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Systematic review: a scientometric analysis of the status, trends and challenges in the application of digital technology to cultural heritage conservation (2019–2024)

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Since 2019, the application of digital technology (DT) in cultural heritage conservation (CHC) has transitioned through various phases: from structural prediction and maintenance, to parametric modeling workflows, to collaborative heritage management and assessment, and finally to the integration of technologies and new applications across interdisciplinary fields. What development trends can be observed in the application of DT to CHC in recent years? What difficulties and challenges does it face? Recent studies have primarily focused on technology-driven approaches, but there is a lack of systematic reviews on the current state of research, application progress, and development trends. This paper addresses these research gaps by utilizing bibliometric techniques, including trend analysis through yearly publication and citation line graphs, mapping with visual tools, subject categorization and distribution statistics, co-authorship and keyword-based biclustering, keyword frequency analysis, thematic co-occurrence networks, and content analysis of key articles. A scientometric analysis, conducted using COOC 6.725 and VOS Viewer, applied a Boolean search strategy to filter 345 articles from the Web of Science Core Collection, covering the period from 2019 to 2024. The document types analyzed include articles, reviews, and conference proceedings, all in the English language. The objectives of this paper are to: (1) summarize progressive research trends; (2) analyze interdisciplinary integration; (3) map out author collaboration networks; (4) explore the application potential of DT; (5) reveal cutting-edge topics; and (6) investigate focal issues. Lastly, this paper discusses ethical and social responsibility concerns in DT applications, particularly the challenges related to technology accessibility and data protection. With the rapid development of AI and DT, DT is expected to demonstrate even greater potential and value in CHC.

Cultural heritage embodies significant testimonies of human history and cultural evolution, valued not only for its material form but also for the profound historical and cultural meanings it encapsulates[1]. As a cornerstone of cultural continuity, material heritage authentically reflects societal changes, architectural skills, and the materialization of past societal ethos, playing an irreplaceable role in the study of societal transformations and cultural evolution[2]. Since the release of the United Nations' "Convention Concerning the Protection of the World Cultural and Natural Heritage" in 1972, CHC has gained increasing international attention, with sustainable development becoming a crucial consideration in global cultural

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preservation efforts[3]. Material heritage, serving as a cultural pacemaker for nations and regions, has been integrated as a vital component of global cultural output[4]. However, on a technical level, the conservation of material heritage commonly faces challenges such as vulnerability to natural and anthropogenic damage, alteration of original cultural features during modernization processes, and limitations due to insufficient financial and technical resources, with rapid technological advancements occasionally resulting in compatibility and continuity issues, such as earlier digital records becoming unreadable by newer systems[5–7]. Furthermore, increasing reliance on technology could potentially undermine the transmission of traditional conservation techniques and knowledge.

DT represents a revolutionary approach to traditional CHC methods, aimed at achieving detailed documentation, in-depth analysis, and innovative presentation of heritage through modern technological means[7]. Technologies such as high-precision scanning, 3D modeling, and virtual reality (VR) significantly enrich the research, display, and educational methods related to cultural heritage, enhancing the accessibility and interactivity of these activities[8]. Unmanned aerial vehicle (UAV) mapping and laser scanning (LC) allow for efficient and precise spatial data collection of heritage sites, while digital modeling and VR can recreate heritage scenes, enhancing public engagement and experiential involvement[9].

Apaydin[10] points out that material heritage sites, such as historical buildings[11], shipwreck sites, architectural murals[12,13], urban defenses, and ceramics[14], not only bear witness to the changes in social structures but also embody collective regional memories. Meissne[15] further emphasizes that intangible heritage, such as music, poetry, and tribal rituals, is facing homogenization and the weakening of cultural symbols and emotional values. Based on the K-emans intelligent color classification method, Ao et al.[16] attempt to identify color symbols from export paintings that represent the urban imagery of Guangzhou, aiming to discover innovative values that can promote regional cultural identity and heritage revitalization. As Brosius and Polit[17] state, heritage revitalization is not only about material preservation but also about its role in maintaining group identity and promoting social order. Despite the advancement of DT, how to ensure the authenticity and intrinsic value of culture in a technology-driven environment remains a key issue to be addressed.

Using the formula "allintitle: heritage review" for searches in Google Scholar, this study found that the number of publications annually from 2019 to 2024 increased from 143 to 173, reflecting society's growing attention to CHC. After reviewing the titles and abstracts, the 173 papers retrieved as of October 13, 2024, were categorized into five thematic areas. The first category focuses on heritage management and planning, discussing governance models, planning strategies, and effective protection of heritage resources, especially in the context of sustainable management amid modern urbanization. The second category examines the role of DT in CHC, display, and restoration processes. The third category explores the relationship between heritage tourism, protection, and economic development. The fourth category investigates the challenges posed by climate change to CHC, including the impact of floods and other natural disasters on heritage buildings. The fifth category considers the integration of education with cultural heritage, addressing how heritage is passed down through education and its application in modern teaching models. 34 articles directly reflect DT applications in heritage preservation, highlighting their potential and value.

