

How digital technologies have been applied for architectural heritage risk management A systemic literature review from 2014 to 2024

Yu, Yingwen; Raed, Abeer Abu; Peng, Yuyang; Pottgiesser, Uta; Verbree, Edward; van Oosterom, Peter

DOI

[10.1038/s40494-025-01558-5](https://doi.org/10.1038/s40494-025-01558-5)

Publication date

2025

Document Version

Final published version

Published in

npj Heritage Science

Citation (APA)

Yu, Y., Raed, A. A., Peng, Y., Pottgiesser, U., Verbree, E., & van Oosterom, P. (2025). How digital technologies have been applied for architectural heritage risk management: A systemic literature review from 2014 to 2024. *npj Heritage Science*, 13(1), Article 45. <https://doi.org/10.1038/s40494-025-01558-5>

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

<https://doi.org/10.1038/s40494-025-01558-5>

How digital technologies have been applied for architectural heritage risk management: a systemic literature review from 2014 to 2024



Yingwen Yu¹, Abeer Abu Raed^{1,2}, Yuyang Peng³, Uta Pottgiesser^{1,4}, Edward Verbree¹ & Peter van Oosterom¹

This systematic literature review critically examines the application of digital technologies in architectural heritage risk management from 2014 to 2024, focusing exclusively on English-language publications. As the significance of architectural heritage continues to be recognized globally, there is an increasing shift towards integrating digital solutions to ensure its preservation and management. This paper explores the evolution and application of digital technologies such as Building Information Modeling (BIM), Geographic Information Systems (GIS), and advanced imaging techniques within the field. It highlights how these technologies have facilitated the non-destructive evaluation of heritage sites and enhanced accessibility and interaction through virtual and augmented reality applications. By synthesizing data from various case studies and scholarly articles, the review identifies current trends and the expanding scope of digital interventions in heritage conservation. It discusses the interplay between traditional conservation approaches and modern technological solutions, providing insights into their complementary roles. The analysis also addresses the challenges and limitations encountered in the digital preservation of architectural heritage, such as data integration, the compatibility of different technologies, and the need for more comprehensive frameworks to guide the implementation of digital tools in heritage conservation practices. Ultimately, this review underscores the transformative impact of digital technology in managing architectural heritage risks, suggesting directions for future research and the potential for innovative applications in the field.

Architectural heritage refers to the historically significant buildings, structures, and sites that represent a valuable part of a society's cultural, historical, and esthetic history¹. According to this definition, certain buildings and structures within historic gardens and architectural clusters in historical urban districts also broadly constitute architectural heritage^{2,3}. As an essential category of cultural heritage, they are part of our legacy from the past, what we live with today, and what we pass on to future generations. They are both irreplaceable sources of life and inspiration (UNESCO, 2023). In 2003, the United Nations Educational, Scientific and Cultural Organization (UNESCO, 2003) promulgated the *Charter on the Preservation of the*

Digital Heritage, defining digital preservation as the process of using digital technology to record, preserve, and access the cultural and historical values of historical buildings and sites. Focusing on architectural heritage, the application of digital technology in its preservation possesses inherent advantages, including the non-destructive nature of data acquisition⁴⁻⁶, the convenience of data collection and exchange^{7,8}, and the authenticity of the data maintained^{9,10}. These benefits have directly translated into practical measures, such as the widespread adoption of laser scanning and photogrammetry for documenting complex architectural details without causing physical damage¹¹. Furthermore, the ability to easily share and exchange

¹Department of Architectural Engineering and Technology, Faculty of Architecture and the Built Environment, Delft University of Technology, Julianalaan Delft, The Netherlands. ²Department of Architecture, American University of Ras Al Khaimah, Ras Al Khaimah, UAE. ³Department of Urbanism, Faculty of Architecture and the Built Environment, Delft University of Technology, Julianalaan Delft, The Netherlands. ⁴Institute for Design Strategies (IDS), OWL University of Applied Sciences and Arts (TH OWL), Detmold, Germany. e-mail: P.J.M.vanOosterom@tudelft.nl

high-quality digital models has facilitated international collaborations on restoration projects, such as the joint conservation efforts for Pakistan¹². Over the years, the role of digital technology in this field has evolved to include new application scenarios with observable impacts. For instance, visualization and display aimed at public engagement^{13,14}, design analysis of architecture and the built environment^{15,16}, comprehensive lifecycle management of architectural heritage¹⁷, architectural pathology identification^{18,19}, as well as risk prediction, development, and management^{20,21}.

Architectural heritage has been constantly risking various damages, including natural disasters, overuse, war, urban renewal, and construction^{22–24}. Risk management of architectural heritage refers to the systematic process of identifying, assessing, mitigating, and monitoring various risks that architectural heritage, such as historic buildings, cultural sites, and monumental structures, may face throughout their lifecycle. The utilization of digital technologies for risk management of architectural heritage has emerged as a notable application scenario in recent years^{25,26}. Within these risk management endeavors, the use of digital technology in architectural heritage risk management exhibits diverse characteristics across various cases, including different types of buildings and related heritage sites²⁷, and the development and application of these technologies reveal a complexity marked by the intersection and compatibility issues among different technologies^{28,29}. However, there is a lack of comprehensive literature reviews on applying digital technology in disaster management of architectural heritage^{30,31}. Such reviews would be constructive for understanding the current research preamble and application status in the field and for assessing future trends and directions.

Therefore, the purpose of this paper is to systematically review the literature from 2014 onward on the use of digital technology in risk management within architectural heritage to clarify the current state of research in this area. This goal can be subdivided into several specific objectives:

- (a) To grasp the main focus of the current literature, including the types and scales of objects studied, and to summarize the specific digital technologies involved in the research;

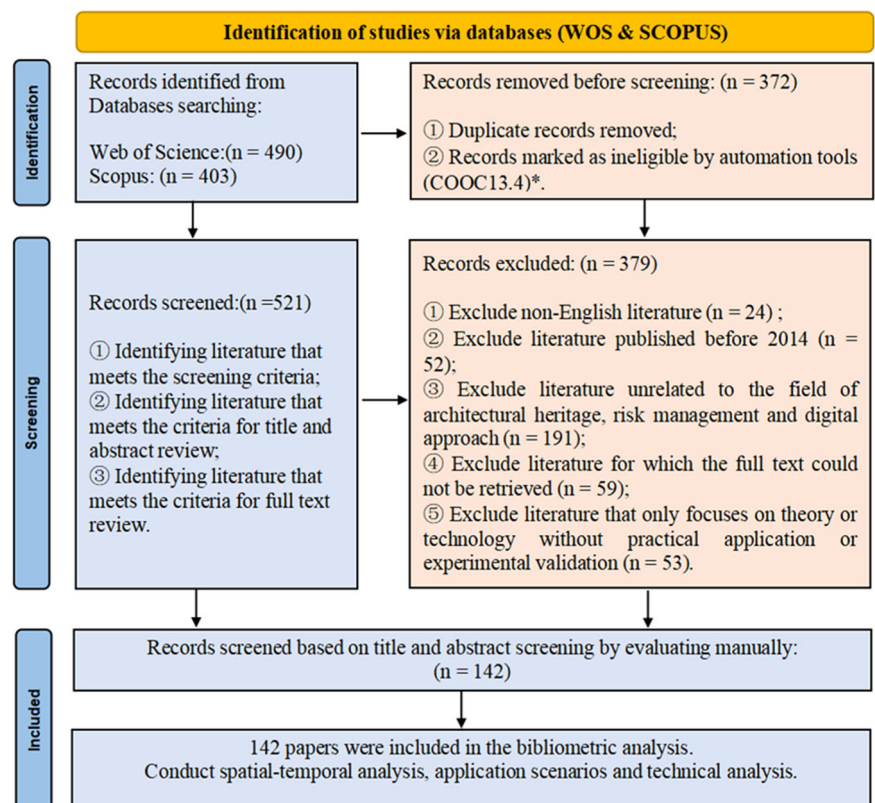
- (b) To understand the connections between different technologies as well as the relationships between methods and their application targets;
- (c) To identify current challenges and gaps in research and technology and, based on these, to predict future directions and breakthroughs for the application of digital technology in heritage building risk management.

Therefore, the structure of this paper includes the following sections: “Methods”, which outlines the specific technical approach for literature selection and analysis; “Results”, which provides a visual and descriptive presentation of the findings from the literature analysis; and “Discussion”, which explores the past developments, current challenges, and future trends in the research field based on the preliminary results.

Methods

The literature analysis method employed in this study can be divided into three parts. First, Using Web of Science (WoS) and Scopus to search for and collect literature, these databases will serve as the primary sources for subsequent analysis. Second, we utilized PRISMA (a standardized set of reporting guidelines designed to assist researchers in systematically organizing, conducting, and reporting systematic reviews and meta-analyses) to visually obtain an overview of the paper’s basic information (e.g., the number of studies published each year and site coverage) through paper coding and statistical methods³². PRISMA was also used to establish multiple criteria to classify and identify the specific content of the target literature in a detailed manner³². Thirdly, we used VOSviewer (a software tool specifically developed for creating, visualizing, and exploring bibliometric networks)³³, CiteSpace (a bibliometric analysis and visualization tool designed for identifying emerging trends and dynamic patterns in scientific literature)³⁴ and Co-Occurrence 13.4 (COOC 13.4) (a software tool designed for bibliometric analysis and knowledge mapping)³⁵ to illustrate and simulate the scientometric network between research literature on a macro level. This approach enabled us to gain a more integrated understanding of

Fig. 1 | Workflow for the methodology of literature review (source: by author).



the academic gaps and tendencies in the research field and to identify gaps in the current research landscape (Fig. 1).

Data collection

WoS and Scopus³⁶ offer diverse, accessible databases for publications that explicitly articulate and use digital approaches to conserve and develop architectural heritage from multiple disciplines, including architecture, archeology, engineering, and urban planning. For this study, we chose the Conference Proceedings Citation Index-Social Science & Humanities, Emerging Sources Citation Index, Conference Proceedings Citation Index-Science, Science Citation Index Expanded, Social Sciences Citation Index, and Arts & Humanities Citation Index as data sources. The topic was divided into three main categories specific to architectural heritage: “architectural heritage,” “risk management,” and “digital approach,” with each category having a set of related keywords:

- (a) *Architectural heritage*: TS1 = (“architecture* heritage” OR “architecture* method*” OR “architecture* planning” OR “historic* building*” OR “historic* structure*” OR “historic* infrastructure*” OR “historic* construction” OR “monument*” OR “build*” OR architecture* OR culture*)
- (b) *Risk management*: TS2 = (“structure* health” OR “structure* risk” OR “environment* risk” OR “human risk” OR “risk management” OR “disaster management” OR “hazard management” OR “risk” OR “disaster” OR “hazard” OR “heritage at risk”)
- (c) *The digital approach*: TS3 = (“digital* tool*” OR “digital approach*” OR “digital* equipment*” OR “digital documentation” OR “digital technology*” OR “digital* heritage” OR “digitization”)
- (d) (TS1) AND (TS2) AND (TS3).

The period was set from 2014 to 2024. Due to the overlap of literature between the two databases, the automated screening tool COOC 13.4 will be used to remove duplicate and substandard records to ensure the reliability and relevance of the dataset.

Literature screening and paper coding

According to the PRISMA statement³⁶ (Fig. 2), two major academic databases, Web of Science (WoS) and Scopus, were used to conduct the literature search. A total of 809 records were retrieved, with 490 from WoS and 403 from Scopus. After applying COOC 13.4 to remove 372 records based on duplication and other criteria identified by the automated system, the remaining 521 records were then subjected to a manual screening process consisting of three stages. First, records were assessed to identify those that met the predefined screening criteria. Second, titles and abstracts were reviewed to ensure that the studies aligned with the scope of the research. Third, a subset of the records was further evaluated for full-text review to confirm their relevance.

