanced technologies (Kar et al., 2021). Agrawal et al. (2022) stated that implementing Digital Twin and introducing technological innovation require manpower equipped with digital technology-related skills, which many institutions often lack. This study shows that training and development activities are required to increase the capacity of the manpower to overcome this issue and be able to utilize the technologies in an effective and efficient manner (Ozkan-Ozen & Kazancoglu, 2022).

Additionally, laws and policies on barriers are a significant factor when applying digital twins (DT) in heritage management (Guo et al. 2024). According to Carlsson & Rönnblom (2022), the government is supposed to do the right things to offer incentives that are well supported to embrace digital technologies in this sector and come up with policies towards the application of this technology. The implication of this research is that the absence of favourable policies and regulations serves as an impeding factor in digital technology adoption in this field (Costa et al., 2023).

Most of the previous studies (Tzachor et al., 2022; Wickberg & Lidström, 2025) primarily concentrate on the technical dimensions of digital twins, yet limited studies have contextualised digital twins within the economic governance context. This study has extended the existing literature by representing digital twins as governance tools that help to reduce lifecycle costs, mitigation of negative environmental externalities, and discovering alternative revenue models which are familiar with the term of virtual tourism, that is addressed by both sustainable and fiscal barriers in heritage management.

3. Methodology and data

3.1 Research design

The qualitative research design was also appropriate in this study because the objective was to concentrate on the investigation of how the notion of a dual-purpose Digital Twin (DT) could be incorporated to achieve sustainability in heritage management (Hou et al., 2024). Qualitative research was chosen to explore the opportunities to examine the point of view of the stakeholders regarding the preservation of heritage, implementation of digital technologies, and increasing sustainability (Snis et al., 2021). This research design is appropriate and is most effective in research that intends to explore,

investigate, or gain knowledge of the meaning of the context, such as the relationship between digital innovation and cultural heritage management (Lian & Xie, 2024). The proposed research was conducted to investigate the visions and perspectives of stakeholders in relation to the implementation of a Digital Twin (DT) in heritage management, risk and barrier evaluation, sustainability, and structural integrity (Alnaser et al., 2024; Jiménez Rios et al., 2025). Thematic analysis was applied to identify the valuable observations of the interviewers and important contributions to identify the patterns and themes of the data in this study (Xu & Zammit, 2020).

The primary objectives of the study were to find out the perceived benefits and drawbacks of digital twin technology in the sphere of heritage management, to examine the impact the technology has on the operation of efficiency and sustainability of organisations, and discuss whether the community can be involved and visit the sites virtually (Naeem et al., 2023). This analysis was also aimed at providing both theoretical and practical data regarding how the digital twin technology could support the sustainable, affordable, and accessible heritage preservation practice (Vuoto et al., 2024).

3.2 Sampling technique

In this study, the subjects were selected using the non-probability sampling method known as purposive sampling because it enables one to select the participants according to their knowledge and experience as far as the study is concerned (Stratton, 2023; Baltes & Ralph, 2022). A total of 10 key informants (KIIs) were selected, including heritage site managers, experts in digital twins, environmental sustainability experts, heritage building architects, policymakers, heritage tourism experts, NGO leaders, providers of technology solutions, academics, and leaders of the local community (Hasan et al., 2022; Kamara et al., 2023; Lokot 2021). These respondents were chosen because they had profound knowledge of heritage management, digital twin technology, and sustainability practices. The varied stakeholders meant that they were able to have a holistic view of the issues, opportunities, and implications of implementing a digital twin technology in the heritage sector. The purposive sampling method ensured that the sample had a wide perspective and experience in the area of heritage management and digital technology.