Ramtohul and Khedo[18] focus on the challenges of AR in enhancing user perception, cultural engagement, and learning within CHC. Mishra and Lourenço[19] review the latest research on AI-assisted visual inspection, noting its great potential when combined with drone and IoT technologies in CHC. Utilizing the PRISMA method, Rodriguez-Garcia et al.[20] analyze the key factors in VR applications for heritage virtual reconstruction and supportive program development. Silva and Oliveira[21] summarize the current applications and challenges of digital imaging in damage monitoring, 3D modeling, and enhancing heritage authenticity. Privitera et al.[22] explore the positive roles and developmental directions of sound interaction technology in heritage experiences. In databases such as Scopus, Web of Science, and Mendeley, Hasssan et al.[23] examine key issues, future sustainable strategies, and trends in the application of DT in CHC across 424 articles. From 932 articles, Harth[24] reviews the thematic classifications and trends regarding the application of machine learning in heritage color restoration from 1999 to 2023. Suryana et al.[25] introduce trends in the application of digital image restoration of ancient manuscripts. Kumar and Gupta[26] provide a systematic review of methods such as image processing, machine learning, and encoder-decoder neural networks in restoring damaged artworks, comparing the strengths and weaknesses of different approaches. Additionally, Liu and Li[27], Ding and Liang[28], Nikolarakis and Koutsabasis[29], Rocha et al.[30], Towarek et al.[31], and Grazianova and Mesaros[32] explore the extension of DT into the fields of ancient costume restoration, cultural narratives, heritage management, historical building assessments, and material restoration through HBIM, AR, UAVs, and digital twin technologies.

The growing number of publications each year indicates the value of DT in CHC, while the diverse thematic areas show the broad scope of DT applications. Many studies employ manual review methods, while some scholars focus on the application of specific DT technologies. A few studies use scientometrics to review the current status and trends of DT in CHC, such as the work of Lian and Xie[33], Zhang et al.[34], Harisanty et al.[35], and Puerto et al.[36] Although these studies span a wide time range and provide detailed classifications of specific DT technologies, they still present the following limitations: (1) A lack of systematic analysis of DT at different stages of development, making it difficult to comprehensively present its evolution; (2) Insufficient analysis of focal topics and their changes over time; (3) A lack of discussion on the impact of technologies across different regions and internationally; (4) Limited focus on the collaborative and innovative potential of DT in interdisciplinary research. These limitations hinder a more comprehensive exploration of the overall application trends and impact of DT in CHC. Although AI and DT have developed rapidly, there are currently few articles summarizing their applications in CHC over the past six years, particularly in terms of development stages, focal topic changes, regional and international influence, and disciplinary classification and collaboration. This paper aims to address these research gaps.

In recent years, DT has driven the digital presentation and educational functions of cultural heritage, enabling audiences to gain a deeper understanding of the social significance of heritage through multi-sensory experiences. Relevant research has undergone a multi-phase development, evolving from data collection and digital archiving to virtual reconstruction and immersive experiences. What developmental trends are currently evident in the application of DT in CHC? What difficulties and challenges does it face? In response to these issues, this paper aims to analyze the latest application trends and current situation of DT in CHC from 2019 to 2024, with the following analytical objectives: (1) Summarizing the phase-specific research trends from the statistics of yearly publications and citations, and using map visualization to display the international influence of regional research; (2) Analyzing the application of DT in multidisciplinary integration through statistics on subject classifications and the number of articles under each category; (3) Exploring the collaboration among authors through a co-clustering analysis based on authors and keywords; (4) Presenting important DT and technological trends through word frequency analysis; (5) Introducing several core research topics using a thematic co-occurrence network; and (6) Focusing on frontier topics and hot issues by analyzing key literature. Finally, this paper systematically summarizes the current status and trends of DT applications in CHC and extends the discussion to the level of ethical and social responsibility, especially regarding challenges in technological accessibility and data protection. The development of DT not only provides new perspectives and tools for CHC but also faces challenges such as technological adaptability, funding sustainability, policy support, and cultural sensitivity.

