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Digital Twin in Heritage Buildings: A Comparative Literature Review of Integrated Technologies, Devices, and Applications (2020–2025)

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Abstract

The concept of Digital Twin has attracted growing interest within research communities in recent years, including heritage conservation. It combines detailed geometric documentation, real-time monitoring, and semantic information to create dynamic digital replicas of historic buildings. This paper presents the results of a scoping review of 204 peer-reviewed studies published between 2020 and 2025. The aim is to identify the main technologies, devices, and methods used to develop a Digital Twin for heritage buildings. The review reveals that terrestrial laser scanning, UAV photogrammetry, BIM, and IoT sensor networks form the core technological base. It also highlights the growing use of artificial intelligence for automated defect detection, predictive maintenance, and semantic processing. Based on the reviewed literature, the paper introduces a six-stage workflow for building a heritage Digital Twin, covering baseline documentation, static reality capture, semantic modelling, sensor integration, data fusion, and operational use. The findings show a clear shift from static 3D documentation toward dynamic, data-rich systems that support continuous monitoring and more informed decision-making. However, the review also identifies major challenges, including limited interoperability, complex data integration, incomplete AI validation, and long-term digital preservation issues. Overall, the study outlines the current state of Digital Twin technologies in architectural heritage and identifies key areas that require further research to support reliable and sustainable applications.

1. Introduction

Architectural heritage buildings are considered as vital links between contemporary society and the cultural, historical, and architectural legacies of past civilizations. However, they face challenges arising from environmental factors, natural disasters, climate change, rapid urbanization (Vuoto et al., 2024) and the devastating consequences of human conflicts (Pasupuleti, 2025). Furthermore, the conservation and management of these valuable structures appear sensitive and complicated due to their age, historical significance, and often fragile condition (Jouan & Hallot, 2020).

The concept of Digital Twin, originally developed for industrial and aerospace applications, has emerged as a powerful technology for creating dynamic, data-rich virtual replicas of physical assets (Liu & Wang, 2024) and has expanded into building management, smart cities, and increasingly, heritage conservation (Angjeliu et al., 2020). Unlike traditional documentation methods that produce static representations, Digital Twin integrates continuous data streams from multiple sources, enabling real-time monitoring, predictive analytics, and scenario-based decision support for conservation interventions (Ni et al., 2025) ; (Hosamo & Mazzetto, 2024).

The idea and necessity of this literature review emerged during the main author’s doctoral research on the Digital Twin application in heritage buildings. In exploring the potential of Digital Twin technology and the possibilities of integrating existing tools and technologies for its implementation, the authors reviewed previous studies to gain a comprehensive understanding of the advantages, limitations, and current state of research in this field. Because, despite growing research activity and promising case studies, the field still lacks a comprehensive methodological approach and a systematic evaluation of technological options (Battina & Jaganathan, 2023). In many studies, Digital Twin is still viewed merely as a three-dimensional geometric model, overlooking its broader potential for data integration, real-time interaction, and decision support. Moreover, the diversity of tools and methods poses difficulties in using these innovations.

To address these gaps, this paper draws on a scoping review of research and case studies from 2020 to 2025, providing an overview and preliminary classification of existing approaches. It aims to identify and categorize the technologies, devices, and tools used across the Digital Twin lifecycle, from data acquisition to visualization and application deployment. The review also considers the common use cases, technology combinations, and reported outcomes. Finally, it identifies emerging trends such as AI-enhanced workflows, real-time monitoring systems, and open-source platforms, as well as ongoing challenges of standardization, scalability, and validation. The findings aim to clarify the current state and future directions of Digital Twin technologies in architectural heritage.

2. Methodology

2.1 Literature Search Strategy

The scoping literature review focuses exclusively on peer-reviewed journal articles and conference papers published between January 2020 and October 2025. The search considers major academic databases: Scopus, Web of Science, IEEE, ACM Digital Library, ScienceDirect, SciSpace, SpringerLink, MDPI, Taylor & Francis, and PubMed. These databases were selected so that the study covers different relevant disciplines, including computer science, civil engineering, conservation science, and cultural heritage management.