3.3 Data collection method

Study data were gathered through semi-structured interviews with the participants. This approach was selected because of its flexibility, as participants will be able to express their opinions in their own words but still have an opportunity to cover the major themes and research questions. Semi-structured interviews are especially useful in qualitative research because of the balance between guided enquiry and the self-directed responses of the participants, as the researcher is able to investigate further in certain areas of their interest. Interview questions were developed to comment on a number of central themes, such as the place of digital twin technology in the management of heritage, the possibility of energy optimisation and predictive maintenance, the role of sustainability outcomes (reduced carbon emissions and resource efficiency), and the possibility of virtual tourism and community participation in the project. Interviews were conducted face-to-face or through virtual applications (Zoom or Skype), depending on the availability of the participants. The interviews took approximately 45–60 minutes and were recorded on audio tape with the permission of the interviewees. Transcription was done verbatim to have a real picture of the responses of the participants (Aguinis et al., 2021).

3.4 Data analysis

Thematic analysis was used to analyse the data collected from the semi-structured interviews. This is a qualitative data analysis method which enables the researcher to identify, analyse, and report patterns or themes in the data. Thematic analysis is especially appropriate in studies of complex phenomena, where meaning patterns can arise as a result of the experience and perspective of the participants. The analysis process was meta-step-based, in that the transcripts were read and re-read to become conversant with the content; initial codes were created by identifying meaningful chunks of text that encapsulated the data concerns to the research questions, and finally, the generated themes were reviewed and narrowed to ensure that they reflected the meaning of the data as well as correlated to the research objectives. Finally, the themes were labelled and developed to explain what they entailed

and their extent. This process of iteration provided an opportunity for the researcher to delve into the depths and insights of the experiences of the people involved in the research while ensuring the integrity and richness of the data were maintained.

3.5 Ethical consideration

This study was designed and implemented in accordance with ethical considerations. An ethics committee was selected to provide ethical approval for the research, as it abided by the ethical guidelines and principles. An informed consent form was given to the participants, which informed them of the purpose of the study, their free will to take part in the study, their right to opt out without any punishment, and guarantee of confidentiality and anonymity. The interviews were conducted after obtaining the consent of the participants, and to ensure the anonymity of the participants, all data were anonymised. Data protection regulations were adhered to by ensuring the safety of the storage of the transcription and audio records and their availability to the research team.

Although the strengths of this study were very strong, there were several limitations to this study. First, the sample of 10 participants could restrict the applicability of the results; however, the purposive sampling method resulted in the inclusion of major stakeholders from different sectors. The qualitative nature of the study implies that the results obtained would be limited to the context and may not be expected at all sites of heritage or in every geographic area. Second, the research was based on self-reported information, and participants were also subject to the influence of personal prejudice or subjective opinions regarding the advantages and difficulties related to the digital twin technology. Third, the research was conducted in a particular cultural and technological environment, and the results are not necessarily applicable to countries or regions where such heritage management practices are mastered or have a different technological base.

Finally, this methodology section provides a clear and detailed description of the research design, methods of collecting data, sample or participants, and methods of analysing data. This method has a strong foundation in the best practices in qualitative research, such that the research is able to capture both the rich and complex experiences of the participants without sacrificing positive and ethical concerns. These study results are useful data on how the concept of a digital twin can bring sustainable management of heritage practice, and the research methodology in this case is the basis of the analysis and discussion of its results.

4. Analysis and findings

This chapter introduces a thematic analysis of the data collected through the Key Informant Interview (KII) to conduct a study on the Dual-Purpose Digital Twin model of managing sustainable heritage. The analysis incorporated qualitative coding, network mapping, and multilayer visualisation tools to examine the relationships between themes, participants, and sustainability outcomes.

4.1 Thematic analysis findings

The table below summarises the main themes identified during the Key Informant Interviews (KII). It provides a description of each theme, quotations used to exemplify them, participants of different important themes, and interpretations made from the analysis. Three prevailing clusters were outlined in the analysis: Technological Core (Digital Twin, IoT, and Predictive Maintenance), Sustainability Core (Energy Optimization, Carbon Reduction, and Virtual Tourism), and Adoption Challenges (Capex Barriers, Capacity Gaps, and Policy Enablement). Community Impact is a cross-cutting social theme.

