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Digital Twins in Heritage Conservation and Visitor Engagement: Comparative Case Studies from Four Historic Sites

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Abstract

This study explores the application of digital twin technologies in heritage conservation and visitor engagement, focusing on their practical use in preserving and enhancing access to culturally significant sites. Digital twins, which are virtual replicas of physical environments, enable real-time monitoring and simulation, offering innovative tools for conservation management and experiential interpretation. Through a systematic literature review and comparative analysis of four case studies, Pompeii, Notre-Dame, the Colosseum, and Hagia Sophia, this research examines how digital twins are implemented across varying contexts. The findings reveal that digital twins support predictive maintenance, structural monitoring, and restoration planning while also enabling immersive experiences through virtual and augmented reality. These technologies provide remote access, interactive storytelling, and tailored tours, fostering a deeper connection with heritage. In terms of conservation, digital twins support predictive maintenance, structural monitoring, and evidence-based decision-making. The structured comparison highlights how digital twin systems balance preservation needs with modern engagement demands. While challenges such as data accuracy, cultural sensitivity, and technological infrastructure remain, the study concludes that digital twins represent a valuable model for integrating conservation and visitor experience in heritage site management. Future developments in immersive technologies and broader adoption of digital twins could further enhance the management and appreciation of cultural heritage worldwide.

Keywords

digital twins, artificial intelligence, heritage tourism, virtual reality, cultural preservation

1 Introduction

The integration of digital twins in various industries has marked a new era in technological innovation (Moshood et al., 2024). Among those industries, heritage conservation is also one of the pillar that integrated digital twins technology in its practice (Vuoto et al., 2024). Digital twins are virtual replicas that can mirror real-time conditions of physical environments, capturing structural and environmental details through advanced data collection methods (Jiang et al., 2021). While this technology has transformed sectors such as architecture, urban planning, and management, its potential in heritage tourism remains an emerging field with a big number of possibilities (Ertz et al., 2024). In heritage conservation, digital twins offer a unique way to preserve and showcase culturally significant sites, merging historical value with advanced digital interaction.

Artificial intelligence (AI) plays a vital role in this transformation by enabling these digital twins to go beyond static representations of buildings and sites. AI-driven digital twins in heritage tourism create dynamic and interactive experiences for visitors by simulating historical environments and real-time conditions of heritage sites and structures (Lian and Xie, 2024). By incorporating elements such as virtual reality (VR) and augmented reality (AR), these AI-powered models allow users to engage with heritage sites in ways previously unimaginable (Akyol and Avci, 2023). These experiences enable remote access and interactive learning, giving tourists opportunities to connect with cultural heritage from anywhere globally (Google Arts & Culture, 2023).

The objective of this study is to explore how digital twins are being applied in heritage site management with

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respect to two core functions: conservation planning and visitor engagement. Through a comparative case study analysis of four historic sites, the paper evaluates the practical integration of digital twin systems across multiple dimensions, including technological tools, monitoring functions, immersive features, and implementation challenges. The analysis highlights how current implementations of digital twins contribute to aligning preservation priorities with contemporary approaches to public engagement in heritage contexts.

1.1 Literature review

1.1.1 General developments in digital twins and AI for heritage

The concept of digital twins originated in the aerospace industry, where NASA's Apollo program used a "twin" spacecraft on Earth to replicate and troubleshoot conditions experienced by astronauts in space (Boschert and Rosen, 2016). Over the decades, digital twins have evolved into complex virtual models capable of simulating real-time conditions across diverse sectors, including manufacturing, healthcare, and urban management (Lucchi, 2023). Their core function is to mirror a physical entity's state by continuously integrating sensor data, which can then support predictive analysis, maintenance, and optimization efforts (Luther et al., 2023). Recent advancements, particularly the integration of Internet of Things (IoT) and artificial intelligence (AI), have enabled digital twins to dynamically represent and interact with the physical environments they mirror (Lucchi, 2023). This evolution has expanded digital twin applications from static replicas to adaptive, real-time systems, enhancing precision and decision-making across industries (Dang et al., 2023).

In the realm of cultural heritage, digital twins have been instrumental in preserving and managing historical sites by providing digital replicas that simulate both environmental conditions and structural attributes (Dang et al., 2023; Luther et al., 2023). For heritage conservation, digital twins gather data from various sources, including 3D scanning, historical records, and environmental monitoring systems, to create highly detailed models that aid in visualizing wear patterns, predicting deterioration, and even simulating visitor interactions (Karatzas et al., 2024). These models are not only valuable for managing physical preservation but also for engaging the public, allowing virtual access to heritage sites and fostering a deeper connection with cultural assets (Luther et al., 2023). As digital twin technology goes forward, its applications in heritage conservation makes the balance of historical preservation with contemporary engagement more important.

AI applications have profoundly transformed the way heritage conservation and tourism is approached. These advancements offer tools for the effective preservation, monitoring, and accessibility of cultural assets (Raman et al., 2024). AI techniques such as machine learning and computer vision have been implemented to automate tasks like historical document classification, 3D reconstruction, and predictive damage assessments, thus ensuring that cultural heritage assets are preserved more accurately and effectively (Gîrbacia, 2024). Predictive maintenance models utilizing AI can forecast and prevent damage by analyzing environmental and structural data, a critical advancement for the upkeep of heritage sites that suffer from gradual deterioration due to both environmental and anthropogenic factors (Casillo et al., 2024). Additionally, IoT-enabled digital twins provide real-time monitoring that integrates AI-driven information, allowing heritage managers to make timely decisions that maintain structural integrity and cultural value (Murthy et al., 2022).