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The search strategy employed Boolean combinations of core terms and specific keywords related to the domain: TS= (“Digital Twin*” OR “Digital Replica*” OR “Virtual Replica*” AND "heritage building*" OR "historic building*" OR architectural heritage*" OR "built heritage*" OR "monument*" OR "historic structure*") AND PY = (“2020–2025”) AND DT= (“Article”). TS refers to the search topic, PY represents the publication year, and DT indicates the document type. The language was limited to English. Using this Boolean combination, a total of 564 publications were initially retrieved. The manual selection process followed a set of well-defined inclusion and exclusion criteria to ensure the relevance and quality of the reviewed studies. Eligible studies explicitly mentioned “Digital Twin” in the title, abstract, or keywords and focused on heritage buildings, historic sites, world heritage properties, or ancient monuments. Both practical applications, such as case studies, and theoretical contributions, including systematic reviews or methodological frameworks, were considered.

On the other hand, studies were excluded if they focused only on modern buildings or infrastructure without referring to heritage contexts, or if they addressed general Building Information Modelling (BIM), photogrammetry, or Internet of Things (IoT) applications without an explicit digital twin framework. Studies referring to cultural heritage at scales or in domains other than sites, buildings, or structures were also excluded with duplicates subsequently removed. In addition, Memory Twins and Ambient Twins studies were also excluded, as their focus was not relevant to the specific scope of this review. Following this manual review phase, 204 studies were retained. A PRISMA 2020 flow diagram for the identification and selection of studies is illustrated in Figure 1. These 204 articles form the core dataset for this study. The full list of reviewed publications is available in the dataset (Tootoonchi, 2026).

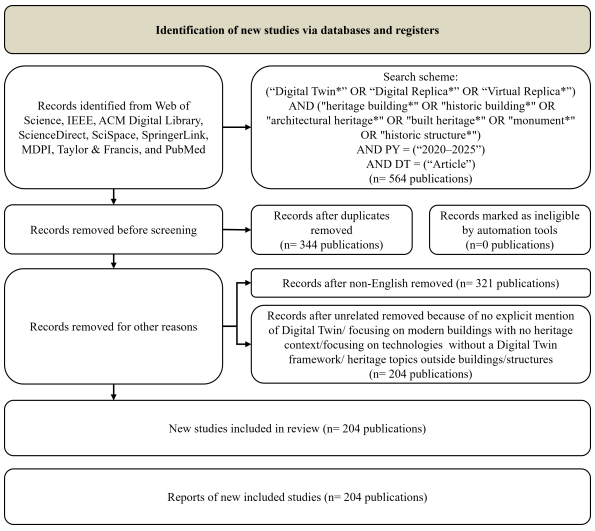


Figure 1. PRISMA flow diagram illustrating the identification, screening, and eligibility assessment of studies in the scoping review.

2.2 Literature Analysis and Visualization

From each included study, the following information was extracted: data acquisition technologies, 3D modelling approaches, integration platforms, visualization technologies, application domains, case study assets, and reported challenges. A qualitative thematic analysis of the extracted data was conducted to uncover key technological trends and integration strategies. The findings of this review are presented in detail in Section 3.

Eventually, the study employed a bibliometric analysis framework using VOSviewer version 1.6 (VOSviewer-Visualizing Scientific Landscapes, 2025) that enables the visual identification of research hotspots through network maps and reveals associations among keywords, offering a macroscopic view of the research scope (Xiao et al., 2025). As it can be seen in Figure 2, keywords are represented as circular nodes whose size reflects their centrality or weight while link thickness indicates the strength of co-occurrence relationships (Jentner et al., 2023). A co-occurrence analysis was conducted in VOSviewer using bibliographic data exported from Zotero. A minimum occurrence threshold of 10 was applied, resulting in 70 terms; generic terms (e.g., “point,” “article,” “solution”) were manually removed to produce the final visualization. Eventually, the VOSviewer network reveals four main thematic clusters that together describe the current structure of Digital Twin research in heritage buildings.