The thematic analysis revealed that there were some central areas of concern in the discussion of the participants. The table below is the theme frequency table which indicates the most commonly mentioned themes amongst all the participants. Energy optimisation, as per the table, is the most likely theme that was discussed, with nine out of ten claiming the importance of this theme. This confirms our hypothesis of the first assumption that operational efficiency is a key factor in the adoption of digital twins in heritage sites, in particular, the minimization of energy needs and maintenance expenses. Likewise, Carbon Reduction and Predictive Maintenance were directly related to energy optimization, indicating that the participants were highly concerned with sustainable operation methods.

Table 1. Thematic analysis

Theme	Description	Representative quotes	Key participants	Interpretive insights
Digital twin applications	Use of digital twins for real-time monitoring, simulation, and decision making in heritage management.	"Digital twins can simulate climate conditions and predict maintenance needs." (P1) "Virtual replicas manage resources efficiently." (P2)	P1, P2, P4, P5, P7, P8, P9, P10	Forms the technological foundation for sustainability; central to all outcomes.
IoT Integration	Combining IoT sensors with digital twins to gather real-time environmental data.	"IoT sensors tracking temperature and humidity can optimize preservation climates." (P1) "Sensor data makes twins dynamic." (P3)	P1, P2, P3, P4, P7, P8, P10	Bridges data and practices, enabling precision heritage management.
Energy optimization	Reducing energy consumption and cost through smart climate control and simulation.	"Energy consumption is one of the largest challenges." (P3) "Digital tools reduced energy use by 25%." (P4)	All participants (esp. P1, P3, P4, P5, P6, P8, P9)	Most prevalent theme linking digital innovation directly to carbon reduction.
Predictive maintenance	Digital twins are used to forecast and prevent structural or material failures.	"Predictive maintenance prevents costly emergency repairs." (P2) "We can intervene before structural damage occurs." (P4)	P1, P2, P3, P4, P7, P8, P9, P10	Supports proactive conservation and reduces material waste.
Structural monitoring	Continuous observation of building integrity using digital and visual sensors.	"Digital twins let us track structural stress and detect cracks early." (P4)	P4	Enhances preservation quality and safety of heritage structures.
Virtual tourism	Digital experiences replacing or supplementing physical tourism.	"Virtual tourism offers access while reducing over-tourism." (P6) "Virtual tours increase inclusivity." (P9)	P1, P6, P9	Promotes low-carbon engagement and broader accessibility.
Revenue models	Generating funds through virtual access and operational efficiency.	"Virtual tours can become a revenue source for conservation." (P6)	P6	Creates sustainable funding pathways for underfunded heritage sites.
Policy enablement	Government frameworks, incentives, and alignment with SDG goals.	"Policies should encourage adoption of digital twin technologies." (P5)	P1, P3, P5, P6, P9	Acts as a governance enabler linking innovation to long-term sustainability.
Capacity gaps	Lack of training, digital skills, and interdisciplinary expertise.	"Technical expertise is missing in many institutions." (P7)	P2, P3, P5, P7, P8, P10	Key non-technical barrier to scaling digital heritage initiatives.
Capex barriers	High initial investment costs and	"High costs make it difficult for smaller	P1, P4, P5, P7, P8, P10	Financial constraints limit adoption;

Theme	Description	Representative quotes	Key participants	Interpretive insights
	technological retrofitting challenges.	heritage sites to adopt digital solutions." (P5)		requires policy and partnership support.
Carbon reduction	Reduction of greenhouse gas emissions through efficient operations.	"Digital twins helped cut our carbon footprint by 20%." (P2)	P1, P2, P3, P4, P5, P6, P7, P8, P9	Demonstrates measurable environmental benefits from digital adoption.
Community impact	Local participation, awareness, and cultural continuity.	"Technology helps preserve our identity while protecting the environment." (P10)	P7, P10	Links social sustainability with community ownership and inclusivity.

Source: Researchers' own work.

As observed in Table 2, virtual tourism and community influence were less often discussed, which means that these factors are significant, but they are less significant than the more functional ones such as energy optimization and predictive maintenance. This tendency indicates that, although such a virtual aspect as new sources of income due to digital tourism are identified, as well as social inclusion, the main reasons why digital twins should be implemented in heritage management are focused on efficiency and ecology.