The role of digital twins and IA extend beyond preservation to enhancing the accessibility of heritage sites, thereby democratizing cultural experiences (Li et al., 2024). AI-based applications in virtual and augmented reality allow remote access and interaction, enabling visitors to engage with heritage sites from anywhere in the world with the exact digital replicas (Pisoni et al., 2021). For instance, explainable AI (XAI) enhances interaction by tailoring the visitor's experience based on accessibility needs, such as through personalized tours or interactive, multisensory experiences, thus making cultural heritage more inclusive (Barredo Arrieta et al., 2020). Such applications facilitate a deeper understanding and appreciation of cultural sites, supporting both tourism growth and social inclusion, especially for lesser-known or underfunded heritage sites (Casillo et al., 2024; Maietti, 2023). These advancements highlight AI's potential in connecting people with heritage in meaningful ways, fostering both preservation and engagement in the cultural sector.

AI-powered digital twins represent a significant evolution over traditional 3D modeling and VR approaches in heritage conservation and tourism (Ribeiro et al., 2024). While traditional models and VR renderings can visually recreate heritage sites, they are largely static representations that lack real-time interaction with the physical asset. Digital twins, by contrast, incorporate real-time data inputs from sensors and IoT devices, allowing for dynamic simulations and predictive capabilities that respond to ongoing changes in the physical environment (Mihai et al., 2022). This interactivity enables digital twins not only to model a site's current condition but also to forecast potential structural issues and environmental impacts. By embedding AI algorithms, digital twins can continually adapt based on new data, making them a more versatile and effective tool for monitoring, conserving, and engaging visitors in cultural heritage experiences compared to conventional VR or 3D models (Jiménez Rios et al., 2024).

Integrating AI-driven digital twins into heritage sites presents a range of challenges and opportunities. Technologically, heritage sites often require robust data collection infrastructure, yet the availability of high-quality, real-time data can be limited, particularly in older buildings or in regions with restricted access to advanced technology (Mazzetto, 2024). Ethical considerations also emerge, such as ensuring the digital representation respects the cultural significance of a site and safeguards sensitive heritage data (Wagner and de Clippele, 2023). Furthermore, digital twins demand significant data storage and processing capabilities, raising concerns around sustainability and long-term data management. However, these challenges become balanced by promising opportunities: digital twins can facilitate more inclusive and accessible heritage experiences, offer detailed conservation insights, and create sustainable engagement strategies for lesser-known or fragile sites (Mutibwa, 2024). By addressing these challenges, the adoption of AI-driven digital twins could greatly enhance heritage preservation, aligning well with the goals of this study to connect visitors with heritage through dynamic, interactive experiences that prioritize both accessibility and cultural integrity.

1.1.2 Derivation of evaluation criteria from the literature

In order to conduct a robust and comparative evaluation of digital twin applications across diverse heritage sites, this study derives its analytical framework directly from literature that documents real-world implementations. Rather than relying exclusively on general theoretical models, we systematically reviewed site-specific studies to identify recurring operational dimensions of digital twin use in heritage contexts. These include technological components, conservation roles, modes of visitor interaction, AI integration, immersion levels, monitoring strategies, and practical limitations. Grounding the evaluation criteria in applied literature ensures that the subsequent case analyses reflect not only conceptual advances but also documented practices from the field. For instance, the role of advanced 3D scanning, photogrammetry, and sensor-based environmental tracking emerges consistently as the technological backbone of digital twin systems in heritage (Akçam Ergin, 2023; Kim and Park, 2023). These technologies serve as enablers for both preservation planning and experiential enhancement, thereby forming the first evaluation criterion: Technologies Used. In addition, the methodological transparency and high-fidelity modeling pipelines advocated by Demetrescu et al. (2016) further highlight how robust documentation standards and multi-source data integration contribute to the technological soundness of digital heritage systems.

In terms of conservation, many heritage studies emphasize the value of digital twins for predictive maintenance, post-disaster reconstruction, and preventive conservation (Massafra et al., 2022; Mukhacheva et al., 2022; Valero et al., 2014). These functions are facilitated by continuous data monitoring and simulation capabilities, which enable timely intervention and resource optimization. This forms the basis for the second criterion: Conservation Focus.

The third dimension, Visitor Engagement, stems from increasing academic attention to virtual storytelling, educational narratives, and remote accessibility through digital twins (Cruz Franco et al., 2022; Luther et al., 2023). While some sites prioritize public-facing immersive content, others use digital models primarily for internal conservation, resulting in significant variance in this category. Closely tied to this is the fourth criterion, AI Usage, which is guided by literature documenting the deployment of machine learning, predictive analytics, and automation tools for both conservation and personalized visitor experiences (Casillo et al., 2024; Gîrbacia, 2024; Hermon et al., 2024).

As digital twins evolve, the level of Immersion offered, ranging from static 3D views to fully interactive AR/VR environments has become a key differentiator among implementations. This criterion is grounded in studies on immersive heritage design and the transition from documentation-oriented models to experiential digital environments (Gabellone, 2022; Vuoto et al., 2024). In particular, Landeschi et al. (2016) demonstrate how fully 3D GIS-based visual analysis can be used not only for architectural documentation but also to simulate past human perception and spatial cognition. Their work on the House of Caecilius Iucundus in Pompeii underscores the potential of immersive digital twins to support interpretive storytelling based on line-of-sight analysis and virtual engagement patterns (Landeschi et al., 2016).