Following the initial screening, 379 records were excluded based on the following criteria¹: non-English-language studies², publications prior to 2014³, literature unrelated to the fields of architectural heritage, risk management, or digital approaches⁴, studies for which the full text could not be retrieved, and⁵ studies that focused solely on theoretical or technological discussions without practical application or experimental validation (Appendix A).

A paper coding system was applied to categorize the selected literature for both quantitative and/or qualitative analyses, drawing upon previous research methodologies^{37,38}. Inspired by explorations on taxonomic and thematic analysis in qualitative research^{39,40}, we developed a refined classification system. This system included six key elements: research design, research questions, study objectives, mixed-method data (qualitative and quantitative), analysis techniques, and findings. By systematically dissecting these aspects, we established a comprehensive framework for organizing and analyzing the selected studies. Through thematic analysis, we identified recurring domains across different studies and conducted a constant comparison analysis to highlight commonalities. The results were then organized under thematic headings, which served as group labels for clustering purposes.

Literature analysis

Two widely recognized software tools, VOSviewer and CiteSpace, were employed for the bibliometric analysis and visualization of connectivity between the selected studies. These tools provided the capability to map bibliographic data and visualize clusters of related studies. The inclusion of as many relevant papers as possible ensured a robust database for further analysis. Both tools, based on Java, allowed the creation of color-coded maps that offered visual insights into the data⁴¹. CiteSpace, in particular, was used for co-citation and co-occurrence analysis, identifying clusters of co-cited references and mapping networks of frequently occurring keywords. This process enabled the identification of important keywords and the detection of emerging topics within the broader field of research⁴².

Results

Overall, from 2014 to 2024, the cumulative number of publications on the use of digital technology for risk management of heritage buildings has shown an increasing trend year by year. In addition, the citation analysis for research papers that relate to the use of digital tools in architectural conservation and risk management in the architectural heritage sector over the last ten years is presented in Fig. 2. The number of citations is rising steadily, which points to the fact that the applications of digital tools for architectural heritage risk management are getting more attention in academia.

In terms of the geographical distribution of research, Europe accounts for the majority, with a significant number of studies focusing on heritage protection in Italy^{43,44}. This is partly because Italy is a country with a long history and is rich in cultural heritage, including remnants of the Roman Empire, Renaissance architecture, and artworks⁴⁵. Similarly, other European countries such as Greece, France, Germany, and Spain also possess a large number of historical buildings and cultural sites⁴⁶. On the other hand, many European countries have been awakening early to the importance of heritage protection⁴⁶. For example, Italy established a national agency for the protection of cultural heritage as early as 1909⁴⁷.

The preliminary results of the visualization

The network diagram showcases relationships between key concepts identified through a bibliometric analysis of risk management literature in the context of digital technologies and heritage conservation (Fig. 3). The nodes represented influential terms, and the edges depicted their co-occurrence within the analyzed body of research. The size of a node corresponds to its frequency of appearance, while the thickness of an edge reflects the co-occurrence strength between connected terms. The change in node color reflects the shift in focus and application of these technologies from 2014 to 2024. This visualization serves to illuminate the thematic structure of this research domain³³, highlighting potential areas of synergy and emerging trends in applying digital tools for risk assessment and mitigation strategies within the field of heritage preservation.

Scholarly publications in this field can be analyzed using a bibliometric approach to reveal current trends and uses for such technologies. The analysis concluded that BIM, Photogrammetry, big data, and AI had obtained great attention in the academic field in the past ten years (Fig. 3). This trend shows the increased awareness of the need to apply new digital technologies in the process of risk management in order to increase the protection and sustainability of architectural history.

The application of digital methods in architectural heritage risk management

In this section, the focus is on analyzing the clustering, connections, and temporal evolution of the interrelationships between different digital technologies as they are applied to the risk management of architectural heritage.

Clustering the different digital technologies. The development of technologies in disaster management demonstrates a high level of collaboration and multidimensional innovation, forming seven core technological clusters. These clusters encompass the entire process of disaster

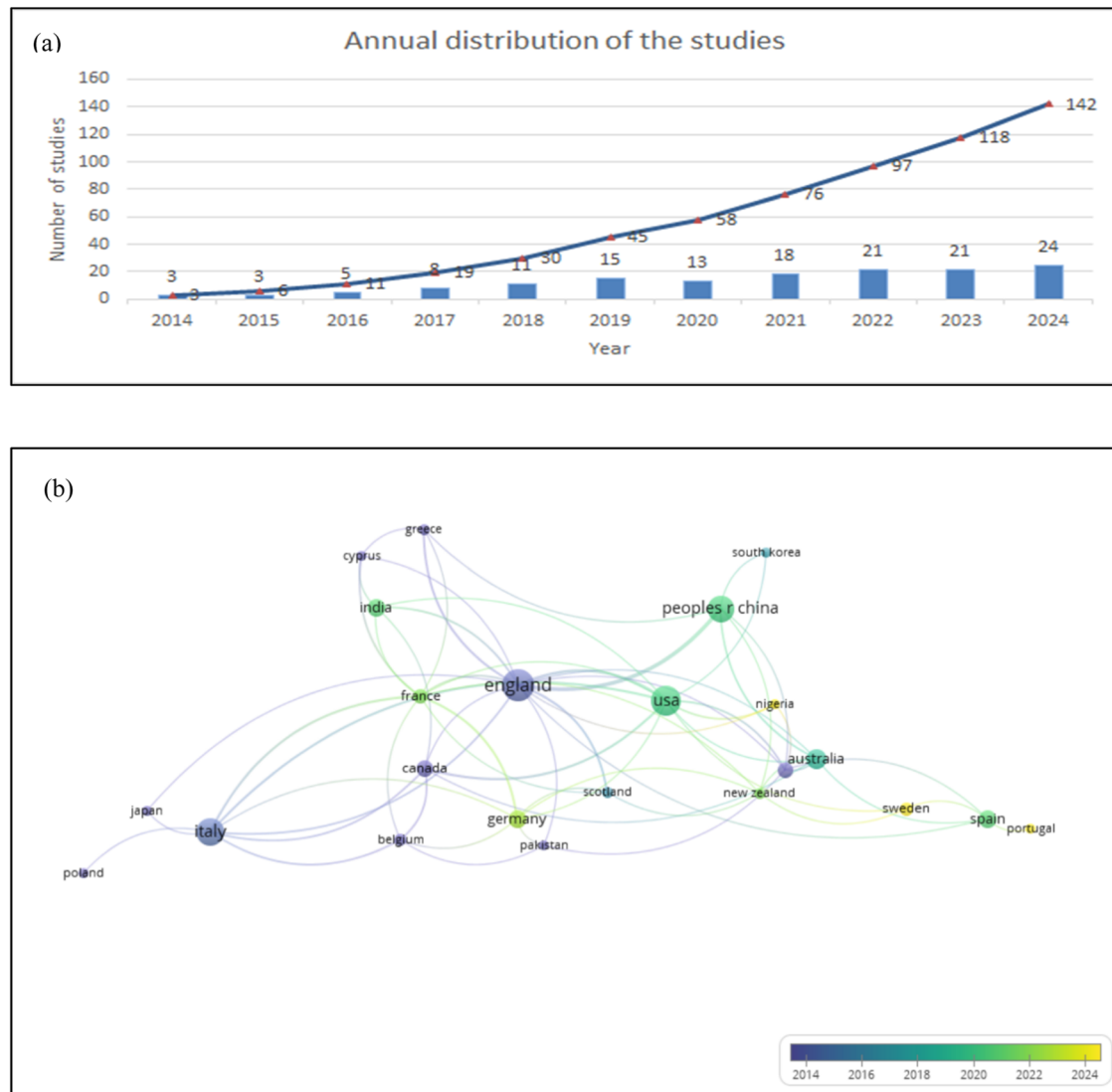


Fig. 2 | The preliminary results. a The number of publications and **b** the number of publications from different nations.

management, including data collection, modeling and analysis, intelligent prediction, visualization, and disaster assessment (Fig. 3b).

Data Collection Clusters: (a) *Blue Cluster (GIS and Remote Sensing)*, GIS and remote sensing are core tools for data collection and spatial analysis in disaster management. GIS integrates remote sensing imagery and 3D reconstruction technologies to provide detailed geographical information and environmental modeling for disaster scenarios. Remote sensing, on the other hand, rapidly captures spatial data over large areas, offering precise foundational information for disaster monitoring, risk assessment, and response planning. This cluster collaborates with other technologies to establish a foundation for dynamic modeling and subsequent analyses. (b) *Orange Cluster (Drone and Terrestrial Laser Scanning Technologies)*, Photogrammetry combined with drones provides flexible and efficient data collection methods for disaster management. Photogrammetry reconstructs 3D models from 2D imagery, rapidly generating digital representations of disaster scenarios. Drones further extend the applicability of photogrammetry by quickly acquiring high-precision data from complex terrains and disaster sites.

Modeling and Simulation Clusters: (c) *Light Green Cluster (BIM-Based Modeling and Analysis Technologies)*, this cluster centers on BIM, integrating digital simulation and disaster-resilient design optimization techniques to enhance the disaster resistance of buildings. BIM employs high-precision modeling and data integration to dynamically analyze structural

characteristics and potential disaster risks, supporting the development of protective strategies for various disaster scenarios. Digital simulation technologies further strengthen disaster impact predictions and evaluations, providing scientific foundations for optimizing architectural designs. Widely applied to disaster prevention in both historical and modern buildings, this cluster offers robust support for building safety and post-disaster recovery planning. (d) *Red Cluster (HBIM and Modeling-Monitoring Technologies)*, this cluster incorporates Structural Health Monitoring (SHM) and Digital Twin technologies, focusing on the dynamic monitoring of buildings and infrastructure. SHM utilizes sensors and data acquisition systems to assess structural performance and potential risks in real time. Digital Twin technology maps virtual models to actual buildings, enabling dynamic disaster scenario simulations and predictions. These technologies work in synergy to deliver precise support for disaster prevention, real-time monitoring, and post-disaster recovery planning, with applications in both historical heritage protection and modern building management.