Table 2. Theme frequency table

Theme	Number of participants mentioning theme
DT_Applications	9
IoT_Integration	7
Energy_Optimization	9
Predictive_Maintenance	8
Structural_Monitoring	1
Virtual_Tourism	4
Revenue_Models	1
Policy_Enablement	5
Capacity_Gaps	6
Capex_Barriers	7
Carbon_Reduction	9
Community_Impact	2

Source: Researchers' own work.

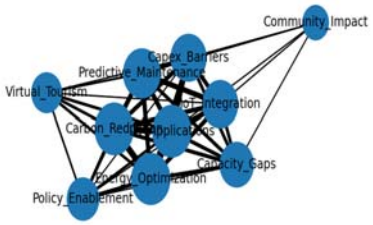
The most frequent and interrelated themes were identified in all 10 transcripts of the participants using thematic analysis. The major themes are energy optimisation, digital twin applications, predictive maintenance, and carbon reduction. These findings are consistent with the concept of dual-purpose digital twins which serve both operational and sustainability purposes.

The enablers and barriers were also found to be common in this analysis. The most common barriers were Capacity Gaps (skills shortages) and Capex Barriers (financial limitations), and IoT Integration and Policy Enablement were generated as enablers.

4.2 Network mapping and co-occurrence

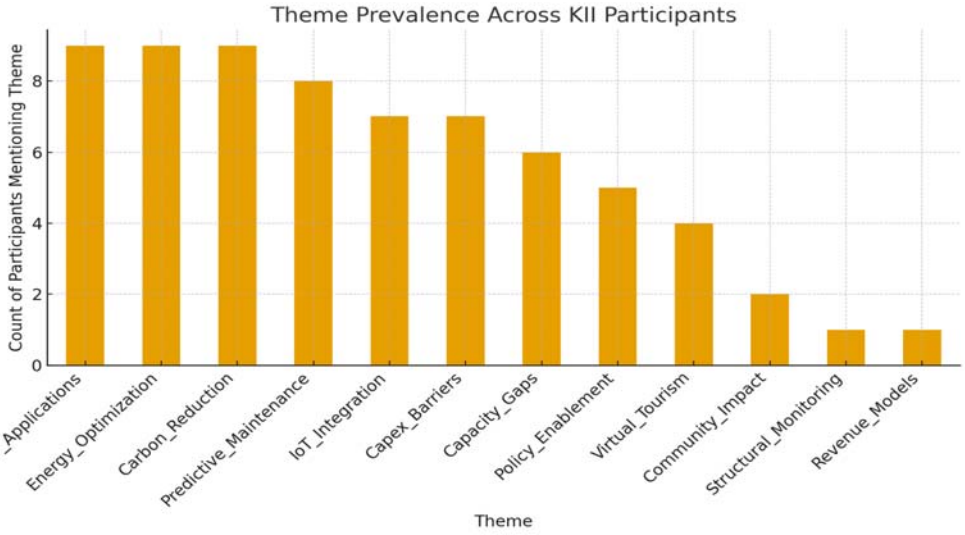
Network analysis was performed to test the co-occurrence of themes among the participants. The co-occurrence network showed a dense central node related to digital twin applications, IoT integration, energy optimisation, predictive maintenance, and carbon reduction. These themes form the basis of the technical-sustainability core of the digital twin framework. Policy Enablement is a liaison between technical and governance themes, enabling the connection between innovation and institutional preparedness.

Figure 1. Theme co-occurrence network (edges shown for co-occurrence > 1)



Source: Researchers' own work.