Similarly, the Monitoring Type criterion reflects the operational use of sensor networks to track structural integrity, environmental conditions, or acoustical behavior, all of which are emphasized in literature on site-specific heritage diagnostics (Jouan and Hallot, 2019; Sü Gül, 2021). Finally, the dimension of Implementation Challenges acknowledges the critical discourse around the ethical, technical, and infrastructural obstacles that arise during digital twin integration. These challenges are well-documented and include issues such as data overload, interdisciplinary coordination, and limitations in digital fidelity (Mazzetto, 2024; Roussel and De Luca, 2023; Wagner and de Clippele, 2023), while Demetrescu et al. (2016) highlight the importance of transparent reconstruction pipelines and the formalization of interpretive assumptions, which often present practical challenges during large-scale heritage digitization projects.

Altogether, the literature forms the empirical and methodological grounding of this study. It ensures that each selected heritage site is evaluated through a framework supported by applied research and documented practice. This dual-level literature integration, general developments and case-based applications, reinforces the validity of the study's comparative analysis and helps align the technological, cultural, and experiential aspects of digital twin implementation in heritage conservation and tourism.

2 Methodology

This study employs a multi-layered methodological approach to investigate how digital twins enhance visitor engagement and support heritage conservation. Data for evaluating the digital twin implementations at the selected heritage sites were compiled through a targeted review of peer-reviewed literature and supplemented with grey literature, including technical reports, institutional documents, and validated online sources specific to each case. The methodology focuses on systematically analyzing the implementation of digital twin technologies in heritage sites through a set of structured evaluation criteria. Rather than broadly assessing their potential, the study compares real-world applications across seven dimensions: technologies used conservation focus, visitor engagement, AI usage, immersion level, monitoring type, and implementation challenges. Four heritage sites, which are Pompeii, Notre-Dame, the Colosseum, and Hagia Sophia, were selected for in-depth analysis based on their documented use of digital twins. These case studies provide insights into how digital twins are currently shaping both conservation practices and visitor experiences in heritage management.

The findings from the literature review and case studies were synthesized to provide a holistic understanding of the applications of digital twins in heritage tourism. This thematic synthesis involved integrating results from multiple sources to identify recurring patterns and address discrepancies. Cross-site comparisons were conducted to explore commonalities and site-specific variations, enabling a deeper understanding of how digital twins are utilized in different contexts. To facilitate systematic comparison, each case study was evaluated based on seven core dimensions identified from the literature and refined during thematic analysis:

- Technologies Used: specific digital tools and platforms (e.g., photogrammetry, Building Information Modeling (BIM), sensor networks) employed in each site's digital twin implementation.
- Conservation Focus: the role of digital twins in structural health monitoring, restoration planning, or preventive maintenance.
- Visitor Engagement: the extent and nature of digital twin applications for enhancing visitor interaction through virtual or augmented experiences.
- AI Usage: the presence and role of artificial intelligence in automation, simulation, prediction, or content personalization.
- Immersion Level: the degree of experiential engagement supported by VR/AR integration, ranging from passive viewing to interactive simulation.
- Monitoring Type: the type of data monitored (e.g., structural, environmental, acoustic) and its relevance to conservation outcomes.
- Challenges Highlighted: technological, contextual, or ethical difficulties encountered in implementation or use.

To ensure reliability, data triangulation was applied through multiple source types and author cross-checking. The validity of the findings was strengthened by grounding the framework in well-established digital heritage and conservation literature on heritage technology. Ethical sensitivity was maintained by respecting cultural significance in representations, avoiding speculative reconstructions, and citing sources that adhere to professional conservation standards.

3 Case studies

In recent years, digital twin technologies have gained increasing attention in the field of heritage conservation and tourism. To explore how these technologies are applied in practice, this study presents a comparative analysis of four significant heritage sites: Pompeii, Notre-Dame, the Colosseum, and Hagia Sophia. Each case was selected for its documented use of digital twin systems and its unique cultural and technological context. The evaluation is based on a set of key categories, technologies used, conservation focus, visitor engagement, AI integration, immersion level, monitoring type, and challenges encountered, which provide a structured basis for comparison. This approach allows for a deeper understanding of how digital twins function across different heritage settings and how they contribute to both preservation efforts and public accessibility.

3.1 Case study 1: Pompeii, Italy

Pompeii has implemented digital twin technologies to address its ongoing conservation challenges and to enhance visitor engagement at the archaeological site. The system integrates sensor networks and 3D scanning tools specifically adapted to monitor the environmental conditions and structural stability of the ruins. These technologies support preventive maintenance and allow for the simulation of deterioration scenarios unique to Pompeii's exposed and fragile context.

Technologies Used: Pompeii has increasingly adopted digital twin technologies to support both preservation and tourism management. Core technologies include IoT sensors, environmental monitoring devices, and advanced 3D scanning methods such as photogrammetry and laser scanning. These tools provide continuous data on temperature, humidity, and structural integrity. One project focusing on Casa di Caecilius Iucundus in Pompeii (Fig. 1) employed a combination of laser scanning and immersive visualization via CAVE systems, highlighting how archaeological data, 3D scanning, and interpretive modeling can work together to support both research and preservation (Akçam Ergin, 2023). According to Mukhacheva et al. (2022), this digital twin architecture consists of three integrated layers: data collection, data processing, and model generation.

Conservation Focus: The primary conservation application in Pompeii is predictive maintenance. Real-time data is used to assess environmental and structural changes, enabling conservationists to anticipate risks and intervene before significant damage occurs. The 3D

Fig. 1 View of the peristyle in the House of Caecilius Iucundus, Pompeii, Photo by Mister No, licensed under CC BY-SA 3.0 via Wikimedia Commons (Mister No, 2015)

models also support simulation of deterioration scenarios, aiding in the planning of restoration techniques. It is emphasized that how digital twins enable evidence-based decision-making, particularly valuable in fragile heritage sites like Pompeii (Liu and Wang, 2024).