Intelligent Analysis and Management Clusters: (e) *Light Blue Cluster (Intelligent Data Processing and Analysis)*, this cluster leverages big data, artificial intelligence (AI), and the Internet of Things (IoT) to achieve intelligent disaster analysis and prediction. IoT collects real-time sensor data, serving as input for big data analysis and AI modeling. Machine learning enhances pattern recognition and trend prediction capabilities,

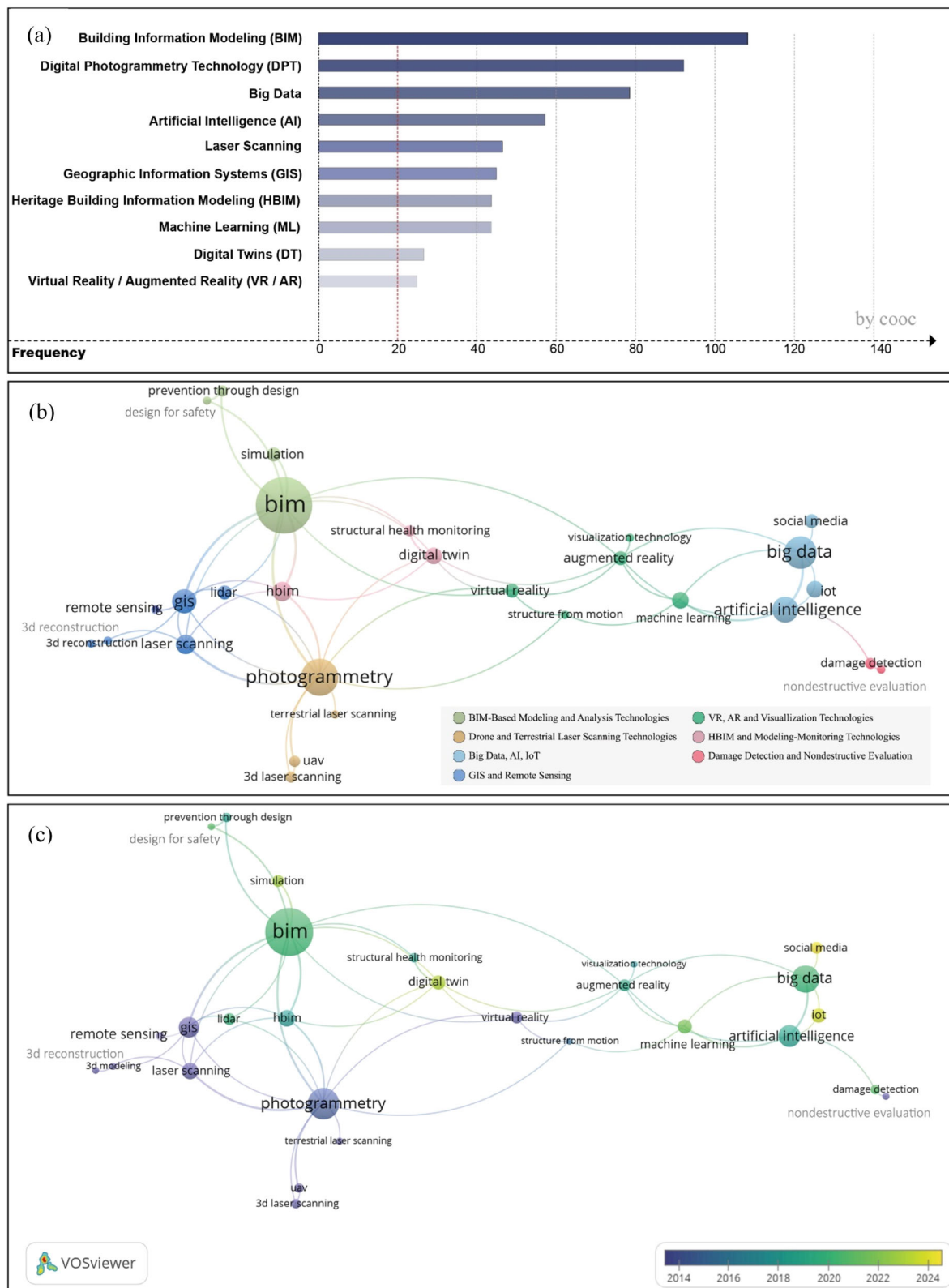


Fig. 3 | Relationship among different technologies applied (source: by author).
a The number of literature applying different technologies (only those applied more than 20 times are showcased); **b** the relationship among the different technologies;

c a color gradient is applied to showcase the publication time of the literature (the light yellow refers to the new ones, and the dark blue refers to the old); the sizes of the keywords represent the frequencies of the application.

while social media data expands disaster perception dimensions, enabling real-time scenario assessment and dynamic responses. (f) *Dark Red Cluster (Disaster Assessment and Damage Detection)*, this cluster specializes in damage detection and non-destructive evaluation, aiming at optimizing post-disaster building and infrastructure recovery. By integrating with machine learning, damage detection technologies achieve efficient and precise analyses. Non-destructive evaluation offers comprehensive diagnostics of structural conditions. The feedback from these technologies further strengthens the scientific basis of disaster analysis and decision-making processes.

Interaction and Communication Cluster: (g) *Green Cluster (Visualization and Interactive Technologies)*, this cluster focuses on augmented reality (AR), virtual reality (VR), and visualization technologies to enhance the interactivity and comprehensibility of disaster scenarios. AR and VR provide innovative platforms for disaster prevention and emergency response through immersive scenario displays and simulation training. Visualization technologies also facilitate collaboration among multiple stakeholders, offering intuitive tools for disaster decision-making and information communication.

Connections among the different digital technologies. The study of interrelationships between different technologies in disaster management is of great importance as it not only fosters technological collaboration and innovation but also enhances the efficiency and effectiveness of disaster management. This paper analyzes the interconnections among various digital technologies as follows:

The blue cluster (GIS, remote sensing, photogrammetry, and laser scanning) and the orange cluster (drones and terrestrial laser scanning) serve as the core for data collection, providing essential spatial information for disaster management. GIS integrates data from remote sensing and photogrammetry to enable 3D modeling of disaster scenarios, while drones and laser scanning excel in large-scale, rapid data collection and precise localized modeling. These data collection technologies lay a solid foundation for subsequent modeling and analysis, establishing strong connections with the light green and red clusters (BIM, HBIM, and digital twin technologies). These clusters act as the core for modeling and simulation by leveraging 3D data generated from data collection technologies to digitally represent disaster scenarios. BIM and HBIM integrate data from photogrammetry and laser scanning to generate accurate architectural and environmental models, supporting disaster assessment and recovery. Digital twins further enhance this by integrating IoT sensor data to enable dynamic monitoring of disaster scenarios and future predictions. These modeling technologies not only support static analysis of disaster sites but also provide dynamic solutions for emergency response and risk forecasting through simulation techniques.

The light blue cluster (big data, AI, IoT) drives intelligent analysis and decision-making in disaster management. Big data aggregates real-time sensor data from IoT networks, providing substantial input for AI and machine learning models. AI processes spatial data from GIS and photogrammetry through pattern recognition and trend forecasting, and the outcomes from these analyses feed back into modeling technologies like BIM and digital twins, improving their disaster simulation capabilities. Furthermore, the integration of big data and AI enhances real-time risk prediction and dynamic decision-making, advancing disaster management toward greater intelligence. The dark red cluster (damage detection and non-destructive evaluation) specializes in disaster assessment and recovery optimization and is closely linked with AI and related technologies. Damage detection relies on high-precision data from laser scanning and photogrammetry, while AI and machine learning improve analysis efficiency and accuracy, enabling more precise disaster evaluation and recovery planning.

The green cluster (AR, VR, and visualization technologies) focuses on enhancing disaster scenario visualization and stakeholder interaction. AR and VR technologies utilize 3D models generated by BIM and digital twins, alongside data from GIS and photogrammetry, to create immersive disaster scenarios. Visualization technologies transform complex analytical results from big data and AI into intuitive graphical representations, facilitating

collaboration among multiple stakeholders and optimizing decision-making processes. As such, this cluster forms critical links with scanning and modeling technologies, as well as AI and machine learning algorithms, making it an integral component of modern disaster management strategies.

Temporal evolution of digital technologies in disaster management.

In recent years, digital technologies in disaster management have undergone significant development, transitioning from basic data collection to intelligent collaboration (Fig. 3). In the early phase (2014–2018), technologies like photogrammetry, laser scanning, and GIS primarily focused on reconstructing disaster scenarios through 3D modeling and spatial analysis. The introduction of drones (UAVs) further enhanced the efficiency of data collection, enabling real-time disaster response. However, technological interconnections during this phase were relatively limited, primarily involving localized collaborations among data collection and analysis tools. From 2018 to 2020, BIM emerged as a core technology for integration, working closely with HBIM, Structural Health Monitoring, and GIS to strengthen systematic disaster information management and prevention capabilities. Simultaneously, advancements in remote sensing and laser scanning technologies enabled more efficient disaster management, ranging from large-scale assessments to detailed local analyses. Since 2020, big data and artificial intelligence have become the central driving forces in disaster management, integrating with IoT and social media to deliver real-time data and predictive capabilities. AR and VR technologies have gained prominence in disaster scenario visualization, while digital twins, combined with BIM and AI, have achieved closed-loop management through real-time monitoring and future scenario prediction. This period marks a significant shift toward deeper technological collaboration, propelling disaster management toward greater intelligence and dynamism.

Overall, between 2014 and 2024, digital technologies in disaster management have evolved from standalone data collection tools to integrated intelligent platforms. The early phase emphasized data collection and modeling, while the mid-phase focused on technology integration and analysis. In the recent phase, advancements in AI and digital twins have driven intelligent decision-making and real-time disaster response. As interconnections between technologies become increasingly robust, disaster management is expected to evolve further toward more intelligent and dynamic approaches, offering efficient and precise solutions for complex disaster scenarios.

Classification of research subjects and sites

Based on the research cases and sites involved in the literature selected for this study (Appendix A), they can be categorized into the various types described below. From the perspective of research subjects, the areas of study encompass various categories that integrate advanced digital technologies for architectural heritage risk management. These include:

(a) **Individual constructions:** This category focuses on protecting and analyzing historical buildings such as churches and bridges. BIM and structural analysis technologies assess structural integrity and preservation needs. Utilizing digital documentation and virtualization technologies such as HBIM and VR to enhance their cultural heritage value.

(b) **Archeological sites and ruins:** This includes the study of archeological sites and ancient ruins, often utilizing GIS, laser scanning, and 3D modeling to support the preservation, management, and educational presentation of these sites.

(c) **Historic Urban Areas:** Attention is given to the cultural and structural preservation of entire urban districts, employing large-scale scanning and modeling techniques, such as panoramic scanning⁴⁸ and extensive GIS analysis, to evaluate and plan for the sustainable development of historic districts.

(d) **Specific Architectural Elements:** Research focuses on detailed analysis of specific architectural elements like murals and structural components. Technologies such as infrared thermography for mural analysis

and micro-damage assessments of structures are used to gain a deeper understanding and protection of these vulnerable artistic and architectural elements.

Discussion

This chapter mainly includes the following sections: first, a summary of the development trends in the application of digital technologies in architectural heritage risk management from 2014 to 2024; second, an identification of the current challenges and research gaps in this field based on a review of existing literature; and finally, a discussion on the potential future development trends in this area. In addition, the limitations of this study will also be addressed.

Summary of current research trends

From 2014 to 2024, the role of digital technology in the risk management of architectural heritage has become increasingly significant^{25,27}. Building on the foundation laid out in the results section, this section analyzes the current frontiers and trends in this field, including the relationship between emerging and established technologies, changes in the objects of study, variations in analytical demands, and the interplay between methodologies and their subjects⁴⁹.

Complementarity rather than simple replacement of old by new technologies. The analysis results have highlighted that in applying digital technologies to the risk management of architectural heritage⁵⁰, there is a trend toward increasing diversity of technologies and their concurrent use rather than a simple replacement of old technologies by new ones. For example, GIS, which emerged in the 1970s, remains one of the primary tools for risk analysis and management today^{51,52}. This persistence is partly due to the expansion of different GIS software systems and platforms to accommodate a wider range of applications. On the other hand, emerging digital technologies strive to complement scenarios where GIS may not be applicable, thereby forming a symbiotic relationship⁵³. In contemporary disaster emergency management, while technologies such as sensors, UAVs, and IoT have been integrated and now provide accurate geospatial information, these advancements have primarily replaced the traditional role of manual GIS-based annotation for disaster location mapping. However, GIS remains the primary method for organizing and coordinating spatial information, rather than being replaced by newer technologies such as BIM. Instead, these emerging technologies work in tandem with GIS, creating a cohesive network system for disaster emergency response and management. This integration highlights the complementary relationship between GIS and modern technologies, enhancing the overall efficiency and effectiveness of disaster management systems.

