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 Yu[1], Abeer Abu Raed[1,2], Yuyang Peng[3], Uta Pottgiesser[1,4], Edward Verbree[1] & Peter van Oosterom[1]

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 history[1]. 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 acquisition[4–6], 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 damage[11]. Furthermore, the ability to easily share and exchange

[1]Department of Architectural Engineering and Technology, Faculty of Architecture and the Built Environment, Delft University of Technology, Julianalaan Delft, The Netherlands. [2]Department of Architecture, American University of Ras Al Khaimah, Ras Al Khaimah, UAE. [3]Department of Urbanism, Faculty of Architecture and the Built Environment, Delft University of Technology, Julianalaan Delft, The Netherlands. [4]Institute 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 Pakistan[12]. 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 heritage[17], 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 sites[27], 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:

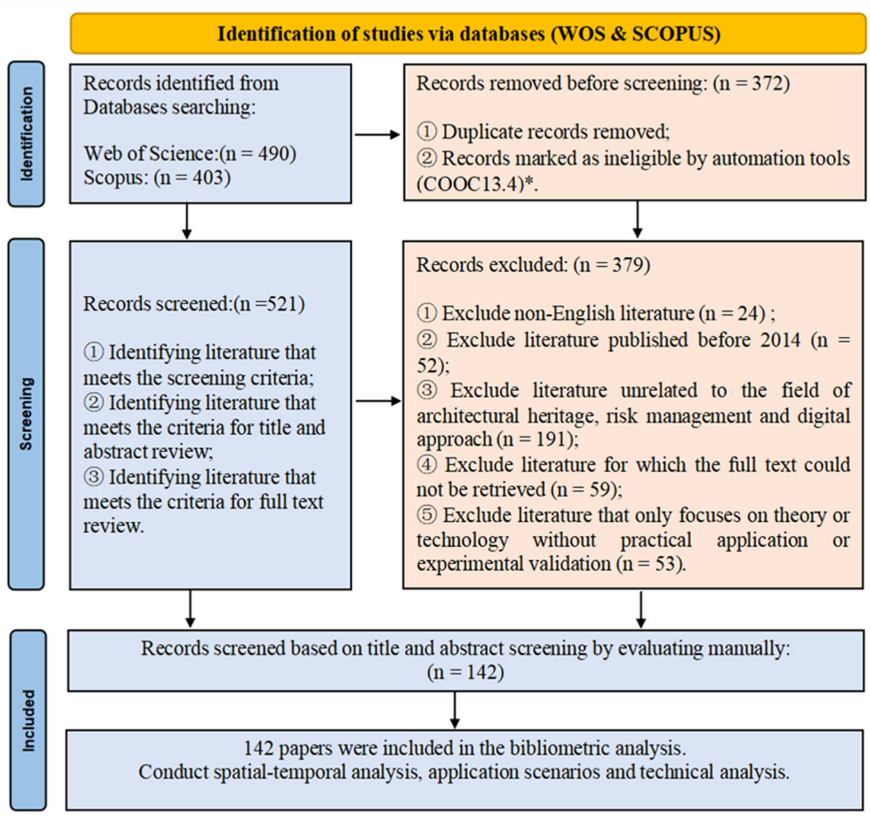
(a) To grasp the main focus of the current literature, including the types and scales of objects studied, and to summarize the specific digital technologies involved in the research;
(b) To understand the connections between different technologies as well as the relationships between methods and their 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 methods[32]. PRISMA was also used to establish multiple criteria to classify and identify the specific content of the target literature in a detailed manner[32]. 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 Scopus[36] 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 statement[36] (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 criteria[1]: non-English-language studies[2], publications prior to 2014[3], literature unrelated to the fields of architectural heritage, risk management, or digital approaches[4], studies for which the full text could not be retrieved, and[5] 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 data[41]. 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 research[42].

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 artworks[45]. Similarly, other European countries such as Greece, France, Germany, and Spain also possess a large number of historical buildings and cultural sites[46]. On the other hand, many European countries have been awakening early to the importance of heritage protection[46]. For example, Italy established a national agency for the protection of cultural heritage as early as 1909[47].