Visitor Engagement: Digital twin models are also leveraged to improve visitor engagement. Virtual reality (VR) and augmented reality (AR) technologies allow users to experience reconstructed environments and interactive storytelling. This enhances both on-site experiences and remote access, offering educational narratives that deepen cultural understanding. Such immersive experiences increase both learning outcomes and emotional connection with the site (Zhao et al., 2022).

AI Usage: Currently, the implementation of artificial intelligence in Pompeii's digital twin system is limited. Most operations rely on static or sensor-driven modeling rather than AI-driven prediction, simulation, or personalization. However, the potential for future AI integration, such as anomaly detection or automated scenario planning, is acknowledged in the broader literature (Hutson et al., 2023).

Immersion Level: Pompeii is among the more immersive examples of digital twin usage in heritage. With VR/AR tours, interactive digital storytelling, and spatial simulations, the site offers a high level of immersion. These features not only enhance tourism but also help divert foot traffic from sensitive areas by offering virtual alternatives.

Monitoring Type: Pompeii utilizes both environmental and structural monitoring systems. Data from IoT sensors is used to track conditions such as humidity, air quality, and vibration, all of which are critical to preserving ancient materials. A notable example is the House of

Ariadne, where it is implemented a detailed sensor network to diagnose environmental variability and its impact on mural conservation, highlighting the importance of location-specific data analysis for early deterioration detection (Merello et al., 2014). These inputs are processed and visualized in the digital twin, forming the basis for conservation action.

Challenges Highlighted: Despite its strengths, Pompeii faces significant challenges related to tourism pressure and environmental degradation. The digital twin helps address these concerns through visitor flow modeling and predictive maintenance planning, but gaps in AI integration and the high costs of sustained digital infrastructure remain issues for long-term implementation.

The Pompeii case demonstrates how real-time monitoring and 3D modeling are actively used for restoration planning and visitor experience design. These tools are directly tied to the site's environmental vulnerability and high tourist volume. By leveraging real-time data collection, advanced modeling techniques, and immersive technologies, stakeholders can enhance both the conservation efforts and the visitor experience. This multifaceted approach not only safeguards the integrity of Pompeii but also ensures that its rich history is accessible to future generations. This innovative approach not only safeguards the archaeological site for future generations but also enhances the educational and experiential aspects of visiting such a historically rich location.

3.2 Case study 2: Notre-Dame, Paris

Following the catastrophic fire in April 2019, Notre-Dame (Fig. 2) became a prominent example of how digital twin technologies can support post-disaster heritage restoration. The reconstruction process relies on high-resolution 3D scans and BIM to document the cathedral's structure and guide restoration strategies. These digital tools are tailored to Notre-Dame's specific architectural features and have enabled simulation of structural behavior, testing of restoration materials, and coordination among interdisciplinary teams.

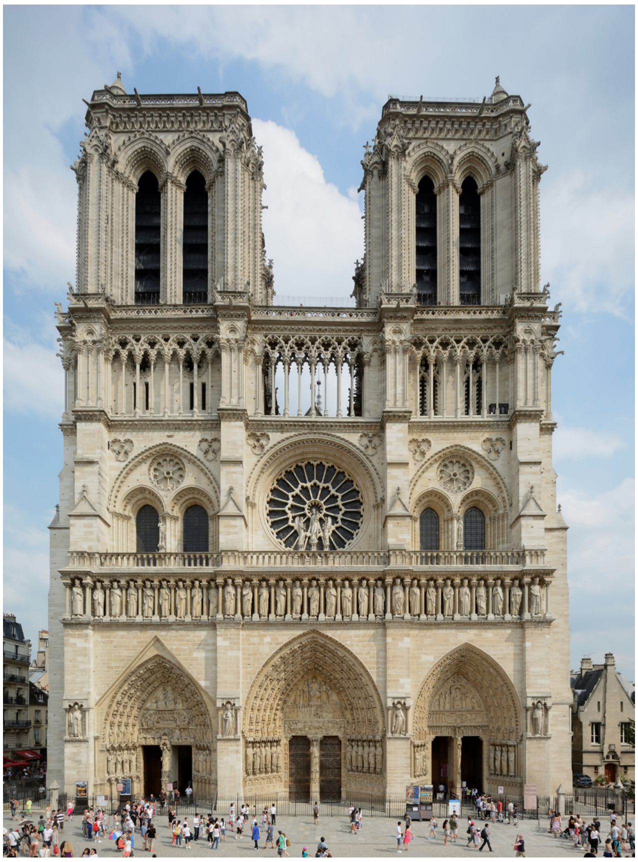

Fig. 2 Notre-Dame de Paris, July 2013, Photo by Peter Haas, licensed under CC BY-SA 3.0 via Wikimedia Commons (Haas, 2013)

Technologies Used: Following the 2019 fire, Notre-Dame became a flagship example of digital heritage innovation. Its digital twin implementation is grounded in high-resolution 3D scanning, BIM, and AI-supported simulation models. These tools have been used to document architectural details, test restoration materials, and simulate structural behavior. A digital twin-based workflow structured around four complementary stages, physical anastylosis, reverse engineering, spatiotemporal annotation, and operational modeling, was developed specifically to guide the reconstruction of collapsed components such as the nave and vaults (Hong, 2024). According to Roussel and De Luca (2023), these technologies are centrally managed via the AIOLI platform, ensuring comprehensive digital documentation for interdisciplinary collaboration. The integration of AR and VR into these digital representations can further enrich the visitor experience, providing interactive elements that educate users about the cathedral's history and architecture (Deng et al., 2024). This approach not only preserves the cultural significance of Notre-Dame but also promotes its global visibility as a tourist destination.