In terms of application scenarios, in certain specialized domains, there is a trend toward the refinement and specialization of new technologies over older ones^{54,55}. For instance, smart point cloud enhances the types of data information contained within point clouds⁵⁶, providing a multidimensional array of information for subsequent risk management⁵⁷. The enhancement from BIM to HBIM demonstrates a similar trajectory; HBIM is more focused on the unique needs and preservation of historical buildings^{58–60}, whereas BIM is broadly applied to modern architectural projects.

During the timeframe of this literature review, the rise and integration of machine learning-based technologies, coupled with hardware advancements, have enhanced the computational power and application scenarios of these technologies^{61,62}. Smart devices and head-mounted VR equipment have broadened the potential applications in risk management, making remote risk management and assessment feasible^{63,64}. In addition, advancements in cloud computing and machine learning have transformed risk management in architectural heritage from merely monitoring the present and past to enabling more reliable predictions of the future^{65–67}. Moreover, the integration of the Internet of Things (IoT, often embedded with sensors, software, and other technologies, collect and transmit data) devices into the risk management strategies of heritage buildings have been

instrumental^{21,68}. These devices collect real-time data from the environment, such as humidity, temperature, and structural stresses, which is crucial for preemptive measures against potential damages⁶⁹. The interconnected nature of IoT, combined with robust data analytics, offers a comprehensive overview of the health of heritage structures, allowing for timely interventions^{70,71}.

Focus on virtualization rather than diversification of research subjects. Chronologically, the research subjects have not changed significantly, encompassing both medium to large-scale historical urban spaces and individual monuments, including architectural decorations such as frescoes^{72,73}. However, post 2020, there has been a proliferation of virtualized risk management cases in the literature^{74,75}. These examples include the use of AR technology at the Cathedral of Santa Maria del Fiore in Florence, Italy, where AR enables researchers and visitors to witness the historical evolution of murals and sculptures while monitoring the structural integrity of the building in real time⁷⁶. To achieve a fusion of past and present in the visitor experience, this project integrates historical literature and imagery to construct virtual models of the church across different time periods. Using augmented reality and real-time tracking, visitors can view the historical appearance of specific scenes while exploring the current site. Other examples include: High-precision laser scanning technologies have been employed for 3D modeling of buildings and decorations in the Forbidden City, enhancing the precision of restoration and conservation efforts and facilitating better analysis of aging issues and environmental risks through digital models^{77–79}. VR technology has been applied to the Pyramids of Egypt^{80,81}, allowing researchers to inspect the internal structures without physical entry, reducing physical contact and damage to the site, and providing a research and teaching tool for scholars worldwide⁸².

The reasons for this shift include (a) the advancement of digital technologies: For example, laser scanning and image scanning technologies have made it easier to acquire high-precision data⁸³; similarly, VR and AR technologies have provided immersive and interactive ways to visualize and explore heritage sites. Which provide unprecedented tools for heritage management that allow for detailed risk assessment and management without disturbing the actual environment⁸⁴; (b) the impact of the COVID-19 pandemic, which, due to travel restrictions and social distancing mandates, has forced the heritage conservation field to seek remote management and virtual access solutions to continue protecting and studying these valuable cultural heritages⁸⁵; (c) increased environmental and anthropogenic risks, as historical sites face greater natural and human-made hazards with environmental changes and urbanization^{86,87}. Digital technologies offer an effective way to monitor and respond to these risks.

Diversification of risk management demands. The advancement of digital technologies in architectural heritage risk management enables more application sceneries and satisfies more diverse demands, such as research, management, and policymaking^{88,89}. These technologies not only provide new methods for monitoring and protection but also help managers to more precisely address a variety of challenges and meet diverse needs. This includes:

(a) More detailed risk prevention: Utilizing repeated scans, which refers to the process of conducting multiple scans of the same object, structure, or area over time, heritage managers can precisely monitor the condition of architectural heritages over a time series^{69,90}, detect minute cracks and structural weaknesses, analyze the problems, and intervene early to prevent severe damage. Examples include the work of Kong et al. on remote monitoring and preservation of a heritage structure in Spain⁹¹. Their approach aimed to reduce local government expenses and minimize the need for on-site engineers. By utilizing drones for scanning, they created a digital twin of the structure, enabling real-time, remote risk management and control. This method showcases the potential of combining emerging technologies with heritage conservation to achieve efficient and sustainable management practices⁹¹. In addition, by utilizing AI and interdisciplinary

research methods in architecture, along with scanning and machine learning technologies, contributions can be made to the pathology identification of architectural heritage. A study using this approach identified the types, locations, and characteristics of masonry cracks in a modern heritage building in Wuhan. It further analyzed the causes of the cracks and proposed corresponding graded repair strategies⁹².

(b) Addressing environmental and climate change risks: GIS and environmental monitoring systems enable managers to track in real time how environmental conditions affect architectural heritage^{25,93}. This data aids in formulating strategies to combat climate change, such as adjusting humidity controls or flood prevention measures to protect heritage sites vulnerable to climatic impacts^{94,95}. For instance, the development of the STORM risk assessment and management model demonstrates a comprehensive approach to mitigating the impact of extreme weather and climate change on the architectural heritage of Troia. This model incorporates multiple management objectives and evaluates key factors such as exposure, vulnerability, and risk identification. By systematically analyzing these elements, the STORM model aims to reduce potential damage to heritage structures, ensuring their preservation in the face of evolving environmental challenges⁹⁶.

(c) Responding to emergencies: In the aftermath of earthquakes, floods, or other natural disasters, digital technologies can be rapidly deployed to assess damage levels, prioritize restoration efforts, and effectively allocate resources^{97–99}. For example, the integration of drones, sensors, and IoT technologies has been used to establish emergency response monitoring networks. These networks enable real-time data collection and analysis during disaster events, facilitating timely responses to minimize damage and losses. By providing accurate and immediate situational awareness, such systems enhance the efficiency of disaster management and improve decision-making processes in critical scenarios. Moreover, real-time data streams allow for immediate responses, reducing long-term damage to the heritage²¹.

The relationship between subjects and methods: from a limited binding to diversity. Another trend is the gradual diminishing of the “binding” relationship between specific technologies and research objects, shifting towards a scenario where different technologies are applied to diverse objects. For instance, in the early 2010s¹⁰⁰, the application of GIS was more closely associated with urban heritage^{101,102}, whereas scanning technologies were more commonly linked with monuments and buildings. However, nowadays, GIS has also become associated with other types of architectural heritage, such as monuments, and point cloud technologies, which were initially used for high-precision scanning of small-scale monuments^{103,104}, are now employed for risk management of urban-scale architectural heritage. The reasons for this shift have been mentioned earlier: on the one hand, technological advancements have broadened the potential applications of these technologies^{105,106}; on the other hand, the diversification and enrichment of risk management demands across different types of architectural heritage necessitate more detailed data. Large-scale urban heritage increasingly requires finer data, while monuments, architectural structures, or archeological sites can also be modeled, simulated, and managed within GIS^{84,107,108}. Moreover, GIS provides possibilities for studying larger geographical distributions and managing multiple projects simultaneously^{109,110}.

Current research gaps

The literature analysis reveals the current application and research frontiers of digital technologies in heritage building risk management and the dilemmas faced by current research. These challenges are mainly manifested in three aspects: interactions between technologies, demands of risk management, and limitations of the research subjects^{111,112}.

Low integration between methods in building risk management. The application of digital technologies in building risk management has yet to

achieve deep integration with traditional structural analysis methods, presenting a clear research gap. While technologies such as Structural Health Monitoring and Damage Detection (SHMD) are frequently used in building risk management, they primarily focus on real-time monitoring and post-disaster assessment, lacking systematic integration with conventional methods like Finite Element Analysis (FEA). Moreover, traditional structural analysis methods typically emphasize static structural performance, whereas digital technologies lean toward dynamic monitoring and data-driven analysis. This functional divergence has resulted in insufficient collaborative research between the two approaches. In complex disaster scenarios, the challenge lies in combining the precision of traditional structural analysis with the real-time, dynamic capabilities of digital technologies to create a systematic, multi-layered framework for building risk management. This integration would enhance both pre-disaster preparedness and post-disaster recovery. The absence of such a framework limits the overall effectiveness of risk management and impairs a comprehensive understanding of structural performance in disaster contexts. Addressing this gap is critical for advancing the field and optimizing the resilience of buildings under diverse risk conditions.

Interaction issues between different technologies. In the risk management of architectural heritage, using different digital technologies indeed presents several interaction issues, such as interoperability compatibility challenges^{113,114}.

The main aspects are (a) Challenges for informative/semantic modeling: These models often need to integrate various types of data, such as geometric, historical, material, and contextual information. However, the challenge lies in ensuring that these diverse data types can be effectively combined and interpreted within a single model. Different digital tools and platforms may use varying standards and protocols for data representation, leading to interoperability issues. Moreover, the specificity of heritage data, which might include unique historical details, conservation records, or restoration histories, requires highly customized modeling approaches that are not always supported by general-purpose software. The need for consistent and comprehensive data standards is critical, yet achieving this across different systems and disciplines remains a significant challenge. (b) Encoding and enrichment of the data: Encoding involves converting complex heritage data types into digital formats, which poses issues related to standardization, data integrity, and cross-platform interoperability. Enrichment, which enhances digital models by integrating diverse data sources and adding metadata, must address challenges of data consistency, metadata complexity, and scalability. In addition, ensuring the accuracy and quality of enriched information is critical. These challenges necessitate the adoption of robust methodologies and tools to effectively manage and preserve heritage assets in their digital form; (c) Data processing with different software: The processing of data related to architectural heritage often involves multiple software tools, each specializing in different aspects of the workflow, such as data capture, modeling, analysis, and visualization. However, these tools often operate in silos, with limited interoperability between them. This lack of seamless integration can lead to several issues, such as data inconsistencies, redundant workflows, and increased complexity in managing data across different platforms.

Adopting open standards and shared platforms can somewhat alleviate these compatibility issues and promote better integration between different technologies¹¹⁵. Examples of such efforts include the Heritage Documentation Programs (HDP) tools provided by the National Park Service (NPS), such as the HABS (Historic American Buildings Survey), HAER (Historic American Engineering Record), and HALS (Historic American Landscapes Survey) documentation^{116,117}, specifically designed to record and protect America’s architectural and engineering heritage. These tools and methods provide detailed historical and structural data for architectural heritage risk management^{21,118,119}. Additionally, HBIM, a specific application of BIM designed for historic buildings, utilizes the traditional BIM framework to record and manage complex data of old buildings^{60,120}, suitable for

risk management and conservation work. However, current standards and digital software platforms, while somewhat mitigating these issues, still fall short of fully achieving integration between different digital technologies (such as VR/AR, point clouds, DT, etc.) and various application scenarios (such as documentation, modeling, interaction, etc.).

Increased functional demands on risk management for architectural heritage. While the past decade (from 2014 to 2024) has seen significant functional improvements in the risk management of architectural heritage through digital technologies—ranging from timeliness and predictiveness in management to remote monitoring and digital modeling—there are still several areas where further advancements are needed^{69,121,122}. These include:

(a) Efficient and convenient management: The demand for an efficient and user-friendly management system continues to be high. Stakeholders are looking for solutions that streamline the day-to-day management of architectural heritage sites and make it easier to access and analyze data^{123,124}. This could involve the development of integrated platforms that consolidate data from various sources—such as sensors, drones, and satellite imagery—into a single, easily navigable interface^{125,126}. Such platforms should support real-time data feeds and have robust mobile capabilities, allowing managers to oversee site conditions and respond to alerts from anywhere, thereby enhancing the effectiveness of heritage management^{127–129}.