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 domain[33], 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

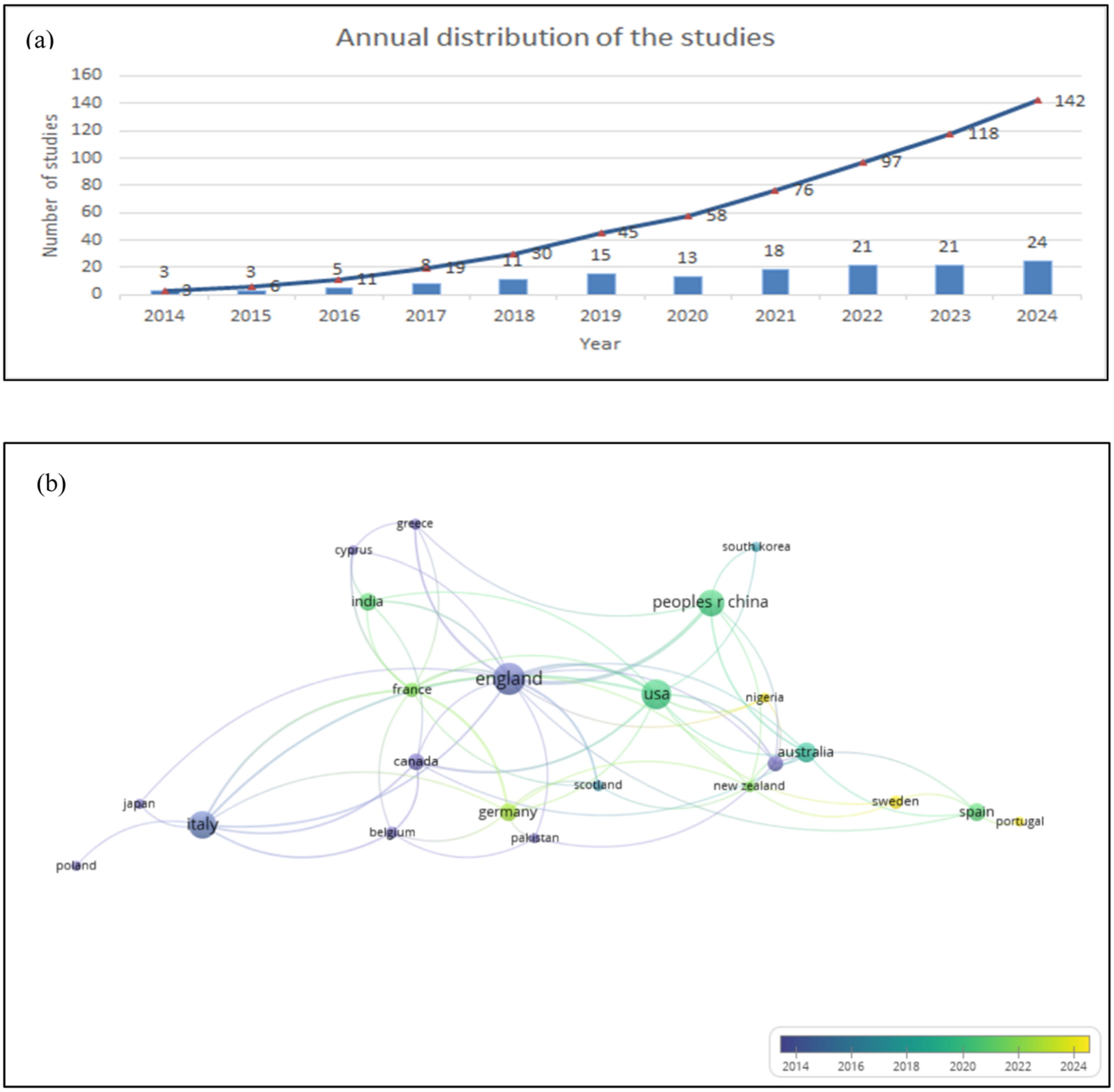


Fig. 2 | **The preliminary results.** **a** The number of publications and **b** the number of publications from different nations.