Conservation Focus: The digital twin of Notre-Dame is primarily used for post-disaster restoration, focusing on material compatibility, structural testing, and the simulation of restoration strategies. This detailed documentation allows conservators to test interventions virtually before executing them physically, minimizing risk. This digital infrastructure supports ongoing monitoring and enhances precision in restoration decisions (Néroulidis et al., 2024). This capability to evaluate restoration approaches digitally minimizes risks, helping to ensure that any new materials introduced will integrate seamlessly with Notre-Dame's historic fabric, thereby mitigating potential long-term impacts on the structural integrity of the building. Preservation efforts at Notre-Dame have been significantly bolstered by the use of digital twins. The reconstruction process involves detailed 3D scans and models that document the cathedral's structural integrity and historical features (Deng et al., 2024). This data is crucial for ensuring that restoration efforts maintain the authenticity of the original architecture while addressing the damage caused by the fire.

Visitor Engagement: While the physical site remains under restoration, Notre-Dame has leveraged its digital twin for remote visitor engagement. Through virtual reality tours and interactive digital narratives, the public can explore the cathedral virtually. These experiences have helped maintain global visibility and educational value despite limited physical access. Milosz et al. (2024) describe how 3D modeling has enabled high-fidelity reconstructions of damaged sections, enhancing these virtual experiences.

AI Usage: Notre-Dame is the most advanced case in terms of AI integration. AI algorithms are used for material behavior prediction, structural simulations, and automated monitoring. It is described how predictive analytics are embedded in the digital twin system to assess the structural impacts of environmental changes, facilitating data-informed decisions (Steindl et al., 2020). AI is also used to automate documentation processes, enhancing efficiency. Moreover, the integration of a semantic digital twin framework, such as the Heritage Digital Twin ontology, has been applied in the Notre-Dame project to organize and interlink heterogeneous data sources, including imaging, structural analysis, and acoustic documentation, for coordinated research and preservation planning (Hermon et al., 2024).

Immersion Level: The level of immersion provided to the public is moderate. While interactive VR experiences exist, they are mostly designed for remote access rather than on-site augmented exploration. However, the underlying digital infrastructure offers high fidelity, and immersive experiences are expected to expand post-restoration.

Monitoring Type: Notre-Dame's system primarily emphasizes structural monitoring, particularly of elements weakened or destroyed in the fire. Sensor networks are integrated into the digital model, tracking movement, material conditions, and restoration progress. This real-time feedback loop is critical for ensuring safety and accuracy in the reconstruction.

Challenges Highlighted: Key challenges include the integration of multidisciplinary datasets, the complexity of updating digital models in real time, and the ethical management of restoration authenticity. The sheer volume and sensitivity of data, ranging from structural scans to historical documentation, require robust coordination among engineers, architects, and historians. The need to preserve cultural integrity while leveraging advanced technology remains an ongoing balancing act.

In summary, Notre-Dame de Paris exemplifies the transformative potential of digital twin technologies in tourism, preservation, and the application of AI. By creating virtual representations of the cathedral, stakeholders can enhance visitor engagement, ensure meticulous restoration efforts, and leverage intelligent systems for ongoing management and monitoring. These innovations not only safeguard the cathedral's historical integrity but also position it as a leading example of how technology can be harnessed to protect and promote cultural heritage.

3.3 Case study 3: the Colosseum, Rome

The Colosseum in Rome uses digital twin technology to monitor the structural health of the ancient amphitheater, allowing conservationists to predict areas at risk of deterioration and prioritize their restoration efforts (Fig. 3). The digital twin system at the Colosseum includes IoT sensors and AR/VR reconstructions developed to document its structure and improve public access without physical impact. Additionally, the Colosseum's digital twin has enabled the development of virtual and augmented reality experiences for visitors.

Technologies Used: The Colosseum utilizes a hybrid digital twin system composed of IoT sensor networks, solar-powered monitoring devices, and immersive AR/VR

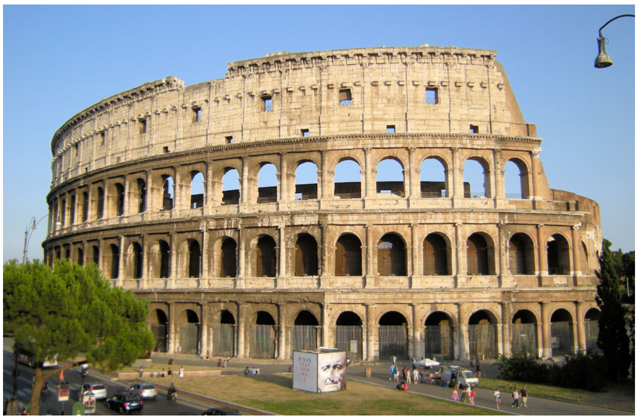

Fig. 3 The Colosseum in Rome, Photo by Urse Ovidiu, licensed under CC BY-SA 3.0 via Wikimedia Commons (Ovidiu, 2009)

environments. These technologies support both structural preservation and interactive engagement. These tools enable real-time data collection on environmental and structural parameters (Kim and Park, 2023). Additionally, AR and VR components have been developed to create reconstructions that allow users to experience the amphitheater's historical evolution (Cruz Franco et al., 2022).

Conservation Focus: The conservation strategy for the Colosseum emphasizes stress analysis and real-time monitoring of structural conditions. The digital twin framework enables site managers to simulate structural behaviors under varying environmental conditions, thereby supporting preventive conservation. This dynamic management approach integrates both historical integrity and sustainability by enabling interventions that are informed by real-time monitoring and simulation data (Massafra et al., 2022). Furthermore, the digital twin framework facilitates preventive conservation measures by simulating various scenarios that could impact the Colosseum's structural integrity. By analyzing potential threats and their implications, site managers can implement timely interventions to mitigate risks associated with environmental factors and human activities (Jouan and Hallot, 2019). This predictive capability is essential for preserving the Colosseum's architectural identity while adapting to modern usage demands.