The green cluster is strongly centered on BIM, HBIM, point clouds, and digital models, showing that most research is still driven by geometric modelling and data acquisition. Terms such as historic building and preventive conservation are closely linked to these technologies, indicating that modelling is often positioned as the core of Digital Twin development. However, the dominance of these terms also confirms that many studies remain focused on representation rather than full integration of dynamic data and system functionality. The red cluster highlights AI, IoT, structural health monitoring, climate change, energy, sustainability, risk, and resilience. This cluster represents the data-driven and monitoring side of Digital Twins. While it introduces concepts related to real-time sensing and proactive conservation, its relatively loose connection to the modelling cluster suggests that sensing and analysis are often treated as separate components rather than fully integrated into a unified Digital Twin system. This supports the observation that real-time and automated data integration is still limited in practice. The blue cluster includes 3D models, GIS, as well as earthquake and sensors, reflecting a strong focus on hazard-related applications in a broader scale. However, despite incorporating sensing and analysis elements, these approaches remain largely technical. Finally, the yellow cluster includes terms such as site, user, visitor, virtual reality, collaboration, and protection, pointing toward user interaction, interpretation, and communication. Although this cluster introduces the idea of user engagement, its weaker connections to the technical clusters indicate that user-oriented design is not yet fully embedded in Digital Twin development. This reinforces the need for more accessible and user-friendly systems that can be used not only by technical experts but also by conservation professionals, building managers, and the public.

Overall, the network structure clearly shows a fragmented landscape where modelling, sensing, and user interaction evolve in parallel but are not yet fully integrated. This fragmentation directly supports the identified gap between the conceptual definition of Digital Twins and their practical implementation, highlighting the need for more coherent, integrated, and user-oriented frameworks.

Furthermore, earlier studies focused mainly on foundational technologies for data acquisition and creating the 3D model. But

more recent publications move toward advanced analytical and smart integration approaches, including artificial intelligence, IoT-enabled continuous monitoring, and real-time data processing. This progress indicates a transition from basic data capture and geometric modelling toward intelligent, dynamic, and semantically enriched Digital Twin systems for heritage buildings and sites. Another notable emerging trend is the use of AI to reconstruct "lost" or intangible heritage, moving beyond the documentation of existing structures.

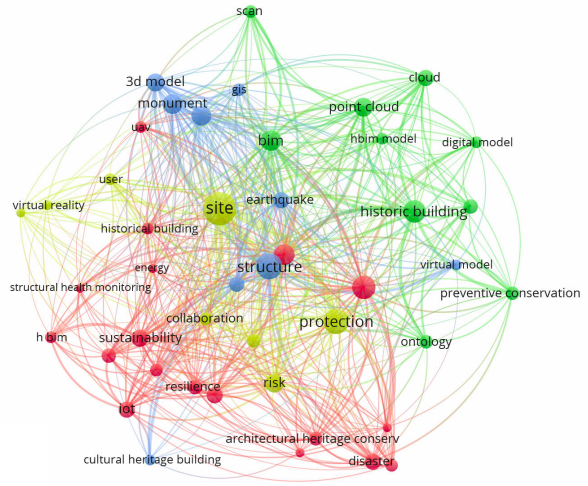


Figure 2. Cluster analysis of high-frequency keywords

3. Results

The analysis of 204 publications from 2020 to 2025 reveals a notable growth in implementing Digital Twin in architectural heritage. This is particularly evident in publications between 2023 and 2024, which highlight the accelerated adoption of Digital Twin as both a conceptual and technological framework for heritage documentation, management, and conservation. Most contributions are scholarly journal articles, followed by conference proceedings and book chapters. This reflects the gradual evolution of research dissemination channels within this field.

According to the literature, a Digital Twin of a heritage building is a data-driven digital replica that is continuously updated. It brings detailed reality capture, sensor monitoring, and semantic modelling together to represent both the physical condition and the cultural significance of a historic asset. Unlike modern buildings or industries where real-time control and optimizing performance. are priorities, the main goal of Digital Twin in heritage buildings is documentation and preservation. Since these structures are old and fragile, Digital Twin must capture high-precision geometry, monitor deterioration, and support non-invasive decision-making, Heritage Digital Twin also integrates cultural and historical context, making them tools for conservation, research, and interpretation rather than pure technical management. The extracted data from the literature related to the main technologies and methods, applications, geographic distribution and focus of the studies are as follows:

3.1 Core Methods and Tools

The literature indicates different clusters of technologies that are consistently employed to build and operate the Digital Twin. Across the reviewed studies, five methodological clusters clearly dominate the development of heritage Digital Twin. Geometry-centered workflows remain the most common path. They draw on laser scanning, Unmanned Aerial Vehicle (UAV) photogrammetry, SLAM systems, and integrated point clouds, forming the spatial core of many projects. A second major group focuses on monitoring. These studies use sensor networks and structural health monitoring frameworks to track climate conditions, material change, and structural response. Semantic information modelling adds another layer. Here, Heritage Building Information Modelling (HBIM) environments and ontology-based frameworks organize data in a structured and interoperable form. AI-based analytics extend these capacities through visual damage detection, performance prediction, and operational optimization. A smaller share of the literature explores rapid documentation and participatory techniques, including virtual technical tours and 360-degree recording.

A comparable pattern is visible in platforms that host and integrate Digital Twin data. The largest group uses HBIM-centred environments, reflecting the architectural focus that defines much of the field. A second cluster adopts hybrid BIM and GIS systems, which support multi-scale and territorial analysis. Cloud dashboards and Common Data Environments appear frequently, especially in work concerned with facility management and continuous monitoring. Immersive tools such as VR, AR, and XR strengthen interpretive, training, and engagement applications. A final group relies on ontology and knowledge-graph platforms, which enable advanced reasoning, cross-system interoperability, and semantic enrichment.

3.2 Primary Application Domains

Real-time structural and environmental monitoring is one of the main areas to implement Digital Twin in heritage buildings. It supports early detection of deterioration and helps conservators act before problems become severe (Hosamo & Mazzetto, 2024; Ni et al., 2025). IoT sensors linked to Digital Twin record structural data such as strain, displacement, vibration, and crack growth. They also track environmental factors such as temperature, relative humidity, CO_2, dust, and light, together with indicators of material decay such as moisture, salt activity, and biological growth. This category represents about 30% of the reviewed studies and includes risk and damage assessment.

Documentation, digitization, and virtual reconstruction account for about 25% of the studies. In this cluster, Digital Twin act as detailed digital records that capture the current state of a site, its conservation history, and changes over time (Abdelalim, 2025; Pasupuleti, 2025). This work is crucial for sites at risk from natural hazards, conflict, or urban pressure. High-resolution documentation provides a reliable reference for conservation planning and enables long-term monitoring through comparison of 3D models created at different stages. Digital Twin also supports virtual access for researchers, educators, and the public when physical access is limited. After the 2019 fire at Notre-Dame Cathedral, the Digital Twin contributed to decision-making and guided the reconstruction process (Gros et al., 2023).

Management and planning applications form around 15% of the reviewed studies. In this category, Digital Twin supports preventive conservation and helps organize conservation tasks. They also strengthen conservation planning by bringing together geometric data, material information, structural analysis, and historical research (Galiano-Garrigós & López-Torres, 2024). During restoration work, Digital Twins help teams test

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intervention scenarios, improve communication among experts, and create clear records of completed work. A related area within this category is energy and facility management (almost 20% of the studies), where Digital Twins help evaluate building performance, optimize HVAC operation, and study visitor flows to reduce conservation risks (Batziou et al., 2025).

The remaining 10% of studies focus on visitor experience and intangible heritage. These projects use extended reality, virtual exhibitions, immersive tours, and social models to enhance public engagement (Brumana et al., 2023; Dang et al., 2023). Digital Twins support virtual visits, show how sites changed over time, and improve learning through interactive or game-based formats.

3.3 Geographic Distribution and Focus

Without mentioning the single case studies, the geographic distribution of case studies reveals a clear concentration in Europe, with Italy and Spain representing the largest shares of contributions. In Asia, China emerges as a major contributor, particularly in the development of conceptual Digital Twin frameworks and museum-technology applications. The Eastern Mediterranean region, including countries such as Greece and Cyprus, demonstrates a notable presence, especially in studies related to monitoring and structural analysis. Additional contributions come from the Middle East and Central Asia, reflecting growing interest in reconstruction and heritage monitoring initiatives. South America is represented through a smaller but relevant number of studies, while Northern and Central Europe contribute mainly through research on energy performance. The remaining body of work consists of global or multi-regional studies that are not associated with a specific geographic location.