Methodology

Bibliometric method

Based on the limitations of traditional quantitative methods, such as restrictions on the number of executions, limitations in dynamic analysis,

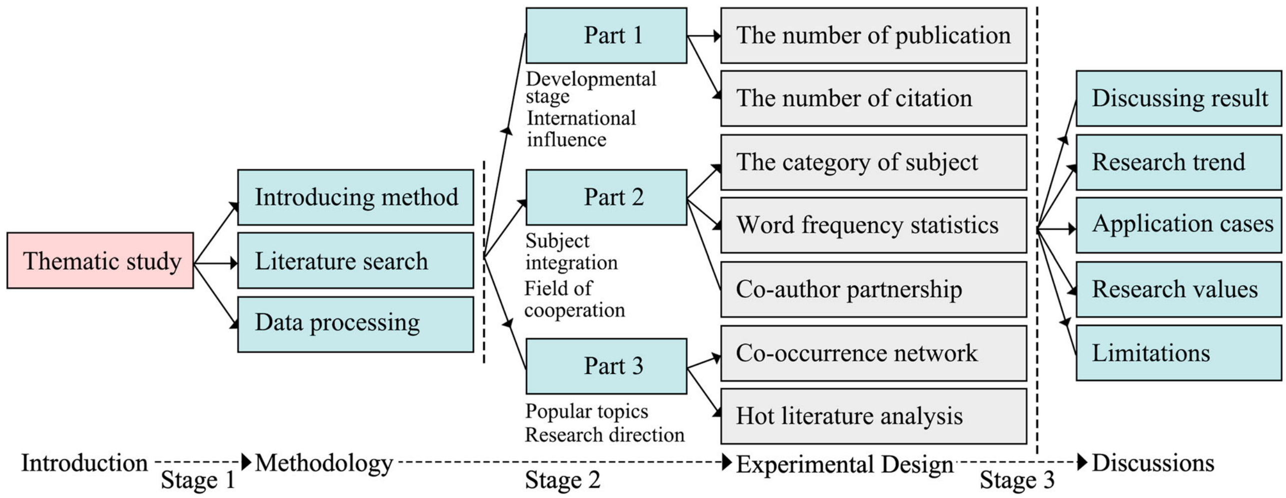


Fig. 1 | Research framework and structure.

and high computational costs[37], Nacke proposed informetrics (also known as intelligence metrics)[38], which was subsequently developed by mathematicians like de Solla Price and Page[39], Leimkuhler[40], Voos[41], Brookes[42], and Garfield[43]. As a branch, bibliometrics is a method based on mathematical and statistical principles to analyze research trends, tracing back to Hulme[44], who proposed the concept of 'Statistical Bibliography', and Pritchard[45], who coined the term 'Bibliometrics'. The anatomical application case by Cole and Eales[46] is an early example of this method, revealing the distribution structure, quantitative relationships, and changing patterns of literature. This method is based on three major laws[47]: Lotka's law of author productivity, Zipf's law of word frequency distribution, and Bradford's law of scientific journals. Compared to text mining[48], content analysis[49], and the Delphi method[50], bibliometrics, as an unstructured data mining method, is particularly suitable for understanding the development trends and characteristics of phenomena[51].

Unlike software such as CiteSpace, HistCite, and VOS Viewer, this study employs version 6.725 of the COOC tool developed by an academic team from Chinese universities to perform bibliometrics, which supports multiple functions like co-occurrence networks, semantic clustering, and frequency statistics[52]. Compared to ROST CM 6.0 developed by Wuhan University[53], COOC 6.725 is more advanced in user interface and data visualization. The VOS Viewer tool, developed by The Centre for Science and Technology Studies, has been integrated into COOC 6.725, making it particularly suitable for academic collaboration networks and citation analysis[54]. Therefore, the software's multifunctionality, ease of use, and data compatibility are the reasons for its selection.

In addition to statistical analysis of publications and citations, this paper employs several bibliometric methods, including word frequency analysis, biclustering mapping, thematic co-occurrence networks, and hot literature analysis. These methods aim to reveal core trends and knowledge structures in the research field through multidimensional data analysis, thereby identifying the current state and trends within the research area. Word frequency analysis, by calculating the frequency of keyword occurrences, helps to identify high-frequency concepts and themes, highlighting concentrated areas of research focus and trending topics. This facilitates the discovery of key research directions and their distribution across the literature[55]. Biclustering mapping is a cross-analysis method used to examine the relationships between two variables. Based on the co-occurrence relationships between authors and keywords, biclustering mapping can identify associations among different research groups, revealing the inherent logical structure within specific research areas[56]. Using the VOS Viewer tool, the generated keyword co-occurrence network can identify major thematic groups and their interconnections within the research domain, thus revealing research trends[57]. Additionally, by reviewing the hot literature listed in the Web of Science data panel, scholars can explore the topics currently receiving widespread attention and identify potential knowledge gaps and emerging research frontiers within the field.