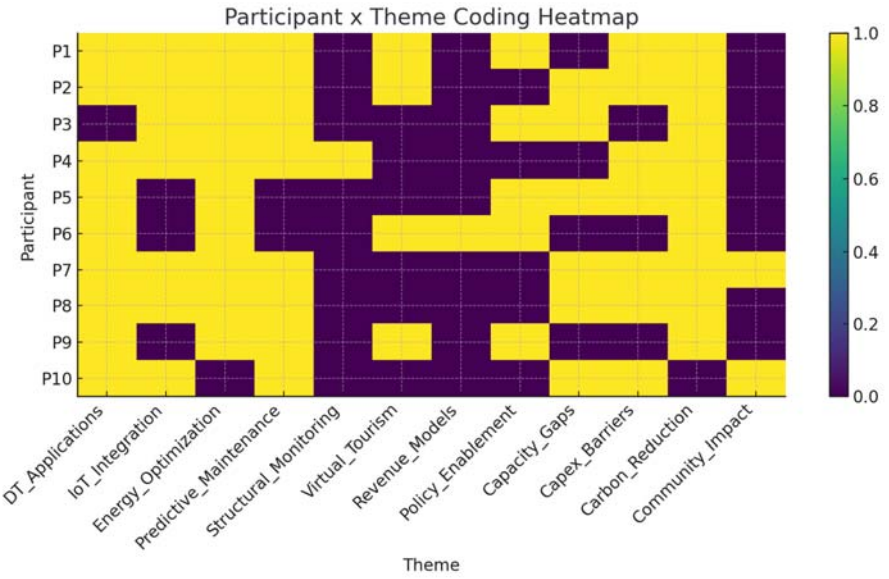
Figure 2. Theme prevalence across participants



Source: Researchers' own work.

Both macro and micro relationships are presented in the three-layer visualisation strategy (prevalence heat map network) (Figure 3). Prevalence analysis reveals the themes that prevail, the heat map reveals the roles of the participants that the specific topics are being driven by, and the network model reveals the relationships between themes.

Figure 3. Participant x theme coding heat map



Source: Researchers' own work.

5. Discussion

This study examined the new role of dual-purpose digital twins in the field of sustainable heritage management using thematic analysis (qualitative analysis) based on interviews with key informants (interviews with ten stakeholder groups, namely heritage site managers, architects, policymakers, sustainability experts, and digital twin solution providers).

The evaluation showed that there are a number of findings that are interconnected and contribute to the comprehension of how digital twin technology can promote sustainable heritage management. To begin with, the findings showed that the technological base of sustainability in heritage management depends greatly on the implementation of digital twin systems, IoT integration, predictive maintenance, and energy optimization. These technologies enable heritage institutions to keep track of things like temperature, humidity, and structural stress in real time, even simulating energy use and predicting maintenance requirements. Such proactive and information-driven solutions do not only assist in minimizing the use of energy and carbon emissions but also make heritage buildings long-term sustainable. This is in line with the current literature (e.g., Akter et al., 2026c; Venkateswarlu & Sathiyamoorthy, 2025), which also presented the role of digital twins in maximizing the performance of operations.

The second important result was the relationship between the outcomes of digital innovation and sustainability. In addition to the efficiency of the operation, stakeholders perceived digital twins as facilitators of carbon reduction, virtual tourism, and economic sustainability, thus turning these digital systems into instruments that yield environmental value as well as new sources of revenue. It builds upon the work of other researchers by introducing the dual-purpose role of digital twins in improving the effectiveness of the operations but also, to offer economic and social sustainability.

The third important lesson is the obstacles to adoption, namely the capital-intensive aspect of the technology, technical skills, and policy gaps that hamper wider adoption. These obstacles were always mentioned, as they represent the difficulties observed in previous studies (Cespedes-Cubides & Jradi, 2024). Lastly, Community Impact was found to be an important societal level of sustainability, and it is important to note that digital heritage projects are not meant to be only of technological use, but have an emphasis on local identity, inclusion, and accessibility. This highlights the importance of incorporating both technological and social aspects into the future management of heritage, as the social sustainability aspect has not been fully addressed in the past.

These findings correspond to the direction of recent research in this area. Ranade et al. (2024) concluded that digital twins combined with energy analytics systems could provide visible energy

consumption reductions through real-time monitoring and predictive control processes at the building operation stage. The focus of their observations is reflected in the present study, which relates to energy optimisation and predictive maintenance as the most popular sustainability mechanisms. Similarly, Liu et al. (2025) affirmed that a digital twin with Building Information Modelling (BIM), IoT, and big-data analytics enhances the quality of indoor environments and reduces carbon emissions, particularly in old facilities with high levels of preservation requirements.