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,

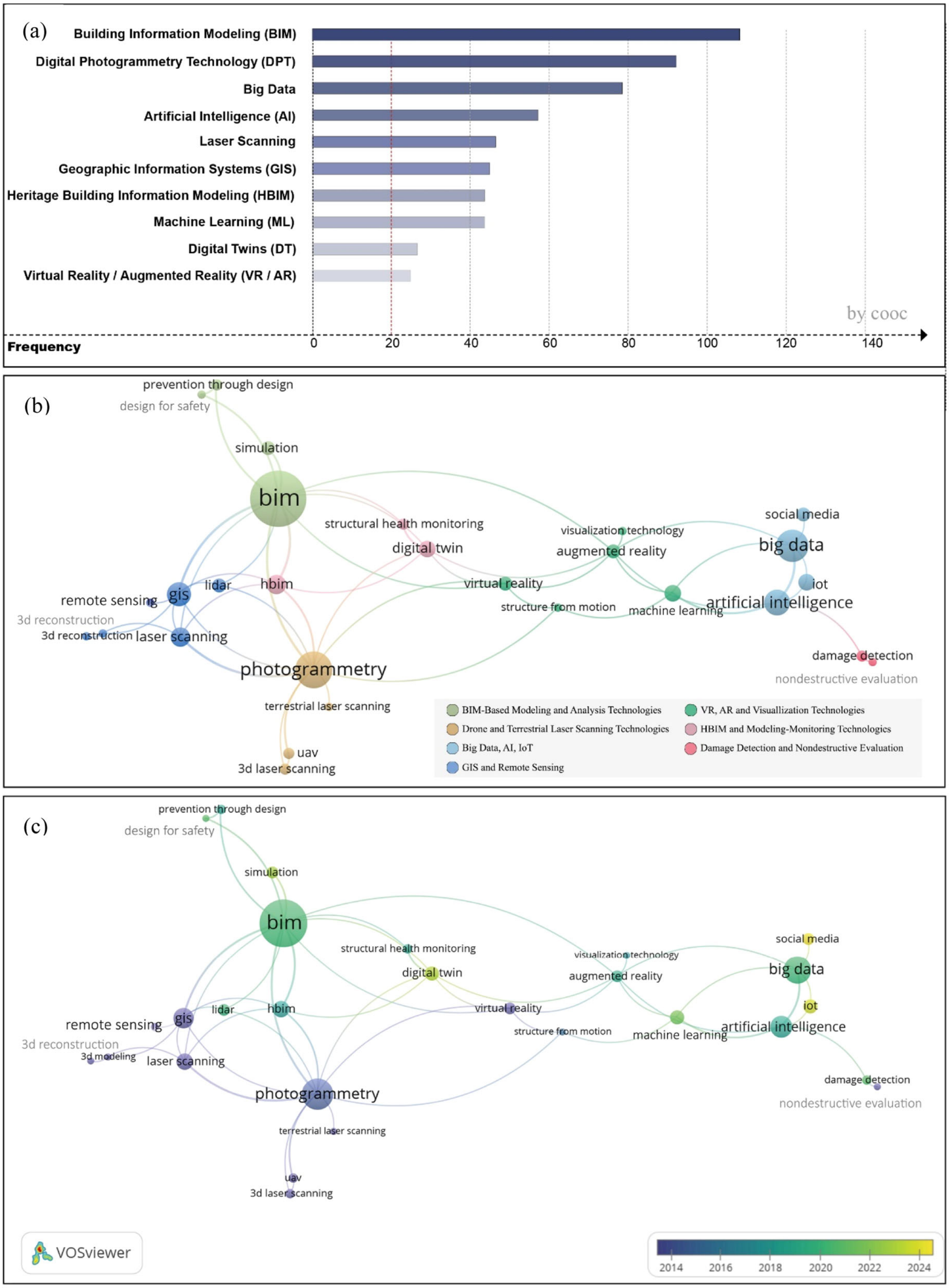


Fig. 3 | Relationship among different technologies applied (source: by author). **a** The number of literature applying different technologies (only those applied more than 20 times are showcased); **b** the relationship among the different technologies; **c** a color gradient is applied to showcase 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 scanning[48] 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 subjects[49].

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 heritage[50], 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 relationship[53]. 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 clouds[56], providing a multidimensional array of information for subsequent risk management[57]. 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 damages[69]. 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 time[76]. 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 worldwide[82].

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 data[83]; 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 environment[84]; (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 heritages[85]; (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 Spain[91]. 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 practices[91]. 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 strategies[92].

(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 challenges[96].

(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 heritage[21].

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 2010s[100], 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 technologies[115]. 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[28,143]. 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 management[145].

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 optimization[160]. 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 dynamically[166]. 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 information[167]. AR and VR technologies further enrich the applications of building risk management by simulating the dynamic processes of disasters through visualization[168], 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 software[179]. The literature clustering used to identify research gaps is automatically generated by the software's built-in algorithm and lacks sufficient subjective selection and intervention[180], 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 under-representation 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

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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.