The typological distribution of case studies demonstrates a concentration on individual historic buildings and sites with 50%, including churches, palaces, and museums. Archaeological sites represent 20% and urban districts and cultural landscapes account for 15%, particularly in tourism and planning studies. Museums and interior spaces represent 10%, including virtual museum and interior-sensor projects. Intangible-heritage and socially oriented cases make up the final 5%, focusing on XR narratives and socio-technical Twins.

Overall, the literature demonstrates an evident transition from static digital documentation toward dynamic, intelligent heritage management systems. The integration of HBIM, IoT, and AI is changing conservation practices and a growing role for sensors and energy modelling. The period 2020–2025 is characterized by a transition from the initial stages of conceptual experimentation to the establishment of mature and consolidated methodologies for the Digital Twin of heritage buildings. Consequently, Digital Twin is considered to be a useful tool for sustainable, data-driven conservation practices.

Nevertheless, the reviewed studies show that research on Digital Twins in cultural heritage is still largely focused on representation rather than true functionality. Most approaches prioritize documentation, visualization, and conservation planning, while the core idea of a Digital Twin as a dynamic, responsive system is often not fully realized. At the same time, sensing, data integration, and user interaction are often treated as separate components rather than parts of a unified system. As a result, many proposed “Digital Twins” remain static or only partially dynamic, lacking real-time connectivity and continuous feedback between the physical asset and its digital counterpart. This highlights a fundamental gap between concept and implementation. Current approaches rarely provide an integrated environment where geometry, data, and user interaction work together to support decision-making. In addition, the strong reliance on technical and specialist-driven workflows limits accessibility and reduces the potential for broader use beyond expert communities. What is missing is a coherent, user-oriented framework that simplifies complexity while maintaining functionality. Therefore, the following section introduces a framework that aims to clarify and operationalize the concept of a Digital Twin for heritage buildings, moving beyond static representations toward a more integrated, interactive, and meaningful system.

4. Developing a Digital Twin of Heritage Buildings

According to the extensive review of the literature, the development of a functional Digital Twin for heritage buildings can be understood as a linear yet interconnected progression of six essential stages including baseline documentation, static reality capture, semantic modelling, sensor integration, data fusion in a Digital Twin platform. As shown in Figure 3, these stages form the minimum conceptual and technical framework required to transform a heritage asset from a static physical structure into a dynamic, intelligent, and continuously updated Digital Twin ecosystem.

The workflow begins with baseline documentation. This step gathers all available historical, architectural, and conservation sources. Archival drawings, photographs, earlier restoration reports, narratives, and diagnostic files form a reference base that defines the significance, evolution, and conservation record of the building. This material supports later modelling and analysis and ensures that the Digital Twin reflects both present condition and historical identity.

The next step is static reality capture. Here the physical fabric is recorded with high detail. Terrestrial laser scanning (TLS) and LiDAR produce dense point clouds with millimeter accuracy and document complex geometry and deformation (Abdelalim, 2025; Fattore et al., 2025). Point cloud registration and preprocessing were mostly carried out with software such as Leica Cyclone, FARO Scene, Trimble RealWorks, CloudCompare, and Agisoft Metashape.

Large projects, such as the Appian Way, show TLS as a core method for multi-scale Digital Twins and for HBIM generation (Brumana et al., 2023; Spano et al., 2023). UAV photogrammetry complements scanning by capturing roofs, elevations, and inaccessible areas and by producing textured mesh models through Structure from Motion (Egodawela et al., 2023; Parrinello & Picchio, 2023; Tsikas et al., 2025). Mobile mapping and SLAM systems facilitate rapid indoor and outdoor acquisition and support large terrain documentation (Brumana et al., 2023). Multi-sensor capture, including thermal images, panoramic sets, and structured light, strengthens material diagnostics. Recent examples, such as the Yellow River heritage Digital Twin initiative, demonstrate that no single technology can meet all requirements, and reflect the necessity of integrated acquisition strategies (Dang et al., 2023; Fattore et al., 2025).
The third step is semantic modelling. Raw spatial data is transformed into structured models through HBIM, parametric modelling, and ontology driven classification. Scan to BIM workflows segment the point cloud and produce parametric elements that represent irregular geometry, materials, construction logic, and conservation history (Alshawabkeh et al., 2024; Spano et al., 2023). Parametric tools such as Autodesk