Figure 1 presents the research framework of this paper: (1) After clarifying the research topics, the methodology introduces the basic principles of bibliometrics, along with an explanation of the analytical tools used and the rationale for their selection (Bibliometric Method). Next, search criteria for the literature were established, and data cleaning was performed on the search results to ensure the accuracy of subsequent analyses (Data Processing). (2) The experimental design stage is divided into three parts with seven content analyses. Part 1 analyzes publications and citations to map the development stages of the research and the influence of different regions (Annual Publication and Citation Statistics). Part 2, using the subjects classification panel from Web of Science and word frequency statistics and the co-author partnership network provided by COOC 6.725, reveals dynamic trends of interdisciplinary integration (Frontier Theme Analysis Based on Disciplinary Classification, 2D Matrix). Part 3 uses co-occurrence network and hot article analysis to uncover popular themes and research directions (Analysis of Research Directions and Hot Topics Based on Co-occurring Networks and Highly Cited Articles). 3) Stage 3 discusses the research findings and trends, analyzing existing application cases to highlight the potential and value of DT in CHC. Finally, the paper outlines new issues, discusses research limitations, and offers suggestions for improvement (Discussions).

Data processing

The first step involves defining the research topic and scope. Data for this paper were sourced from the Web of Science core database. This study utilizes the Web of Science Core Collection for literature analysis, with the time frame set from January 1, 2019, to March 5, 2024, in order to analyze recent research trends and findings. The Boolean search strategy is a method that improves search efficiency by precisely combining keywords, aiming to effectively narrow the search scope using logical operators (such as AND, OR, NOT), ensuring that the retrieved literature closely aligns with the research topic[58]. This method emphasizes considering various forms of keywords during the search phase, such as expanded terms, synonyms, hypernyms, and hyponyms. Table 1 presents the search criteria used, while the following conditions must be met when setting keywords[59–62]: 1) Consideration of synonyms: Since 'Building' and 'Architecture' have similar meanings, both 'Historical Building' and 'Historical Architecture' need to be entered into the search box and connected using 'OR' to ensure that articles with these terms in the title can be retrieved. This method effectively avoids missing relevant literature due to vocabulary differences; 2) Consideration of singular and plural forms of keywords: The search rules of the Web of

Table 1 | Literature Search Conditions.

Search Term		Search Formula
Keyword	**Expanded Word Forms**	
Heritage	Historical Building, Historic Building, Historical Architecture, Historic Architecture, HBIM, Heritage Building Information Model	**Title** = (Heritage OR Historical Building OR Historic Building OR Historical Architecture OR Historic Architecture OR HBIM OR Heritage Building Information model) **AND** **Title** = (Digitize OR Digital OR Digitization OR Digitization OR Virtual Reality OR VR OR Augmented Reality OR AR OR Intelligent OR AI OR Automatic)
Digitize	Digital, Digitization, Digitization, Virtual Reality, VR, Augmented Reality, AR, Intelligent, AI, Automatic	

Database: Science Citation Indey Exnanded (SCI) ;Social Sciences Citation Index (SSCI) ;Arts & Humanities Citation Index (AHCI).
Document Types: Article; Proceeding Paper; Review Article.
Time Range: 2019-01-01 to 2024-03-05.
Language: English.