(b) Emergency alerts and real-time response integration: There is a critical need to integrate emergency alert systems with practical, on-the-ground response strategies^{130,131}. Digital technology can be utilized to develop advanced predictive models that use historical data and real-time environmental inputs to forecast potential risks, such as structural failures, weather-related damage, or other threats^{69,132,133}. Integrating these predictive tools with emergency response protocols can enable swift mobilization of resources and personnel, ensuring that preventive measures or repairs are implemented quickly to mitigate damage^{134,135}.

(c) Enhanced predictive capabilities for true full lifecycle management: Enhancing the predictive capabilities of risk management tools is essential for achieving genuine full lifecycle management of architectural heritage^{86,136}. This involves not only predicting when and where risks might occur but also understanding the long-term impacts of various conservation strategies. Advanced analytics and machine learning models could be employed to analyze decades-long datasets to uncover trends and patterns that inform better preservation practices. Moreover, integrating these insights into planning and decision-making processes can lead to more proactive and sustainable heritage conservation^{137–140}.

(d) From local fragment to global integration: One of the key demands in the digital risk management of architectural heritage today is the transition from local fragmentation to global integration. Achieving this requires the consolidation of data scattered across various locations and formats into a unified digital platform, enabling a comprehensive understanding of heritage sites. Simultaneously, the development and adoption of standardized protocols for encoding, storage, and data exchange are essential to ensure seamless interoperability across different systems. Furthermore, global integration enhances accessibility, making information more readily available to researchers, educators, and the public worldwide, thereby advancing both academic research and public engagement in heritage preservation. Therefore, from the perspective of digital risk management, the establishment and promotion of a global platform, such as Docomomo, is necessary^{141,142}.

The integration of these advanced digital solutions would not only address current demands but also set a new standard for the preservation and management of architectural heritage, ensuring its resilience and sustainability for future generations.

Limitations in research subjects. Current research and projects have encompassed a wide array of architectural heritages and constructions, even making it feasible to manage the risks of these properties through digital virtualization^{94,143,144}. However, these digital technologies are not

widely applied to many explicitly identified architectural or related heritages in risk management^{28,145}. For instance, despite historic gardens being recognized as significant architectural or related heritage and confirmed as cultural heritage in the 1989 *Florence Charter*, there have been scant references in literature and projects from 2014 to 2024 regarding applying digital technologies to their risk management. This oversight is notable, mainly since historic gardens, as living landscapes, are greatly influenced by natural elements such as vegetation, making them ideal candidates for digital monitoring and risk management¹⁴⁵.

Moreover, while many digital risk management tools have been employed to manage the structural, surface, and material aspects of architectural heritage, there is a near absence of risk management that addresses the design methodologies or visual arrangements of these spaces. From a human perceptual standpoint, the spatial and visual characteristics are more readily perceived and potentially at greater risk. The interaction of light, shadow (e.g., the shadow in the historic garden)¹⁴⁶, and visual-spatial form not only contributes to these spaces' esthetic and historical value but also influences their physical vulnerability and the need for preservation (e.g., the spatial characteristics in historic gardens and buildings can be vulnerable to the vegetation growth)¹⁵.

In light of these observations, it is imperative to broaden the application of digital technologies in heritage risk management to encompass more diverse aspects, including less tangible elements such as spatial design and visual esthetics^{147,148}. This could involve the integration of advanced imaging and modeling technologies that capture and analyze the intricate interactions within heritage spaces, enhancing our ability to predict and mitigate risks that are not merely structural but also perceptual and experiential^{1,149,150}.

To adequately address these gaps, there needs to be a concerted effort towards developing tailored digital solutions that capture and respond to the unique characteristics of varied heritage types. This includes not only expanding the scope of what is considered “at risk” but also refining digital tools to interact more effectively with the complex dynamics of living and designed heritage spaces^{88,89,151}. Such an approach would safeguard the physical integrity of these sites and preserve their historical authenticity and experiential qualities, which are essential for future generations to appreciate and learn from our shared cultural past.

Future development trends prediction

As technology rapidly advances and the demand for heritage conservation continues to grow, the architectural heritage risk management field is facing significant transformations^{152–154}. Based on an analysis of current research gaps and literature, the following detailed exposition outlines the key future development trends in this area:

(a) Advancements in technology: Based on emerging research focuses, it is anticipated that the application of digital technologies in building heritage risk management will revolve around two core directions: intelligentization and dynamization^{155–157}. These trends are expected to profoundly influence the entire process of disaster risk assessment and emergency decision-making.

In terms of intelligentization (Fig. 3b, c), AI and Big Data are becoming pivotal technological pillars driving advancements in building risk management^{158,159}. AI, through machine learning and deep learning algorithms, can rapidly extract potential risk patterns from diverse and complex datasets, providing a scientific foundation for dynamic evaluation and decision optimization¹⁶⁰. Simultaneously, Big Data technology integrates IoT sensor networks, structural monitoring devices, and historical disaster data to create a comprehensive data support platform for building condition monitoring, pathology identification, and risk prediction^{161,162}. The combination of smart sensor networks and real-time analysis systems enables dynamic evaluations of building performance and potential risks, providing timely warnings for emergency response^{162,163}. Moreover, automated data processing technologies eliminate barriers to multi-source data integration, allowing GIS, BIM, and photogrammetry to collaborate more efficiently, driving the intelligent transformation of building risk management and significantly improving its precision and efficiency^{164,165}.

Dynamization focuses on real-time monitoring, dynamic modeling, and interactive scenario simulation, with DT technology as its core (Fig. 3b, c). DTs synchronize the real-time state of physical buildings with virtual models, not only accurately reflecting current building conditions but also simulating various disaster scenarios to support risk assessments and post-disaster recovery planning dynamically¹⁶⁶. Real-time monitoring technologies, including laser scanning, remote sensing, photogrammetry, and drone inspections, provide a continuous flow of data updates, ensuring the timeliness and accuracy of building condition information¹⁶⁷. AR and VR technologies further enrich the applications of building risk management by simulating the dynamic processes of disasters through visualization¹⁶⁸, offering immersive interactive platforms for decision-makers^{168–173}. These tools allow stakeholders to understand and address potential risks more intuitively. Together, these technologies form a robust foundation for dynamic responses and multidimensional decision support in the face of complex disaster scenarios. By integrating intelligent and dynamic capabilities, the future of building heritage risk management will be characterized by more efficient, precise, and adaptive solutions, ensuring resilience in a rapidly changing risk landscape.

(b) Enrichment of research subjects: Future risk management will emphasize comprehensive protection of architectural heritage, which includes not only the buildings themselves but also their environments and related intangible cultural heritage^{174,175}. For example, the management of historic urban areas and gardens will encompass protecting architectural structures and monitoring the surrounding environment, microclimates, and socio-cultural factors related to people's daily lives. This holistic protection strategy will better maintain the integrity and authenticity of heritage.

(c) Interaction between different technologies and information (datasets): The industry must establish more unified data standards and interfaces to achieve efficient cooperation between multiple technologies. This will facilitate data exchange and integration between different devices and systems and promote collaboration across different stages of management^{176,177}. For instance, preventive maintenance, emergency response, and restoration care of cultural artifacts can be coordinated through a unified platform that enables data sharing and optimized resource allocation. Regarding this, the establishment and enhancement of AHII (Architectural Heritage Information Infrastructure)¹⁷⁸ can address issues of interaction and interoperability. As technology continues to advance, AHII will further develop towards greater intelligence and globalization, becoming a vital platform that connects heritage preservation efforts worldwide. This will provide more comprehensive and advanced support for the digital risk management of architectural heritage.

Through these key technological advancements and methodological updates, the future of architectural heritage risk management is heading toward a more intelligent, systematic, and comprehensive direction. This will greatly enhance the effectiveness of heritage conservation, ensuring that these irreplaceable cultural assets are better maintained and passed on to future generations.

Limitations

Admittedly, the main limitation of this study is the potential inaccuracies related to using visualization-based literature analysis software¹⁷⁹. The literature clustering used to identify research gaps is automatically generated by the software's built-in algorithm and lacks sufficient subjective selection and intervention¹⁸⁰, which may result in revealing major contradictions but lacking specificity, such as there are many research written with other languages are not included. The reason for selecting English-language literature is to ensure an international perspective and facilitate academic dissemination. English-language sources are easier to cite and integrate across disciplines, while also minimizing comprehension errors and biases caused by language differences. However, this approach may introduce a degree of selection bias by potentially overlooking valuable insights from non-English sources. Apart from that, some of the data on "architectural heritage" are presented in the form of project reports and other types of

printed materials that were published in the early portion of the study period and not in English^{152,181,182}. They are important for the scope of this research but often not included in the core dataset of WoS, which may result in data sample sizes that are not very adequate.

Conclusion

This paper systematically reviewed the application of digital technologies in architectural heritage risk management from 2014 to 2024, addressing three core research questions. The findings are summarized as follows:

(a) Main Focus of Current Literature: The review identified a growing body of research focusing on integrating digital technologies into architectural heritage risk management. Key tools such as BIM, HBIM, GIS, and advanced imaging techniques have been widely applied for data collection, modeling, and visualization. However, certain areas, such as architectural pathology identification and environmental risk assessment, remain underexplored, highlighting the need for targeted research in these domains.

(b) Connections Between Technologies and Applications: The interplay between traditional and digital methodologies has evolved significantly, with a trend toward complementary integration rather than replacement. Technologies like GIS and BIM collaborate effectively with newer approaches such as digital twins, augmented reality (AR), and artificial intelligence (AI). However, challenges persist, including interoperability and the lack of unified data standards, limiting seamless technology interaction and application in real-world scenarios.

(c) Current Challenges, Gaps, and Future Directions: Key challenges include the limited integration of digital technologies with traditional risk management methods, issues of data standardization, and the underrepresentation of specific heritage categories, such as gardens and urban spaces. The review identified a significant gap in using digital tools for proactive and holistic lifecycle management. Future research should emphasize developing integrated platforms, improving AI-driven predictive capabilities, and fostering global data-sharing networks such as Architectural Heritage Information Infrastructure (AHII).

This review underscores the transformative potential of digital technologies in enhancing the resilience and sustainability of architectural heritage. It also highlights the pressing need for interdisciplinary collaboration and innovation to address existing limitations, paving the way for more efficient and comprehensive heritage risk management practices.

Data availability

The datasets used in this study are available from the corresponding author upon reasonable request.

Received: 30 September 2024; Accepted: 8 January 2025;

Published online: 28 February 2025

References

1. Worthing, D. & Bond, S. *Managing Built Heritage: The Role of Cultural Significance* (John Wiley & Sons, 2008).
2. Fakhouri, L. A. & Haddad, N. A. Aspects of the architectural and urban heritage: from registers to conservation for adaptive and modern use at the historic cores of salt and Irbid, Jordan. *ArchNet-IJAR: Int. J. Archit. Res.* **11**, 190 (2017).
3. Theodora, Y. Cultural heritage as a means for local development in mediterranean historic cities—the need for an urban policy. *Heritage* **3**, 152–175 (2020).
4. Adamopoulos, E. & Rinaudo, F. Close-range sensing and data fusion for built heritage inspection and monitoring—a review. *Remote Sens.* **13**, 3936 (2021).
5. Sutherland, N., Marsh, S., Priestnall, G., Bryan, P. & Mills, J. InfraRed thermography and 3D-data fusion for architectural heritage: a scoping review. *Remote Sens.* **15**, 2422 (2023).
6. Zhao, C., Zhang, Y., Wang, C.-C., Hou, M. & Li, A. Recent progress in instrumental techniques for architectural heritage materials. *Herit. Sci.* **7**, 36 (2019).