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Revit, ArchiCAD, Rhino, Grasshopper, and Blender support the modelling of complex shapes and enable scenario testing for conservation (Liu & Wang, 2024). Interoperability remains a challenge, addressed through IFC extensions, CityGML structures, CIDOC CRM based ontologies, and knowledge graph systems linking HBIM, diagnostics, and sensors (Hosamo & Mazzetto, 2024; Niccolucci & Felicetti, 2024). Through these methods, semantic modelling turns geometry into an information system.

Together, these six stages form the minimum essential framework for developing a comprehensive heritage Digital Twin. Each stage progressively enriches the model with historical context, geometric precision, semantic depth, real-time dynamism, and operational intelligence, ensuring that the Digital Twin evolves alongside the physical asset and supports long-term conservation, research, and public engagement.

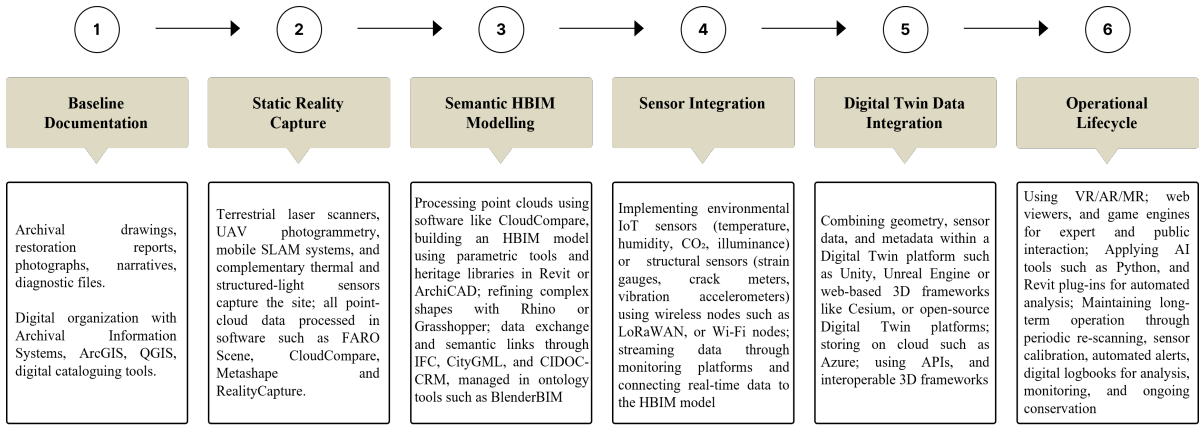


Figure 3. Six-stage workflow for developing a heritage Digital Twin.

The fourth step is sensor integration. IoT networks introduce real-time environmental and structural data, allowing the model to mirror physical behavior. Sensors track temperature, humidity, carbon dioxide, light levels, strain, vibration, and crack activity. These streams enable continuous analysis and early warnings (Hosamo & Mazzetto, 2024). At Löfstad Castle, a network of 84 cloud linked sensors supported climate management and marked the transition toward a data driven Digital Twin (Ni et al., 2025). New ontologies now link sensor observations with semantic HBIM models and support automated defect detection (Niccolucci & Felicetti, 2024). Key issues reported as sensor calibration and long-term maintenance.

The fifth step is data integration within a Digital Twin platform. Here geometric, semantic, historical, and sensor-based information becomes a unified operational system. Heritage projects often rely on custom or open frameworks rather than industrial platforms, though cloud features support remote access and alerts (Fattore et al., 2025; Ni et al., 2024). The interoperability depends on open formats, API connections, and middleware able to translate between tools. The Torino Esposizioni project demonstrated how APIs can open HBIM databases to remote users (Spano et al., 2023). At this stage, separate datasets merge into a single real-time Digital Twin.