Visitor Engagement: Visitor engagement is a central feature of the Colosseum's digital twin. Through immersive AR/VR reconstructions, tourists can explore historically accurate depictions of the site without compromising the physical structure. This technology is especially impactful for off-site users or for interpreting inaccessible areas. Themistocleous et al. (2022) highlight how these experiences not only improve educational impact but also democratize access to heritage.

AI Usage: AI usage at the Colosseum remains limited but emerging. Some AI applications are used to interpret sensor data and simulate structural responses to environmental stress. However, advanced features like predictive analytics or personalized visitor interfaces are still under development. Existing implementations suggest a trajectory toward more sophisticated AI use as infrastructure matures (Cruz Franco et al., 2022).

Immersion Level: The Colosseum delivers a high level of immersion through its robust AR/VR content, which includes reconstructed gladiatorial games, narrated virtual tours, and contextual overlays of architectural history. These features provide not only entertainment but also meaningful educational interactions.

Monitoring Type: The Colosseum employs both structural and environmental monitoring. Solar-powered sensors track temperature, humidity, and vibration levels, while embedded structural sensors monitor load distribution and degradation. This dual-layered system helps to identify risks posed by both natural deterioration and tourism-related wear.

Challenges Highlighted: Challenges include managing climate-related stressors, particularly heat and humidity, and mitigating the impact of fluctuating tourist volumes. The site's ancient materials are highly sensitive to environmental change, and the continuous influx of visitors intensifies preservation risks. Additionally, implementing and maintaining advanced digital infrastructure in a UNESCO-protected site poses technical and regulatory difficulties.

In summary, the Colosseum's utilization of digital twin technologies represents a significant advancement in cultural heritage management. By combining real-time data monitoring, immersive visitor experiences, and predictive conservation strategies, digital twins not only enhance the preservation of this iconic monument but also ensure its relevance and accessibility for future generations.

3.4 Case study 4: Hagia Sophia, Istanbul

The application of digital twin technology to cultural heritage sites, particularly the Hagia Sophia in Türkiye, represents a significant advancement in the preservation and management of historical architecture (Fig. 4). Digital twins serve as real-time digital counterparts to physical structures, allowing for detailed monitoring and analysis of their conditions.

Technologies Used: Hagia Sophia's digital twin implementation primarily utilizes BIM, acoustic modeling, and photogrammetry to document and analyze its complex spatial and material characteristics. These technologies are used to

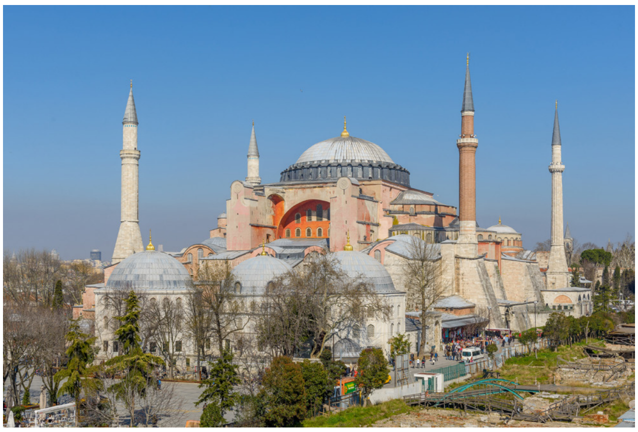

Fig. 4 Hagia Sophia, March 2013, Photo by Arild Vågen, licensed under CC BY-SA 3.0 via Wikimedia Commons (Vågen, 2013)

construct high-resolution 3D models of the monument, aiding both documentation and diagnostic assessment. As outlined in the study, recent advances have made it possible to rapidly digitize large-scale heritage structures like Hagia Sophia with high geometric fidelity (Hutson et al., 2023).

Conservation Focus: The conservation emphasis at Hagia Sophia lies in long-term structural preservation and historical documentation. Particular focus is given to capturing the monument's acoustic and spatial dynamics, which are central to its architectural identity. Creating photo-realistic and animated digital models allows for the reconstruction of lost or altered architectural features. For Hagia Sophia, virtual restitution techniques help visualize its historical states and architectural evolution (Foni et al., 2007). Studies also highlight how acoustic modeling is used to understand the reverberation characteristics of the domed structure, contributing to both historical interpretation and conservation strategies (Sü Gül et al., 2018; Sü Gül, 2021). Moreover, this preventive approach aligns with best practices in heritage conservation, emphasizing the importance of maintaining the structural integrity of significant cultural sites like the Hagia Sophia (Jouan and Hallot, 2019).

Visitor Engagement: Compared to other sites, Hagia Sophia offers minimal digital engagement for visitors. The current digital twin initiatives are primarily used for professional analysis and heritage management rather than for public interaction. Educational content based on 3D models has been developed, but immersive features such as AR or VR experiences remain limited. This approach reflects the sensitivity of the site's religious, political, and historical contexts.

AI Usage: At this stage, no direct integration of AI has been reported in the Hagia Sophia digital twin system. While the modeling and data acquisition are advanced, the use of AI for prediction, automation, or visitor personalization has not yet been adopted. Most digital applications remain manually operated and rely on traditional data analysis techniques.