7. Murphy, M., McGovern, E. & Pavia, S. Historic building information modelling—adding intelligence to laser and image based surveys of European classical architecture. *ISPRS J. Photogramm. Remote Sens.* **76**, 89–102 (2013).
8. Styliadis, A. D. et al. Metadata-based heritage sites modeling with e-learning functionality. *J. Cult. Herit.* **10**, 296–312 (2009).
9. He, Y., Ma, Y. H. & Zhang, X. R. “DIGITAL HERITAGE” THEORY AND INNOVATIVE PRACTICE. *Int. Arch. Photogramm Remote Sens. Spatial Inf. Sci.* **XLII-2/W5**, 335–342 (2017).
10. Noor, S. et al. Modeling and representation of built cultural heritage data using semantic web technologies and building information model. *Comput. Math. Organ. Theory* **25**, 247–270 (2019).
11. Trillo, C. et al. Enhancing heritage and traditional architecture conservation through digital technologies. Developing a digital conservation handbook for As-Salt, Jordan. In *New Metropolitan Perspectives: Knowledge Dynamics, Innovation-driven Policies Towards the Territories’ Attractiveness*. Vol. 1 (Springer International Publishing, 2020).
12. Khalid, A. Conservation challenges and emerging trends of digital preservation for UNESCO Architectural Heritage, Pakistan. *Conservation* **2**, 26–37 (2022).
13. Psomadaki, O. I., Dimoulas, C. A., Kalliris, G. M. & Paschalidis, G. Digital storytelling and audience engagement in cultural heritage management: a collaborative model based on the Digital City of Thessaloniki. *J. Cult. Herit.* **36**, 12–22 (2019).
14. Economou, M. Heritage in the digital age. In *A companion to heritage studies* (eds Logan, W., Nic Craith, M. & Kockel, U.) 215–228 (Wiley-Blackwell, 2015).
15. Peng, Y., Zhang, G., Nijhuis, S., Agugiaro, G. & Stoter, J. E. Towards a framework for point-cloud-based visual analysis of historic gardens: Jichang Garden as a case study. *Urban For. Urban Green.* **91**, 128159 (2024).
16. Berta, M., Bottero, M. & Ferretti, V. A mixed methods approach for the integration of urban design and economic evaluation: Industrial heritage and urban regeneration in China. *Environ. Plan. B: Urban Anal. City Sci.* **45**, 208–232 (2016).
17. Dragoni, M., Tonelli, S. & Moretti, G. A knowledge management architecture for digital cultural heritage. *J. Comput. Cult. Herit.* **10**, 1–18 (2017).
18. Rodrigues, B. N. et al. Digital survey applied to the assessment of pathological manifestations in the architectural heritage of Monte alegre in Piracicaba/SP. *J. Build. Pathol. Rehabil.* **8**, 60 (2023).
19. Wang, H. et al. Research on pathology information management of educational architectural heritage based on digital technology: the case of James Jackson Gymnasium. *Buildings* **14**, 1048 (2024).
20. Torres-González, M., Prieto, A. J., Alejandre, F. J. & Blasco-López, F. J. Digital management focused on the preventive maintenance of World Heritage Sites. *Autom. Constr.* **129**, 103813 (2021).
21. Zonta, D., Pozzi, M. & Zanon, P. Managing the historical heritage using distributed technologies. *Int. J. Archit. Herit.* **2**, 200–225 (2008).
22. McCarthy, C. Re-thinking threats to architectural heritage. *Int. J. Herit. Stud.* **18**, 624–636 (2012).
23. Brimblecombe, P., Hayashi, M. & Futagami, Y. Mapping climate change, natural hazards and Tokyo’s built heritage. *Atmosphere* **11**, 680 (2020).
24. Lagomarsino, S. & Podestà, S. Damage and vulnerability assessment of churches after the 2002 Molise, Italy, Earthquake. *Earthq. Spectra* **20**, 271–283 (2004).
25. Li, Y. et al. A review of the tools and techniques used in the digital preservation of architectural heritage within disaster cycles. *Herit. Sci.* **11**, 199 (2023).
26. Liritzis, I., Al-Otaibi, F. & Volonakis, P. Digital technologies and trends in cultural heritage. *Mediterr. Archaeol. Archaeom.* **15**, 313–(2015).
27. Zhang, X., Zhi, Y., Xu, J. & Han, L. Digital protection and utilization of architectural heritage using knowledge visualization. *Buildings* **12**, 1604 (2022).
28. Lee, J., Kim, J., Ahn, J. & Woo, W. Context-aware risk management for architectural heritage using historic building information modeling and virtual reality. *J. Cult. Herit.* **38**, 242–252 (2019).
29. Rosa, A., Santangelo, A. & Tondelli, S. Investigating the integration of cultural heritage disaster risk management into urban planning tools. The Ravenna Case Study. *Sustainability* **13**, 872 (2021).
30. Mansuri, L. E. et al. A systematic mapping of BIM and digital technologies for architectural heritage. *Smart Sustain. Built Environ.* **11**, 1060–1080 (2022).
31. Vuoto, A., Funari, M. F. & Lourenço, P. B. Shaping digital twin concept for built cultural heritage conservation: a systematic literature review. *Int. J. Archit. Herit.* **18**, 1762–1795 (2024).
32. Sarkis-Onofre, R., Catalá-López, F., Aromataris, E. & Lockwood, C. How to properly use the PRISMA statement. *Syst. Rev.* **10**, 117 (2021).
33. Van Eck, N. & Waltman, L. Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* **84**, 523–538 (2010).
34. Chen, C. CiteSpace II: detecting and visualizing emerging trends and transient patterns in scientific literature. *J. Am. Soc. Inf. Sci. Technol.* **57**, 359–377 (2006).
35. Changjuan, H. & Shikui, C. In *Visualization Analysis of Research Hotspots and Development Trends of Technological Innovation Efficiency Based on COOC* (ProcSPIE, 2023).
36. Page, M. J. et al. Updating guidance for reporting systematic reviews: development of the PRISMA 2020 statement. *J. Clin. Epidemiol.* **134**, 103–112 (2021).
37. Finfgeld-Connett, D. Use of content analysis to conduct knowledge-building and theory-generating qualitative systematic reviews. *Qual. Res.* **14**, 341–352 (2013).
38. Jensen, L. A. & Allen, M. N. Meta-synthesis of qualitative findings. *Qual. Health Res.* **6**, 553–560 (1996).
39. Onwuegbuzie, A. J., Leech, N. L. & Collins, K. M. Qualitative analysis techniques for the review of the literature. *Qual. Rep.* **17**, 56 (2012).
40. Phillips, M., Fosmire, M., Turner, L., Petersheim, K. & Lu, J. Comparing the information needs and experiences of undergraduate students and practicing engineers. *J. Acad. Librariansh.* **45**, 39–49 (2019).
41. Waltman, L., van Eck, N. J. & Noyons, E. C. M. A unified approach to mapping and clustering of bibliometric networks. *J. Informetr.* **4**, 629–635 (2010).
42. Zhang, H., Nijhuis, S. & Newton, C. Freshwater blue space design and human health: a comprehensive research mapping based on scientometric analysis. *Environ. Impact Assess. Rev.* **97**, 106859 (2022).
43. Accardo, G., Giani, E. & Giovagnoli, A. The risk map of Italian cultural heritage. *J. Archit. Conserv.* **9**, 41–57 (2003).
44. Boggio, A. From protections to protection: rethinking Italian cultural heritage policy. *Colum-VLA J. Arts* **24**, 269 (2000).
45. Burke, P. *The Italian Renaissance: Culture and Society in Italy* (Princeton University Press, 2014).
46. Nickolas, Z. The European Geoparks Network—geological heritage protection and local development. *Int. Union Geol. Sci.* **27**, 165–171 (2004).
47. Tsivolas, T. *Law and Religious Cultural Heritage in Europe* (Springer, 2014).
48. Verbree, E., Zlatanova, S. & Dijkman, S. *Distance-value-added Panoramic Images as the Base Data Model for 3D-GIS* (Panoramic Photogrammetry Workshop, 2005).
49. Germanà, M. L. *Technology and Architectural Heritage: Dynamic Connections* (Springer International Publishing, 2019).