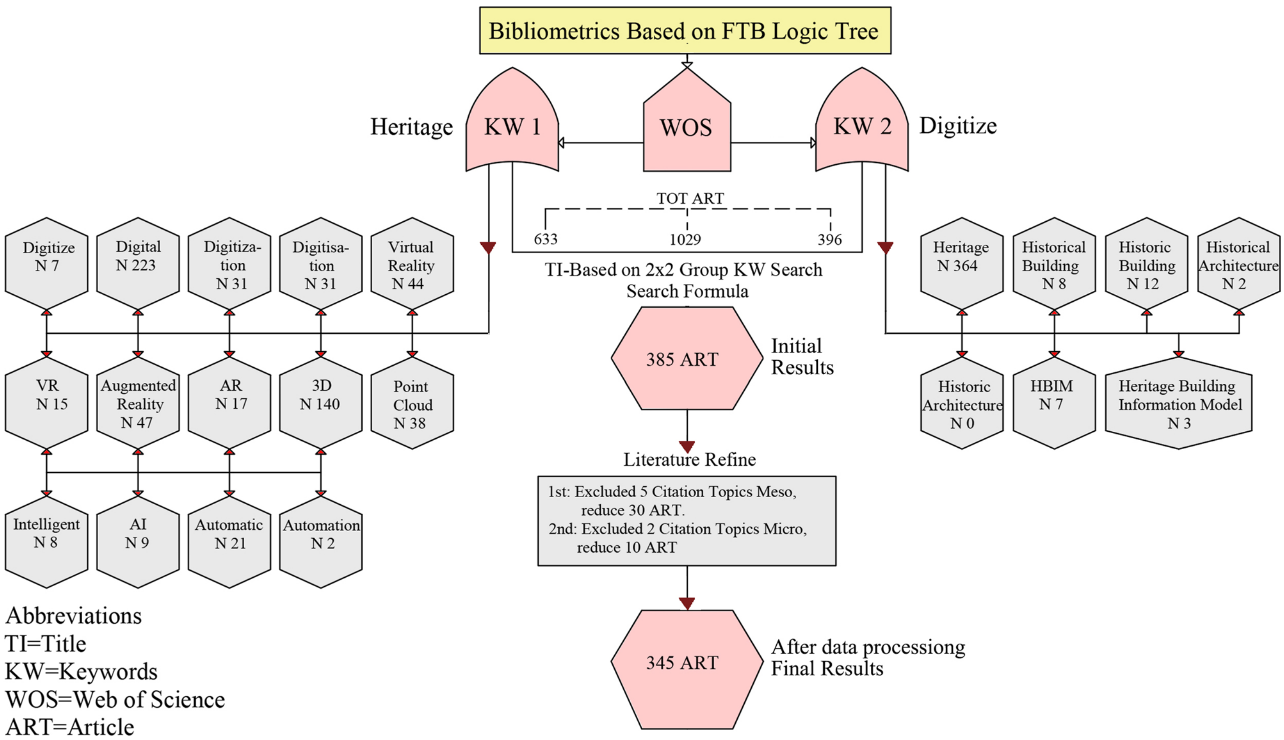


Fig. 2 | Literature search detail map.

Science database automatically recognize and integrate singular and plural terms. When searching for 'Building,' the results will already include articles using 'Buildings' as a keyword, thus avoiding the possibility of duplicate searches or missing relevant literature; 3) Consideration of verb and adjective expansions: 'Digital' and 'Digitize' are the adjective and verb forms of the noun 'Digitization,' while 'Historic' is an expanded form of 'Historical.' Comprehensive coverage of expanded terms helps increase the precision and comprehensiveness of the search; 4) Consideration of British and American English spelling variations: The same term may have different spellings in British and American English. If 'Digitization' is chosen as a keyword, then 'Digitization' should also be included in the search term pool; 5) Consideration of compound words and abbreviations: Many articles related to 'Heritage Building Information Model' may use its abbreviated form, 'HBIM.' When searching, both the full term and its abbreviation should be considered to ensure that all articles using either the full or abbreviated form are retrieved; 6) No need to distinguish between uppercase and lowercase spelling: When searching for 'intelligent,' articles with 'INTELLIGENT' or 'Intelligent' in the title can all be retrieved. By adopting the above strategies, the quality of literature retrieval can be significantly improved. A total of 385 articles were retrieved based on the parameters set in Table 1.

The second step involves extracting and processing the literature data. Data cleaning is a critical data preprocessing technique used to identify and correct errors, inconsistencies, and incomplete data within datasets, thereby ensuring the effectiveness and reliability of analyses[35]. Figure 2 illustrates the process of literature retrieval and data cleaning. Although the Boolean search strategy narrows the scope of literature and improves the relevance of the search results in the initial retrieval stage, it remains difficult to ensure that all articles are highly relevant to the research topic. Therefore, excluding irrelevant articles is essential to improve the quality of the dataset. By accessing the search results panel in Web of Science, this study first excludes categories and their associated articles with lower relevance from the "Citation Topics Meso (30)" and "Citation Topics Micro (10)" columns. The inclusion and exclusion criteria for literature, reviewed manually, are as follows[63,64]: (1) Categories and their articles with low relevance to the application of DT in CHC should be excluded. For instance, a study may be related to heritage, but if its content leans more toward biology or other fields with little relevance to DT applications, the articles under such categories should be excluded; (2) Articles whose titles directly involve the core keywords of the research topic are retained. If the relevance of the articles cannot be clearly determined from the title alone, the abstract should be reviewed to assess their suitability for inclusion; (3) Articles containing ambiguous or polysemous terms that do not explicitly mention their direct relevance to DT applications in CHC in the abstract should also be excluded to ensure dataset accuracy and the precision of the subsequent analysis.

Table 2 | Year-by-year publications and citations in the Top 5 countries

Year	Year-by-year publication in the Top 5 countries					Year-by-year citation in the Top 5 countries				
	Italy	Spain	Portugal	China	USA	Italy	Spain	France	China	Greece
2019	39	5	1	6	2	609	62	81	169	60
2020	22	10	5	1	2	483	297	91	15	42
2021	23	8	4	3	2	307	124	64	16	17
2022	33	11	14	6	7	175	77	4	36	9
2023	33	18	1	7	8	75	27	1	2	1
2024	5	4	2	0	0	0	0	0	0	0
Total	155	56	27	23	21	1649	587	239	238	129

Based on the above screening criteria, 40 low-relevance articles were excluded. The remaining 345 articles were then exported from Web of Science in plain text format (preserving full records and referenced citations) and integrated using COOC 6.725. Subsequently, the data were sorted, reviewed, and filtered in Excel based on publication year, author, keywords, and abstracts to remove any anomalies. After inspection, the information of the 345 articles was found to be complete and highly relevant, ensuring the reliability of the subsequent analysis.