Immersion Level: The level of immersion is low, with outputs mostly focused on academic or technical visualization. Public-facing digital content consists mainly of static 3D views or informative videos based on digital documentation. Unlike Pompeii or the Colosseum, immersive technologies such as VR tours or interactive storytelling are not currently prioritized at Hagia Sophia.

Monitoring Type: Hagia Sophia's monitoring system emphasizes structural conditions and acoustic behavior. BIM-integrated models track geometric and material data, while acoustic simulations are used to understand and preserve the building's historical sound environment. However, environmental monitoring (e.g., humidity or air quality sensors) is less emphasized compared to other sites like Pompeii or the Colosseum. The integration of BIM with digital twin technologies allows for the incorporation of extensive data about the building's materials, structural integrity, and historical context, which is crucial for effective preservation strategies (Jouan and Hallot, 2019). Additionally, understanding the value of digital twins in monitoring material performance and informing maintenance planning is essential. The implementation of real-time monitoring systems through digital twins can facilitate proactive conservation efforts. By continuously collecting data on structural health and environmental conditions, stakeholders can identify potential risks and implement timely interventions to mitigate damage (Kim and Park, 2023; Vuoto et al., 2024).

Challenges Highlighted: The main challenges involve the acoustic complexity of the structure, the ethical considerations of digitizing a still-functioning religious and political symbol, and the sensitivity surrounding access to heritage data. It is highlighted the ongoing debate about how to manage inclusive access to Hagia Sophia while respecting its symbolic and spiritual roles (Cho, 2023). Moreover, digital representations must navigate these complexities without oversimplifying or misrepresenting the site's layered identity.

In conclusion, the integration of digital twin technology into the management of the Hagia Sophia offers a transformative approach to cultural heritage preservation. By leveraging advanced modeling techniques and real-time data analysis, stakeholders can enhance their understanding of this iconic structure, ensuring its conservation for future generations while promoting its accessibility and educational value (Cruz Franco et al., 2022; Gabellone, 2022).

4 Comparison of digital twin implementations

To synthesize the insights from the four case studies, the case studies were compared based on the determined criteria in a structured manner. The comparison is based on key dimensions identified throughout the study: technologies used, conservation focus, visitor engagement, AI usage, immersion level, monitoring type, and challenges encountered. This structured approach aims to respond directly to the reviewer's request for analytical depth and clarity.

Technologies Used: Pompeii demonstrates a robust integration of environmental sensors, photogrammetry, and 3D scanning technologies. These tools facilitate detailed digital models and real-time environmental analysis. In contrast, Notre-Dame relies heavily on BIM and AI simulation models, used extensively during its post-fire restoration. The Colosseum employs a combination of IoT sensor networks and solar-powered devices, along with AR/VR systems to manage conservation and visitor access. Hagia Sophia uses photogrammetry and acoustic modeling, supported by BIM systems to capture the building's spatial and structural complexity.

Conservation Focus: The primary conservation aim at Pompeii is predictive maintenance and structural health monitoring. The digital twin enables simulation of environmental effects and degradation over time, supporting restoration strategies. Notre-Dame's digital twin is used for highly specialized restoration testing, ensuring material compatibility and structural safety post-fire. At the Colosseum, the digital twin supports stress analysis and long-term preservation, focusing on structural responses to environmental conditions. Hagia Sophia's efforts are centered on long-term structural documentation and modeling of complex acoustic dynamics, prioritizing heritage recording and material-based interventions.

Visitor Engagement: Visitor engagement varies significantly across the sites. Pompeii and the Colosseum both employ immersive AR and VR applications that reconstruct historical narratives and allow interactive exploration, significantly enhancing educational and experiential value. Notre-Dame offers remote VR-based tours enriched with interpretive content but has more limited on-site engagement due to restoration activities. Hagia Sophia has minimal digital engagement for visitors; its focus is primarily on documentation and preservation rather than interactive applications.

AI Usage: AI integration is most pronounced at Notre-Dame, where it plays a central role in restoration scenario analysis, material behavior prediction, and monitoring automation. The Colosseum includes some AI functionalities, particularly in data interpretation and scenario simulation, though these are still developing. No AI applications are currently evident in the digital twin frameworks for Pompeii and Hagia Sophia, which rely more on real-time sensor data and static modelling approaches.

Immersion Level: In terms of immersive visitor experiences, both Pompeii and the Colosseum are at the high end of the spectrum, offering VR and AR-based reconstructions and interactive storytelling. Notre-Dame provides moderate immersion, mainly through virtual tours rather than on-site interactivity. Hagia Sophia offers low immersion, with engagement limited to passive educational content without immersive technology integration.

Monitoring Type: Monitoring approaches also vary. Pompeii and the Colosseum use both environmental and structural monitoring systems, supporting comprehensive heritage management. Notre-Dame focuses specifically on structural monitoring, especially during reconstruction. Hagia Sophia employs structural monitoring as well, with emphasis on acoustic preservation and geometric stability, but without integrated environmental tracking.

Challenges Highlighted: Each site faces context-specific challenges. Pompeii struggles with high tourist traffic and environmental degradation, which the digital twin aims to manage through simulation and planning. Notre-Dame's main challenges involve integrating vast multidisciplinary data during a sensitive restoration, alongside maintaining digital fidelity and real-time updates. The Colosseum grapples with climate stress and infrastructural load, especially due to fluctuating tourist volumes. Hagia Sophia presents challenges of acoustic complexity, historical sensitivity, and ethical concerns surrounding digital representation and data use.

The summary of the comparisons of the case studies based on the identified criteria are presented in Table 1.