The final step is the operational lifecycle. Visualization and interaction tools such as AR, VR, and MR support expert assessment and public access, while web viewers and game engines allow real-time scenes and remote exploration (Dang et al., 2023; Del Blanco García et al., 2024). Artificial intelligence enhances analysis, from defect detection and point cloud segmentation to predictive maintenance and generative reconstruction (Arsalan et al., 2025). Continuous updates rely on automated alerts, structured maintenance logs, periodic rescanning, and sensor calibration. In this final stage, Digital Twin becomes a long-term companion to physical building and supports conservation, research, and public engagement.

5. Challenges and Limitations

The review identifies several challenges for the development of digital twins in heritage buildings. One major issue is semantic interoperability. Many projects use different data structures, and no single standard links geometric models, sensor data, diagnostics and historical information. This fragmentation makes data exchange difficult.

Another challenge is the effort required for Scan-to-BIM workflows. Modelling irregular historical elements still depends heavily on manual work. Current AI-based tools offer support, but they are not yet reliable enough for detailed conservation tasks.

Sensor integration also remains problematic. IoT devices placed in fragile, historic environments require careful calibration and constant maintenance. Sensors often fail or produce inconsistent data, and linking live data streams to BIM systems is still technically demanding.

AI brings new benefits, but also new risks. Automated defect detection and predictive models need strict validation. Without it, AI output may lead to incorrect interpretations or unsuitable conservation decisions.

Data heterogeneity adds further complexity. Point clouds, BIM models, sensor logs, archival documents, and geospatial layers all use different formats and scales. Building a unified Digital Twin platform that handles this diversity is still difficult.
Finally, there are gaps in global participation. Most Digital Twin projects take place in Europe and East Asia. Regions with high cultural vulnerability often lack the resources and technical capacity needed for such systems. This limits worldwide progress and reduces the potential impact of Digital Twin technologies for endangered heritage.

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Overall, these challenges show that the field is advancing quickly, but still lacks unified standards, long-term strategies, and accessible tools.

6. Conclusion

This scoping literature review demonstrates that Digital Twin research for heritage buildings has progressed significantly in recent years, supported by the widespread adoption of technologies such as TLS, UAV photogrammetry, HBIM, and IoT sensing. At the same time, emerging tools including AI, semantic modelling, cloud platforms, and immersive visualization are gaining increasing relevance. Together, these developments indicate a clear transition from static documentation towards more dynamic and data-driven approaches, enabling more proactive conservation strategies, decision-making based on evidence, and improving stakeholder engagement.

However, despite these advances, the analysis reveals important limitations. The maturity of technologies remains uneven. The geometric capture methods are well-established, while IoT integration and AI applications still require careful validation to be more reliable. More critically, there is a clear gap between the conceptual vision of Digital Twins and their practical implementation. Many studies identified in the literature do not represent true Digital Twins, but rather advanced 3D models lacking real-time data integration, interaction, and automatic feedback mechanisms. Current approaches are often fragmented, with modelling, sensing, data integration, and user interaction treated as separate components rather than parts of a unified system. Modelling workflows, especially BIM and HBIM approaches, are complex, time-consuming, and highly dependent on expert knowledge, which limits accessibility and broader adoption.

In response to this gap identified in the literature, this research presents a six-stage workflow for developing a Digital Twin of heritage buildings, which aims to clarify the concept and distinguish it from purely geometric or static representations. By structuring the process and identifying the key technologies involved at each stage, the proposed workflow contributes to a more coherent and operational understanding of Digital Twins in the heritage context. At the same time, the findings highlight the need for future research to move toward more integrated and user-oriented solutions. There is a strong need to develop more accessible, user-friendly platforms that can integrate models, data, and analysis within a single environment, reducing reliance on specialist-driven processes. This is especially important for users such as conservation experts, heritage professionals or building managers, and even the public, to have more access and benefit from these systems.

Looking ahead, a key direction for future work is the exploration of more automated and streamlined workflows, enabling a smoother transition from data acquisition to fully operational Digital Twins. Such developments would not only improve efficiency but also expand the usability of Digital Twin technologies across a wider range of users and contexts, ultimately contributing to more effective and sustainable heritage conservation.

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