50. li, Y. et al. REVIEW open access a review of the tools and techniques used in the digital preservation of architectural heritage within disaster cycles. *Herit. Sci.* **11**, 199 (2023).
51. Bernhardsen, T. *Geographic Information Systems: An Introduction* (John Wiley & Sons, 2002).
52. Song, Y. et al. Trends and opportunities of BIM-GIS integration in the architecture, engineering and construction industry: a review from a spatio-temporal statistical perspective. *ISPRS Int. J. Geo-Inf.* **6**, 397 (2017).
53. Çetin, S., De Wolf, C. & Bocken, N. Circular digital built environment: an emerging framework. *Sustainability* **13**, 6348 (2021).
54. Arnold, D. & Geser, G. EPOCH research agenda for the applications of ICT to cultural heritage. EPOCH project. http://public-repository.epoch-net.org/publications/RES_AGENDA/research_agenda.pdf (2008).
55. Puerto, A. et al. Building information modeling and complementary technologies in heritage buildings: a bibliometric analysis. *Results Eng.* <https://doi.org/10.1016/j.rineng.2024.102192> (2024).
56. Yasar, A. M., Voûte, R. & Verbree, E. Direct use of indoor point clouds for path planning and navigation exploration in emergency situations. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.-ISPRS Arch.* **48**, 175–181 (2024).
57. Xu, C. et al. Cloud-based storage and computing for remote sensing big data: a technical review. *Int. J. Digit. Earth* **15**, 1417–1445 (2022).
58. El Barhoumi, N. & Hajji, R. HBIM and extended reality for cultural mediation of historical heritage: a review. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **48**, 125–132 (2024).
59. Stober, D., Žarnić, R., Penava, D., Podmanicki, M. T. & Virgej-Đurašević, R. Application of HBIM as a research tool for historical building assessment. *Civ. Eng. J.* **4**, 1565 (2018).
60. Megahed, N. A. Towards a theoretical framework for HBIM approach in historic preservation and management. *ArchNet-IJAR: Int. J. Archit. Res.* **9**, 130 (2015).
61. Massaoudi, M., Abu-Rub, H., Refaat, S. S., Chihi, I. & Oueslati, F. S. Deep learning in smart grid technology: a review of recent advancements and future prospects. *IEEE Access.* **9**, 54558–54578 (2021).
62. Özerol, G. & Arslan Selçuk, S. Machine learning in the discipline of architecture: a review on the research trends between 2014 and 2020. *Int. J. Archit. Comput.* **21**, 23–41 (2023).
63. Zhang, Y., Liu, H., Kang, S.-C. & Al-Hussein, M. Virtual reality applications for the built environment: research trends and opportunities. *Autom. Constr.* **118**, 103311 (2020).
64. Casini, M. Extended reality for smart building operation and maintenance: a review. *Energies* **15**, 3785 (2022).
65. Wang, X. et al. Machine learning for risk and resilience assessment in structural engineering: progress and future trends. *J. Struct. Eng.* **148**, 03122003 (2022).
66. Qolomany, B. et al. Leveraging machine learning and big data for smart buildings: a comprehensive survey. *IEEE Access.* **7**, 90316–90356 (2019).
67. Fiorini, L. et al. Machine learning-based monitoring for planning climate-resilient conservation of built heritage. *Drones* **8**, 249 (2024).
68. Perles, A. et al. An energy-efficient internet of things (IoT) architecture for preventive conservation of cultural heritage. *Future Gener. Comput. Syst.* **81**, 566–581 (2018).
69. Rossi, M. & Bournas, D. Structural health monitoring and management of cultural heritage structures: a state-of-the-art review. *Appl. Sci.* **13**, 6450 (2023).
70. Altohami, A. B. A., Haron, N. A., Ales@ Alias, A. H. & Law, T. H. Investigating approaches of integrating BIM, IoT, and facility management for renovating existing buildings: a review. *Sustainability* **13**, 3930 (2021).
71. Scuro, C., Lamonaca, F., Porzio, S., Milani, G. & Olivito, R. Internet of Things (IoT) for masonry structural health monitoring (SHM): overview and examples of innovative systems. *Constr. Build. Mater.* **290**, 123092 (2021).
72. Pabón-Charneco, A. *Architecture History, Theory and Preservation: Prehistory to the Middle Ages* (Routledge, 2020).
73. Stubbs, J. H. *Time Honored: A Global View of Architectural Conservation* (John Wiley & Sons, 2009).
74. Hamzaoui, M. A. & Julien, N. A digital twin lifecycle vision integrating an evolutive collaboration with its ecosystem. <https://doi.org/10.2139/ssrn.4634142> (2023).
75. Vinod Kumar, T. in *The smart megacity system of Indo-Pacific: emerging architecture and megacities studies*. (eds Vinod Kumar, T. M.) *Indo-Pacific Smart Megacity System: Emerging Architecture and Megacity Studies* 3–159. https://doi.org/10.1007/978-981-99-6218-1_1 (Springer, 2023).
76. Natta, F. & Ambrosio, M. AR for demolished heritage: the First Italian Parliament in Turin. In *Representation Challenges: New Frontiers of AR and AI Research for Cultural Heritage and Innovative Design* (eds Giordano, A., Russo, M. & Spallone, M.) 121–128 (FrancoAngeli, 2022).
77. Wang, J. & Hou, J. The application of digital technology in the protection of architectural cultural heritage. <https://aisel.aisnet.org/iceb2023/61> (2023).
78. Rong, X. & He, B. Recording method of Chinese traditional interior decoration of the Qing dynasty in digital era: a case study of Jingfu Palace in the Forbidden City. In *ICOMOS 19th General Assembly and Scientific Symposium "Heritage and Democracy"* (ICOMOS, 2018).
79. Wang, C., Wang, S. & Chen, H. Combination of lidar technology and Fa-shi calculation method of Chinese ancient architecture heritage reconstruction. In *2022 29th International Conference on Geoinformatics* (IEEE, 2022).
80. Kamel, N. A. & Elshawy, R. Virtual reality and virtual diving technologies: innovative tools to promote maritime and underwater cultural heritage in the Red Sea, Egypt. *J. Tour. Hotels Herit.* **5**, 18–46 (2022).
81. Gonizzi Barsanti, S., Caruso, G., Micoli, L. L., Covarrubias Rodriguez, M. & Guidi, G. 3D visualization of cultural heritage artefacts with virtual reality devices. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **40**, 165–172 (2015).
82. Portman, M. E., Natapov, A. & Fisher-Gewirtzman, D. To go where no man has gone before: Virtual reality in architecture, landscape architecture and environmental planning. *Comput. Environ. Urban Syst.* **54**, 376–384 (2015).
83. Díaz-Vilariño, L., Verbree, E., Zlatanova, S. & Diakité, A., editors. Indoor modelling from SLAM-based laser scanner: door detection to envelope reconstruction. In *ISPRS Geospatial Week 2017* (ISPRS, 2017).
84. Luo, L. et al. Google Earth as a powerful tool for archaeological and cultural heritage applications: a review. *Remote Sens.* **10**, 1558 (2018).
85. Zaimes, G. N., Iakovoglou, V., Maclaren, F. T. & Manchanda, P., editors. Adopting Digital tools & technology to evolve sustainable tourism at world heritage sites: case studies from India and Greece. In *50 Years World Heritage Convention: Shared Responsibility–Conflict & Reconciliation* (Springer International Publishing Cham, 2022).
86. Jigyasu, R. et al. Heritage and resilience: issues and opportunities for reducing disaster risks. <https://nrl.northumbria.ac.uk/id/eprint/17231> (2013).
87. Jin, X. Human-made risks and preventive strategies for architectural heritage under threat from urbanization. In *8th ICBR Lisbon Book of Papers* (eds Martins, A. N. et al.) Vol. 457 (ebook, 2019).
88. Arayici, Y. et al. *Heritage Building Information Modelling* (Routledge Abingdon, 2017).
89. Jordan-Palomar, I., Tzortzopoulos, P., García-Valldecabres, J. & Pellicer, E. Protocol to manage heritage-building interventions using heritage building information modelling (HBIM). *Sustainability* **10**, 908 (2018).

90. De Fino, M., Galantucci, R. A. & Fatiguso, F. Condition assessment of heritage buildings via photogrammetry: a scoping review from the perspective of decision makers. *Heritage* **6**, 7031–7066 (2023).
91. Kong, X. & Hucks, R. G. Preserving our heritage: a photogrammetry-based digital twin framework for monitoring deteriorations of historic structures. *Autom. Constr.* **152**, 104928 (2023).
92. Luo, S. & Wang, H. Digital twin research on masonry–timber architectural heritage pathology cracks using 3D laser scanning and deep learning model. *Buildings* **14**, 1129 (2024).
93. Sánchez-Aparicio, L. J. et al. Web-GIS approach to preventive conservation of heritage buildings. *Autom. Constr.* **118**, 103304 (2020).
94. Ravankhah, M. et al. editors. Risk assessment and risk management for the protection of cultural heritage. In *Cultural Heritage Resilience Against Climate Change and Natural Hazards: Methodologies, Procedures, Technologies and Policy Improvements Achieved by Horizon 2020–700191* (STORM Project, 2019).
95. Hassan, M. & Xie, H. *Climate Change and Conservation of Coastal Built Heritage* (Springer, 2020).
96. Ravankhah, M. et al. A multi-hazard platform for cultural heritage at risk: the STORM risk assessment and management tool. *IOP Conf. Ser.: Mater. Sci. Eng.* **949**, 012111 (2020).
97. Abdalla, R. & Esmail, M. *WebGIS for Disaster Management and Emergency Response* (Springer, 2018).
98. Matracia, M., Saeed, N., Kishk, M. A. & Alouini, M.-S. Post-disaster communications: enabling technologies, architectures, and open challenges. *IEEE Open J. Commun. Soc.* **3**, 1177–1205 (2022).
99. Khan, A., Gupta, S. & Gupta, S. K. Multi-hazard disaster studies: monitoring, detection, recovery, and management, based on emerging technologies and optimal techniques. *Int. J. Disaster Risk Reduct.* **47**, 101642 (2020).
100. Burry, M. *Urban Futures: Designing the Digitalised City* (John Wiley & Sons, 2020).
101. Lezzerini, M. et al. Cultural heritage documentation and conservation: three-dimensional (3D) laser scanning and geographical information system (GIS) techniques for thematic mapping of facade stonework of St. Nicholas Church (Pisa, Italy). *Int. J. Archit. Herit.* **10**, 9–19 (2016).
102. Dore, C. & Murphy, M., editors. Integration of historic building information modeling (HBIM) and 3D GIS for recording and managing cultural heritage sites. In *2012 18th International Conference on Virtual Systems and Multimedia* (IEEE, 2012).
103. Murtiyoso, A. D. *Geospatial Recording and Point Cloud Classification of Heritage Buildings* (Université de Strasbourg, 2020).
104. McCoy, M. D. et al. Unpiloted aerial vehicle acquired lidar for mapping monumental architecture: a case study from the Hawaiian islands. *Adv. Archaeol. Pract.* **9**, 160–174 (2021).
105. Parry, R. *Recoding the Museum: Digital Heritage and the Technologies of Change* (Routledge, 2007).
106. Bekele, M. K., Pierdicca, R., Frontoni, E., Malinverni, E. S. & Gain, J. A survey of augmented, virtual, and mixed reality for cultural heritage. *J. Comput. Cult. Herit. (JOCCH)*. **11**, 1–36 (2018).
107. Wu, J., Lu, Y., Gao, H. & Wang, M. Cultivating historical heritage area vitality using urban morphology approach based on big data and machine learning. *Comput. Environ. Urban Syst.* **91**, 101716 (2022).
108. He, J., Liu, J., Xu, S., Wu, C. & Zhang, J. A GIS-based cultural heritage study framework on continuous scales: a case study on 19th century military industrial heritage. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **40**, 215–222 (2015).
109. Vacca, G., Fiorino, D. R. & Pili, D. A spatial information system (SIS) for the architectural and cultural heritage of Sardinia (Italy). *ISPRS Int. J. Geo-Inf.* **7**, 49 (2018).
110. Agapiou, A. et al. Cultural heritage management and monitoring using remote sensing data and GIS: the case study of Paphos area, Cyprus. *Comput. Environ. Urban Syst.* **54**, 230–239 (2015).
111. Barthel-Bouchier, D. *Cultural Heritage and the Challenge of Sustainability* (Routledge, 2016).
112. Vassilakopoulou, P. & Hustad, E. Bridging digital divides: a literature review and research agenda for information systems research. *Inf. Syst. Front.* **25**, 955–969 (2023).
113. Polo López, C. S., Troia, F. & Nocera, F. Photovoltaic BIPV Systems and Architectural Heritage: new balance between conservation and transformation. an assessment method for heritage values compatibility and energy benefits of interventions. *Sustainability* **13**, 5107 (2021).
114. Chatzigrigoriou, P., Nikolakopoulou, V., Vakkas, T., Vosinakis, S. & Koutsabasis, P. Is architecture connected with intangible cultural heritage? reflections from architectural digital documentation and interactive application design in three aegean islands. *Heritage* **4**, 664–689 (2021).
115. Ghaffarianhoseini, A. et al. Building information modelling (BIM) uptake: clear benefits, understanding its implementation, risks and challenges. *Renew. Sustain. Energy Rev.* **75**, 1046–1053 (2017).
116. Liu, J., Willkens, D. & Gentry, R. A conceptual framework for integrating terrestrial laser scanning (TLS) into the Historic American Buildings Survey (HABS). *Architecture* **3**, 505–527 (2023).
117. Maloney Lo, K. *Documentation of Built Heritage and Disaster Preparedness Plans* (Columbia University, 2020).
118. Konsta, A. & Della Torre, S. Risk management and built heritage: towards a systematic approach. In *Proceedings of the 12th International Conference on Structural Analysis of Historical Constructions SAHC 2021* (eds Roca, P., Pelà, L. & Molins, C.) (CIMNE, 2021).
119. Romão, X., Paupério, E. & Pereira, N. A framework for the simplified risk analysis of cultural heritage assets. *J. Cult. Herit.* **20**, 696–708 (2016).
120. Chiabrando, F., Sammartano, G. & Spanò, A. Historical buildings models and their handling via 3D survey: From points clouds to user-oriented HBIM. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **41**, 633–640 (2016).
121. Mihai, S. et al. Digital twins: a survey on enabling technologies, challenges, trends and future prospects. *IEEE Commun. Surv. Tutor.* **24**, 2255–2291 (2022).
122. Montuori, M. Bridging past and present: cutting-edge technologies for predictive conservation of built cultural heritage. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **48**, 139–145 (2024).
123. Raj, P. & Raman, A. C. *Intelligent Cities: Enabling Tools and Technology* (CRC Press, 2015).
124. Not, E. & Petrelli, D. Empowering cultural heritage professionals with tools for authoring and deploying personalised visitor experiences. *Use. Modeling Use.-Adapted Interact.* **29**, 67–120 (2019).
125. Parrinello, S. & Picchio, F. Digital strategies to enhance cultural heritage routes: from integrated survey to digital twins of different European architectural scenarios. *Drones* **7**, 576 (2023).
126. Cantagallo, C. et al. GENESIS: A WEB-BASED PLATFORM FOR MANAGING THE SEISMIC RISK OF HISTORIC CENTRES OF SOUTHERN ITALY. *REHABEND* <https://ricerca.unich.it/handle/11564/837171> (2024).
127. Kamel Boulos, M. N. et al. Crowdsourcing, citizen sensing and sensor web technologies for public and environmental health surveillance and crisis management: trends, OGC standards and application examples. *Int. J. Health Geogr.* **10**, 1–29 (2011).
128. Chamoso, P., González-Briones, A., Rodríguez, S. & Corchado, J. M. Tendencies of technologies and platforms in smart cities: a state-of-the-art review. *Wirel. Commun. Mob. Comput.* **2018**, 3086854 (2018).
129. Koukopoulos, Z., Koukopoulos, D. & Jung, J. J. A trustworthy multimedia participatory platform for cultural heritage management in smart city environments. *Multimed. Tools Appl.* **76**, 25943–25981 (2017).