Participants displayed the same principle by pointing out the high energy consumption rates in buildings of historical nature that are linked to climate control. In heritage-specific research, Ramonell et al. (2023) established that the connection between knowledge graphs and digital twin models improves the use of data to make decisions in heritage conservation. This research builds on this stream by finding other sustainability outcomes, including virtual tourism and local community benefits, which have not been examined in the previous literature on digital twins. Additional consistency may be achieved by accepting the role of digital twins in enhancing energy efficiency and operational performance in complex-built environments (Akter, 2026b; Iqbal & Mirzabeigi, 2025) and the need to incorporate machine learning layers to forecast energy demand and optimise climate systems in heritage buildings (Boesgaard et al., 2022).

Regarding conformity, the current study adds to the existing opinion that digital-twin technology, when integrated into the context of smart heritage, leads to positive results in terms of resource efficiency, carbon-footprint minimisation, and long-term conservation (Maktabifard et al., 2020). This also reflects earlier research on the continued existence of structural and financial barriers, especially the data interoperability problem, high prices, and challenges with capacity that restrain mass adoption (Liu et al., 2025). However, this study differs from previous studies in several aspects. It is one of the few studies that triangulate the views of various stakeholders, including heritage managers, technologists, policymakers, and communal actors, in a single empirical model. In addition, by connecting digital twin adoption to Virtual Tourism and Revenue Models, this study fills a gap in the currently unstudied core of the intersection of heritage sustainability and business innovation. Finally, this study adds a social sustainability perspective, which is lacking in much of the current digital twin research because of its technical-energy orientation. This mix of approaches makes the research confirmatory and original, as it confirms long-established technological and sustainability mechanisms and expands them to new social and economic fields that are applicable to heritage management.

5.1 Theoretical implications

Based on the recommendations of Hou et al. (2024) to build theories, namely, defining the mechanisms and boundary conditions and making a contribution, the results of this study provide the following theoretical insights into the adoption of digital twins in the heritage field.

The findings are in line with the Dual-Purpose Digital Twin Mechanism (DPDTM), which works in two pathways that are interconnected. The first way is the Operational Efficiency Mechanism, in which the digital twins combine real-time sensor data, analytics, and feedback to streamline climate control, energy consumption, and maintenance cycles in heritage management. Tangible benefits, such as cost savings and resource optimization, are provided by this mechanism because it enhances the performance of operations and reduces the consumption of unnecessary resources.

The second mechanism, the Sustainability Value Mechanism, builds upon the opportunities to achieve operational efficiencies by digital twin systems in order to create more widespread environmental, economic, and social value. Environmentally, digital twins contribute to the reduction of carbon and energy-savings by simplifying the use of energy in heritage locations. On the economic side, virtual tourism helps them to cut down on maintenance expenses and incur new sources of revenue. Socially, digital twins help in accessing heritage sites worldwide, which encourages inclusiveness and heritage identity because of virtual interaction, thereby solving the over-tourism issue. Collectively, these mechanisms indicate that digital twin technology links the objectives of preservation of heritage with the objectives of sustainable development.

The boundary conditions determine the applicability of this mechanism. The model is best used in the case of heritage sites that have some level of digital preparedness, including IoT infrastructure or BIM data. The performance of digital twins can be hampered or demand significant investments in

creation of the right infrastructure in situations where these digital platforms are not available. Moreover, the operation of digital twins relies on organizational preparedness and inter-waltz collaboration. Even technically sophisticated digital twin systems will not manage to provide the intended sustainability results without the help of heritage managers, policymakers, and local communities. Heritage typology as well moderate the effectiveness of the mechanism. Digital twins can be more beneficially implemented in high-traffic, climate-sensitive heritage sites because of their increased operational needs, while their benefits may be less pronounced for smaller, less impactful sites.