5 Discussion and conclusion

The integration of AI with digital twins has revolutionized visitor engagement in heritage tourism. By offering real-time interactivity, visitors can explore heritage sites remotely or augment their physical visits with digital enhancements. AI-powered digital twins create immersive experiences through VR and AR technologies, which bring historical storytelling to life and provide interactive guided tours. These developments have allowed cultural sites to become more accessible, interactive, and educational, fostering a deeper connection between visitors and heritage. Case studies such as Pompeii, Notre-Dame, and the Colosseum have demonstrated the impact of digital twins in providing unique, engaging visitor experiences while preserving the authenticity of these sites.

Digital twins are proving invaluable to the conservation of heritage sites by providing the tools needed for effective monitoring and predictive maintenance. They assist in tracking environmental conditions, structural wear, and visitor impacts, thereby enabling stakeholders to anticipate and address conservation needs before significant damage occurs. Through real-time data collection and analysis,

Table 1 Comparative summary of digital twin implementations

Site	Technologies used	Conservation focus	Visitor engagement	AI usage	Immersion level	Monitoring type	Challenges highlighted
Pompeii	Sensors, Photogrammetry, 3D Scanning	Predictive maintenance, structural integrity	VR/AR tours, virtual storytelling	No	High (VR/AR)	Environmental + Structural	Tourism pressure, environmental risks
Notre-Dame	BIM, AI Simulation, 3D Models	Post-disaster restoration, material testing	Remote VR tour, interactive narratives	Yes	Moderate (mainly VR)	Structural Monitoring	Fire damage, data integration
Colosseum	IoT Sensors, AR/VR, Solar Sensors	Stress analysis, real-time preservation	Immersive reconstructions, global access	Limited	High (VR/AR)	Structural + Environmental	Climate change, visitor pressure
Hagia Sophia	Acoustic Modeling, Photogrammetry, BIM	Structural preservation, historical documentation	Minimal (educational content only)	No	Low	Structural Monitoring	Acoustic complexity, ethics of digitisation

AI-powered digital twins help maintain the integrity of cultural heritage by providing insights that allow for timely restorations and preventive interventions. For example, at Pompeii and Hagia Sophia, digital twins have been instrumental in monitoring environmental factors and planning restoration efforts based on predictive data.

Digital twins offer a virtual alternative to physical site visits, thereby helping to reduce the pressure of tourism on fragile heritage sites. By enabling virtual access to heritage sites, digital twins provide an immersive experience that serves as a substitute for or complement to physical visits. This helps manage visitor traffic, mitigating wear and tear on delicate structures, and contributes to the sustainable preservation of these sites, ensuring they remain intact for future generations. The Colosseum's use of digital twin technology, for instance, has successfully allowed tourists to experience the site virtually, reducing physical stress on the ancient amphitheater.

Despite their advantages, AI-driven digital twins present ethical and technological challenges that must be addressed. Ensuring data accuracy and maintaining the integrity of digital replicas are critical, as inaccuracies can lead to misleading representations of heritage. Ethical concerns also arise with AI's speculative reconstructions, which could misrepresent historical features or overlook cultural sensitivities. Striking a balance between technological advancement and the ethical responsibilities of accurately preserving cultural narratives is essential. The case studies of Notre-Dame and Hagia Sophia highlight the importance of ethical considerations in ensuring that digital replicas respect the cultural significance of these heritage sites.

The findings of this study demonstrate that AI-powered digital twins significantly enhance visitor engagement while providing sustainable solutions for heritage conservation. By integrating advanced data collection, AI-driven analysis, and immersive technologies, digital twins offer an innovative way to balance the needs of conservation with those of heritage tourism, ultimately promoting cultural preservation and accessibility. The case studies presented in this research, Pompeii, Notre-Dame, the Colosseum, and Hagia Sophia, illustrate the transformative potential of digital twins in both visitor engagement and heritage conservation.

Looking forward, the broader adoption of AI-driven digital twins across more heritage sites, combined with the integration of advanced immersive technologies such as AR and VR, holds significant potential. Expanding these tools could improve visitor accessibility and engagement, making heritage experiences more inclusive and informative. Further research and development are recommended to explore the applications of AI in creating even more interactive and immersive heritage tourism experiences. The example of Notre-Dame's reconstruction efforts shows how digital twins can facilitate collaboration among experts and enhance restoration precision.

Digital twins are poised to transform the future of heritage tourism by balancing accessibility, engagement, and preservation. They offer a sustainable means to experience cultural heritage, allowing visitors from across the globe to interact with and appreciate heritage sites without physically being there. By combining immersive digital experiences with traditional tourism, digital twins can help create a more resilient and inclusive model for the future of heritage tourism, ensuring that cultural treasures are accessible, preserved, and enjoyed by diverse audiences. The case studies in this research provide a glimpse into how digital twins can reshape heritage tourism, making it more sustainable and widely accessible. To consolidate the comparative findings across the four case studies, the following key takeaways are highlighted:

- Pompeii demonstrates strong integration of environmental sensors and immersive VR/AR applications, with a primary focus on predictive maintenance and visitor engagement, though AI remains underutilized.
- Notre-Dame leads in AI integration and post-disaster restoration simulation, offering high technical precision and moderate visitor immersion through remote experiences.
- The Colosseum balances conservation and tourism through solar-powered monitoring systems and high-quality immersive reconstructions, though AI use is still limited.
- Hagia Sophia prioritizes structural documentation and acoustic analysis with minimal public-facing digital engagement, reflecting the site's sensitive cultural and political context.

These comparative insights emphasize that while digital twin technologies are increasingly adopted across diverse heritage settings, their implementation strategies vary according to site-specific priorities, technical capacity, and cultural considerations. Future efforts should focus on balancing technological sophistication with ethical and contextual appropriateness to maximize both conservation outcomes and public accessibility.

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