130. Granda, S. & Ferreira, T. M. Assessing vulnerability and fire risk in old urban areas: application to the historical centre of Guimarães. *Fire Technol.* **55**, 105–127 (2019).
131. D'Alessandro, A. et al. Urban seismic networks, structural health and cultural heritage monitoring: the national earthquakes observatory (INGV, Italy) experience. *Front. Built Environ.* **5**, 127 (2019).
132. Angjeliu, G., Coronelli, D. & Cardani, G. Development of the simulation model for Digital Twin applications in historical masonry buildings: the integration between numerical and experimental reality. *Comput. Struct.* **238**, 106282 (2020).
133. Mishra, M. Machine learning techniques for structural health monitoring of heritage buildings: a state-of-the-art review and case studies. *J. Cult. Herit.* **47**, 227–245 (2021).
134. Marshall, J. T. & Rowberry, R. M. Urban wreckage and resiliency: articulating a practical framework for preserving, reconstructing, and building cities. *Ida. L. Rev.* **50**, 49 (2013).
135. Van Balen, K. & Vandesande, A. In *Innovative Built Heritage Models: Edited Contributions to the International Conference on Innovative Built Heritage Models and Preventive Systems (CHANGES 2017)*, February 6–8, 2017 (CRC Press, 2018).
136. Wang, J.-J. Flood risk maps to cultural heritage: measures and process. *J. Cult. Herit.* **16**, 210–220 (2015).
137. Matiz Lopez, P. J. Integrated risk assessment for cultural heritage sites: a holistic support tool for decision-making (Doctoral dissertation, IMT School for Advanced Studies Lucca). (IMT PhD Thesis 2016).
138. Veldpaus, L. Historic urban landscapes: framing the integration of urban and heritage planning in multilevel governance (Doctoral dissertation, Eindhoven University of Technology). (Eindhoven University of Technology, 2015).
139. Coombes, M. A. & Viles, H. A. Integrating nature-based solutions and the conservation of urban built heritage: challenges, opportunities, and prospects. *Urban For. Urban Green.* **63**, 127192 (2021).
140. Sánchez, M. L., Cabrera, A. T. & Del Pulgar, M. L. G. Guidelines from the heritage field for the integration of landscape and heritage planning: a systematic literature review. *Landsc. Urban Plan.* **204**, 103931 (2020).
141. Kaptan, M. A., Ünlü, A. & Pottgiesser U. Connecting the dots: a global exploration of local Docomomo inventories. *Docomomo J.* **69**, 76–85 (2023).
142. Pottgiesser, U. & Quist, W. Shared heritage Africa: rediscovering masterpieces. *Docomomo J.* **69**, 2–3 (2023).
143. Albourae, A., Armenakis, C. & Kyan, M. Architectural heritage visualization using interactive technologies. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **42**, 7–13 (2017).
144. Stubbs, M. Heritage-sustainability: developing a methodology for the sustainable appraisal of the historic environment. *Plan. Pract. Res.* **19**, 285–305 (2004).
145. Bandarin, F. *Changing Heritage: How Internal Tensions and External Pressures are Threatening Our Cultural and Natural Legacy* (Taylor & Francis, 2024).
146. Wang, Y., Pan, B. & Zhang, Q. Rockery morphology based on quantitative analysis of shading. *Herit. Sci.* **12**, 379 (2024).
147. Pietroni, E. & Ferdani, D. Virtual restoration and virtual reconstruction in cultural heritage: terminology, methodologies, visual representation techniques and cognitive models. *Information* **12**, 167 (2021).
148. Laing, R. Built heritage modelling and visualisation: the potential to engage with issues of heritage value and wider participation. *Dev. Built Environ.* **4**, 100017 (2020).
149. Nocca, F. The role of cultural heritage in sustainable development: multidimensional indicators as decision-making tool. *Sustainability* **9**, 1882 (2017).
150. Chianese, A., Piccialli, F. & Valente, I. Smart environments and cultural heritage: a novel approach to create intelligent cultural spaces. *J. Locat. Based Serv.* **9**, 209–234 (2015).
151. Oomen, J. & Aroyo, L. (eds). Crowdsourcing in the cultural heritage domain: opportunities and challenges. In *Proceedings of the 5th International Conference on Communities and Technologies*. (Association for Computing Machinery, 2011).
152. Croci, G. *The Conservation and Structural Restoration of Architectural Heritage* (WIT Press, 1998).
153. Bandarin, F. & Van Oers, R. *The Historic Urban Landscape: Managing Heritage in An Urban Century* (John Wiley & Sons, 2012).
154. Jokilehto, J. *A History of Architectural Conservation* (Routledge, 2017).
155. Wang, S., Duan, Y., Yang, X., Cao, C. & Pan, S. Smart museum' in China: from technology labs to sustainable knowledgespaces. *Digit. Scholarsh. Human.* **38**, 1340–1358 (2023).
156. Wei, Y., Yuan, H. & Li, H. Exploring the contribution of advanced systems in smart city development for the regeneration of urban industrial heritage. *Buildings* **14**, 583 (2024).
157. Hu, H. & Hewitt, R. J. Understanding climate risks to world cultural heritage: a systematic analysis and assessment framework for the case of Spain. *Herit. Sci.* **12**, 194 (2024).
158. Habbal, A., Ali, M. K. & Abuzaraida, M. A. Artificial intelligence trust, risk and security management (AI TRiSM): frameworks, applications, challenges and future research directions. *Expert Syst. Appl.* **240**, 122442 (2024).
159. Chen, J., Ding, L., Ji, J. & Zhu, J. A combined method to build Bayesian network for fire risk assessment of historical buildings. *Fire Technol.* **59**, 3525–3563 (2023).
160. Zhang, W. et al. Application of machine learning, deep learning and optimization algorithms in geoenvironment and geoscience: comprehensive review and future challenge. *Gondwana Res.* **109**, 1–17 (2022).
161. Mishra, M., Lourenço, P. B. & Ramana, G. V. Structural health monitoring of civil engineering structures by using the internet of things: a review. *J. Build. Eng.* **48**, 103954 (2022).
162. Panah, R. S. & Kioumars, M. Application of building information modelling (BIM) in the health monitoring and maintenance process: a systematic review. *Sensors* **21**, 837 (2021).
163. Saini, K., Kalra, S. & Sood, S. K. Disaster emergency response framework for smart buildings. *Future Gener. Comput. Syst.* **131**, 106–120 (2022).
164. Cao, Y., Xu, C., Aziz, N. M. & Kamaruzzaman, S. N. BIM–GIS integrated utilization in urban disaster management: the contributions, challenges, and future directions. *Remote Sens.* **15**, 1331 (2023).
165. Darko, A., Chan, A. P. C., Yang, Y. & Tetteh, M. O. Building information modeling (BIM)-based modular integrated construction risk management—critical survey and future needs. *Comput. Ind.* **123**, 103327 (2020).
166. Astarita, V., Guido, G., Haghshenas, S. S. & Haghshenas, S. S. Risk reduction in transportation systems: the role of digital twins according to a bibliometric-based literature review. *Sustainability* **16**, 3212 (2024).
167. Rao, A. S. et al. Real-time monitoring of construction sites: sensors, methods, and applications. *Autom. Constr.* **136**, 104099 (2022).
168. Sermet, Y. & Demir, I. GeospatialVR: a web-based virtual reality framework for collaborative environmental simulations. *Comput. Geosci.* **159**, 105010 (2022).
169. Martins, N. C. et al. Augmented reality situated visualization in decision-making. *Multimed. Tools Appl.* **81**, 14749–14772 (2022).
170. Guo, Y. et al. Extending X-reality technologies to digital twin in cultural heritage risk management: a comparative evaluation from the perspective of situation awareness. *Herit. Sci.* **12**, 245 (2024).

171. Lerario, A. & Varasano, A. An IoT smart infrastructure for S. Domenico Church in Matera's "Sassi": a multiscale perspective to built heritage conservation. *Sustainability* **12**, 6553 (2020).
172. Allal-Chérif, O. Intelligent cathedrals: using augmented reality, virtual reality, and artificial intelligence to provide an intense cultural, historical, and religious visitor experience. *Technol. Forecast. Soc. Change* **178**, 121604 (2022).
173. Barrado-Timón, D. A. & Hidalgo-Giralt, C. The historic city, its transmission and perception via augmented reality and virtual reality and the use of the past as a resource for the present: a new era for urban cultural heritage and tourism? *Sustainability* **11**, 2835 (2019).
174. Lucchi, E. Environmental risk management for museums in historic buildings through an innovative approach: a case study of the Pinacoteca di Brera in Milan (Italy). *Sustainability* **12**, 5155 (2020).
175. O'Brien, G., O'Keefe, P., Jayawickrama, J. & Jigyasu, R. Developing a model for building resilience to climate risks for cultural heritage. *J. Cult. Herit. Manag. Sustain. Dev.* **5**, 99–114 (2015).
176. Palomar, I. J., Valldecabres, J. L. G., Tzortzopoulos, P. & Pellicer, E. An online platform to unify and synchronise heritage architecture information. *Autom. Constr.* **110**, 103008 (2020).
177. Shen, W. et al. Systems integration and collaboration in architecture, engineering, construction, and facilities management: a review. *Adv. Eng. Inform.* **24**, 196–207 (2010).
178. Gózdź, K. J. & van Oosterom, P. J. M. Developing the information infrastructure based on LADM—the case of Poland. *Surv. Rev.* **48**, 168–180 (2016).
179. Lozić, E. & Štular, B. Documentation of archaeology-specific workflow for airborne LiDAR data processing. *Geosciences* **11**, 26 (2021).
180. Lian, J. et al. Conservation and development of the historic garden in a landscape context: a systematic literature review. *Landsc. Urban Plan.* **246**, 105027 (2024).
181. Benkari, N. The built heritage as a resource for architectural education: documentation of the vernacular settlements and architecture in Oman. *J. Cult. Herit. Manag. Sustainable Dev.* <https://doi.org/10.1108/JCHMSD-12-2021-0211> (2022).
182. Balzani, M. & Maietti, F. Architectural space in a protocol for an integrated 3D survey aimed at the documentation, representation and conservation of cultural heritage. *Disegno* **1**, 113–122 (2017).

Acknowledgements

The authors thank the editor and anonymous reviewers for their helpful comments and valuable suggestions.

Author contributions

Y.Y. and A.A. wrote the main manuscript. Y.P. structured the framework, while the other three authors provided critical revisions. All authors reviewed the manuscript thoroughly.

Competing interests

The authors declare no competing interests.

Consent for publication

All participants provided informed consent for the publication of anonymized data. No identifying personal information is included in this publication.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s40494-025-01558-5>.

Correspondence and requests for materials should be addressed to Peter van Oosterom.

Reprints and permissions information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2025