Results

The presentation of the analysis results will be divided into three sections: (1) The section Annual Publication and Citation Statistics provides annual statistics on the publication and citation of 345 articles retrieved between 2019 and 2024 using Stata SE (64-bit) software. This analysis aims to reveal the growth and evolution of research activities in this field over time, contributing to the understanding of research trends. (2) The section Frontier Theme Analysis Based On Disciplinary Classification, 2D Matrix employs the Web of Science results panel to analyze the subject distribution of these articles, identifying the proportion of contributions from various disciplines to CHC research and trends in interdisciplinary collaboration. Additionally, this section incorporates word frequency statistics and co-authorship network analysis to explore the collaboration patterns among major academic groups and their influence in CHC. (3) The section Analysis of Research Directions and Hot Topics Based on Co-occurring Networks and Highly Cited Articles utilizes the VOS Viewer tool to conduct a co-occurrence network analysis based on keywords, aiming to uncover core thematic areas and reveal the interrelations between different research topics and the construction of their knowledge systems. Furthermore, this paper will analyze 19 hotspot articles to introduce trending topics and content.

By organizing the sections around the temporal development stages, subject distribution of articles, word frequency statistics, social networks, and hotspot article research, this structure facilitates a systematic review from a macro to micro perspective. This progressive analytical framework supports the achievement of the six research objectives proposed in the 'Introduction' section. The analysis results show that although there was a decrease in publications in 2023, the demand for research on DT continues to grow. Research quality is not fully correlated with the number of publications. The application of DT in CHC has undergone an exploring period, a diversified development period, and an integration period, highlighting the key roles of interdisciplinary collaboration and technological advancement. Moreover, there is a clear trend of multidisciplinary integration in the DT field, particularly in remote sensing and imaging sciences, though integration with foundational disciplines still requires improvement. Digital reconstruction and risk assessment have been the two main directions of DT applications in CHC from 2019 to 2024.

Annual publication and citation statistics

Publication and citation analysis is a process of quantifying and analyzing the literature on a specific topic within an academic field to identify shifts and trends in research activity[65]. Table 2 presents the number of articles published and their citations related to studies from 2019 to 2024, along with the term frequency (TF) of keywords synonymous with 'digitalization.' The figure also includes data from the top 5 countries. Figure 3 illustrates the yearly trend changes in this data. In the six-year period, the top five countries in terms of publication volume, from highest to lowest, are Italy (155), Spain (56), Portugal (27), China (23), and the USA (21). In terms of citation volume, the rankings are Italy (1649), Spain (587), France (239), China (238), and Greece (129). The application of DT to heritage conservation began to be emphasized in 2022. Although there was a decline in publications in 2023-2024, the TF of DT mentioned directly in keywords reached 28 times in 2023, reflecting the academic community's demand for DT innovation. The characteristic of having low publications (45) but high citations (1008) indicates that the results published in 2020 were widely recognized, especially Spain's citations (297). This data suggests that attention does not necessarily fully reflect research quality; 4) The total number of publications shows an overall upward trend (from 45 to 91), and the significant publications (the number of annual average publication is 25, the number of annual citation average is 275) also reveal the high level of attention Italian scholars pay to digital heritage. Research topics have evolved from structural prediction and maintenance, to parametric modeling workflows, to collaborative heritage management and evaluation, and to the integration of technology and new applications across interdisciplinary fields. This shift showcases scholars' new thinking and exploration of DT from localized to holistic, micro to macro, and specific to broad applications.