This study adds to the Resource-Based View (RBV) by making digital twins one of the strategic resources that contribute to the dynamic capabilities of heritage institutions. Digital twins can help heritage sites realise the stressors of the environment, anticipate future challenges, and maximise resource allocation, ensuring long-term sustainability and resilience. This concurs with the assumption of RBV that distinct resources can help an organization to acquire a competitive advantage due to their adaptability and responsiveness. Moreover, the given study adds to the Socio-Technical Systems Theory as it proves that digital twins may be regarded as an intermediary between technology, heritage management systems, and social actors. This study demonstrates that digital twins can be used as both operational and social resources, allowing cultural heritage maintenance and community involvement.

Finally, this study introduces the Dual-Purpose Digital Twin Framework (DPDTF), which combines social sustainability with environmental and economic goals and provides a comprehensive model of heritage management. The framework builds upon current models of digital heritage by connecting the performance of a technical aspect to socio-cultural achievement, which offers better insight into the role of digital twins in long-term heritage management.

5.2 Practical implications

The results also have immense practical implications for heritage managers, policymakers, and technology providers interested in operationalising sustainability with the help of digital transformation.

From the context of development policy perspective, digital twins should be integrated into national heritage and urban sustainability strategies, supported by targeted financial incentives and capacity building initiatives. This alignment of policies can minimize entry barriers, increase institutional readiness, and support the long-term economic feasibility of heritage preservation initiatives.

The direct implication for heritage managers is that small-scale, digitally twin pilots focused on energy-intensive systems such as HVAC and lighting must be initiated. Placing IoT sensors that record temperature, humidity, and structural data will facilitate predictive maintenance and provide provisional proof of energy savings, thereby creating an evidence base to justify larger investments in the future. Managers are also encouraged to use digital twins to develop virtual-tourism spaces that can reach audiences anywhere in the world without excessive physical pressure on delicate locations. Moreover, the introduction of transparent data-governance structures will ensure that BIM, IoT, and analytics systems are interoperable, which will allow them to be scaled and made efficient in the long term.

The study indicates a number of interventions for policymakers and heritage authorities. Governments need to provide incentives to see the digital twin by giving heritage innovation grants or fiscal incentives, especially to resource-constrained institutions. They should also invest in digital-heritage training programs to create the technical capacity to fill gaps in skills that are critical to the participants. Lastly, digital-twin implementation, as one of the main avenues leading to the development of Sustainable Cities and Communities and Responsible Consumption and Production objectives of the United Nations Sustainable Development Goals (SDG 11 and SDG 12), should be explicitly incorporated in heritage policies. Such alignment of policies would institutionalise sustainability and digitisation as complementary and not conflicting goals in the governance of heritage.

The implications of the findings for technology providers and industry partners are to be more inclusive and modular in their approach. To help smaller sites participate in the digital transition, providers should develop digital twin packages that are scalable, demand less capital investment, and can run in data-poor situations, thereby aiding the transition. Financial barriers may be further reduced by revenue-sharing or subscription systems which would help incentivise provider and heritage-site

relations. Recording successful case studies in a heritage context will also be critical in demonstrating payback and developing institutional trust.

Finally, at the national or multi-site heritage program level, by incorporating the adoption of digital twins as a specific work stream into sustainability and innovation strategies, there may be a collective impact. It will be possible to monitor both the operational and environmental performance with the help of the creation of clear performance metrics, including energy saved, carbon reduction, and virtual visitors reached. When universities, technology companies, heritage organisations, and local communities work together to ensure cross-sector collaboration, the ecosystems of digital heritage innovation will be empowered, and local identity will be integrated into digital heritage projects.

6. Conclusion

Overall, the discussion verifies that digital twins in heritage management are much more than technological marvels; they are strategic facilitators that can simultaneously improve operational performance, environmental sustainability, and cultural resilience. By defining the dual-purpose mechanism and placing it in theoretical and pragmatic contexts, this study makes a valuable contribution to the dynamic field of smart and sustainable heritage tourism. As the heritage industry confronts the twin aspects of environmental policies and climate change, coupled with the digital revolution, the dual-purpose digital-twin model provides a viable roadmap for developing cultural institutions of the future that are low-impact, inclusive, and future-proofed.

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