In developmental stages, Phase One (2019–2020) marked the exploratory period for DT, particularly in areas such as deep learning[5] and HBIM for damage detection[66]. Research during this period focused on developing and testing DT to enhance the accuracy and efficiency of cultural heritage diagnostics, such as digital photogrammetry[67] and three-dimensional surface analysis[68]. Phase Two (2021-2023) witnessed the diversified development of DT applications under technological advancements, alongside a significant trend towards interdisciplinary integration. This period saw the widespread application of machine learning[69] and HBIM in heritage management[70], though many scholars remained focused on structural forecasts[71] and advanced modeling techniques[72] due to their potential in comprehensive assessment and preservation of architectural heritage. Additionally, the use of parametric models[73] and digital twins[74] significantly increased. DT technologies were also extended to preventative conservation[75] and the use of VR[76,77] and AR in interactive education. Phase Three (post-2023) is the integration phase for DT, focusing on data integration[78], interdisciplinary collaboration[79,80], and sustainability strategies[81]. During this time, challenges persisted in interdisciplinary application integration of DT[82] and data sharing[83], necessitating the development of new methods and tools to enhance the efficiency and impact of technology implementation[84]. Despite significant attention from Chinese scholars to DT in 2022, their publication volume remained relatively low compared to other regions. Furthermore, the research contributions by Chinese scholars Wang et al.[5], Zou et al.[85], and Sun et al.[86] in the field of automatic damage detection and historical building maintenance have been highly cited. The structural prediction and maintenance of cultural heritage remain fundamental applications of DT[8,87].

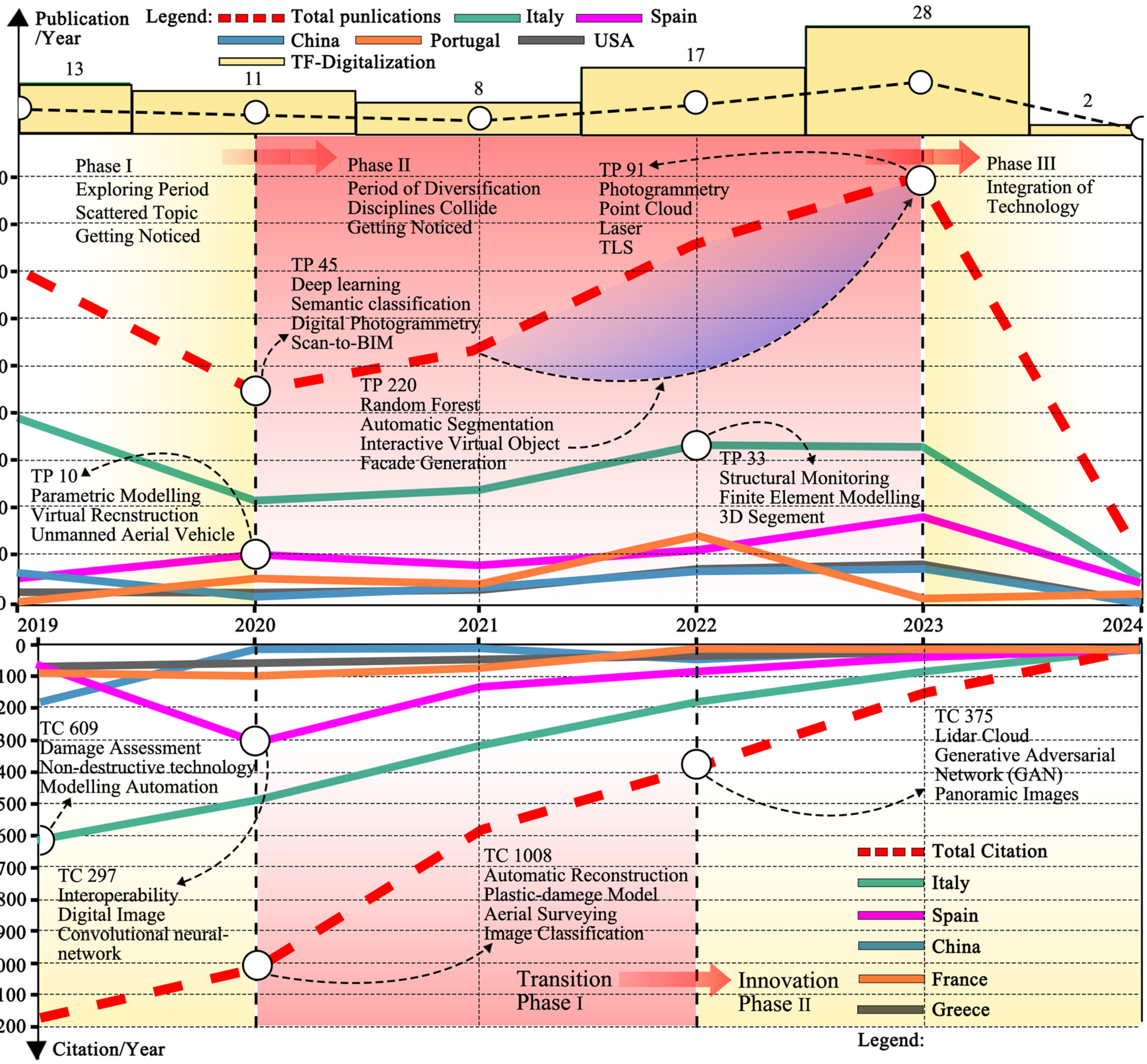


Fig. 3 | Growth of publication and citation 2019–2024.

Figure 4 reveals the citation statistics for a total of 41 publishing regions from 2019 to 2024, among which articles from six regions, namely Bulgaria, Cyprus, Indonesia, Israel, the Netherlands, and Romania, were not cited. Although China lags behind other regions in terms of publication volume, the relatively high citation count indicates good research quality; however, the overall level of DT still lags behind that of European regions. Regions with a long history place greater emphasis on CHC, such as Italy, Spain, Portugal, France, and China. European research outcomes are the most influential (total citations far exceed those of other regions), representing the highest research quality globally, followed by Asia, South America, and North America. Possibly due to differences in urbanization levels, education standards, and technological advancement, the application of DT in the heritage field is relatively marginalized in regions with lower levels of urban development, such as Africa and Oceania.

Frontier theme analysis based on disciplinary classification, 2D matrix

The search panel of Web of Science reveals the classification of subjects for 345 articles published between 2019 and 2024. These articles are categorized into 54 major disciplines, 39 Citation Topics Meso, and 39 Citation Topics Micro. Figure 5a illustrates the number of articles in each category, with subjects related to remote sensing, geography, computer, and information science highlighted in red. Figure 5b presents the number of articles in the top 10 subjects within Citation Topics Meso and Citation Topics Micro, using different colors to distinguish the variations in quantity. The dashed lines connected by white dots indicate the median value of the data. Figure 5 comprehensively reflects the research trend of multidisciplinary integration. CHC academic discussions have transcended traditional boundaries, expanding into various interdisciplinary fields such as remote sensing, imaging science, computer science interdisciplinary, and materials science multidisciplinary, which hold significant importance. This data distribution reveals the potential of modern technology in CHC. Archeology, architecture, humanities multidisciplinary, and construction building technology remain foundational disciplines of CHC, indicating that the integration of this field with other disciplines still requires further development.

In the following sections, this study will illustrate the application trends within the CHC by analyzing the frequency of keywords. First, the 1,632 keywords from 345 articles in the source data table were copied into a blank document, and any formatting inconsistencies—such as leading spaces, inconsistent strings, or differences in capitalization—were corrected. Next,

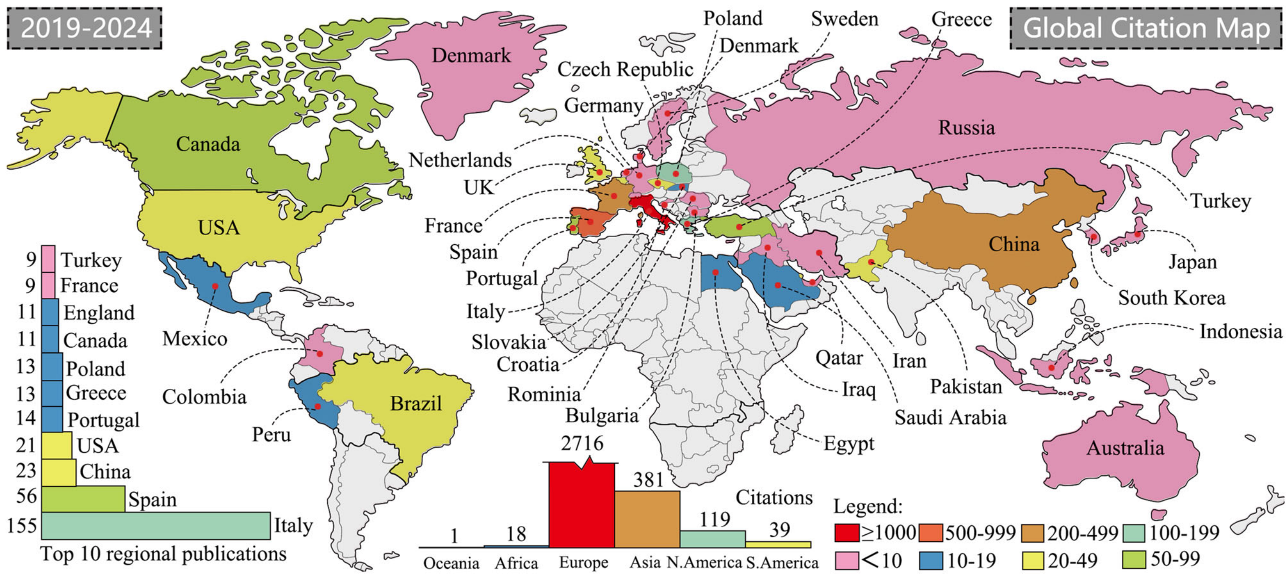


Fig. 4 | Distribution of citations in 41 countries (2019–2024).

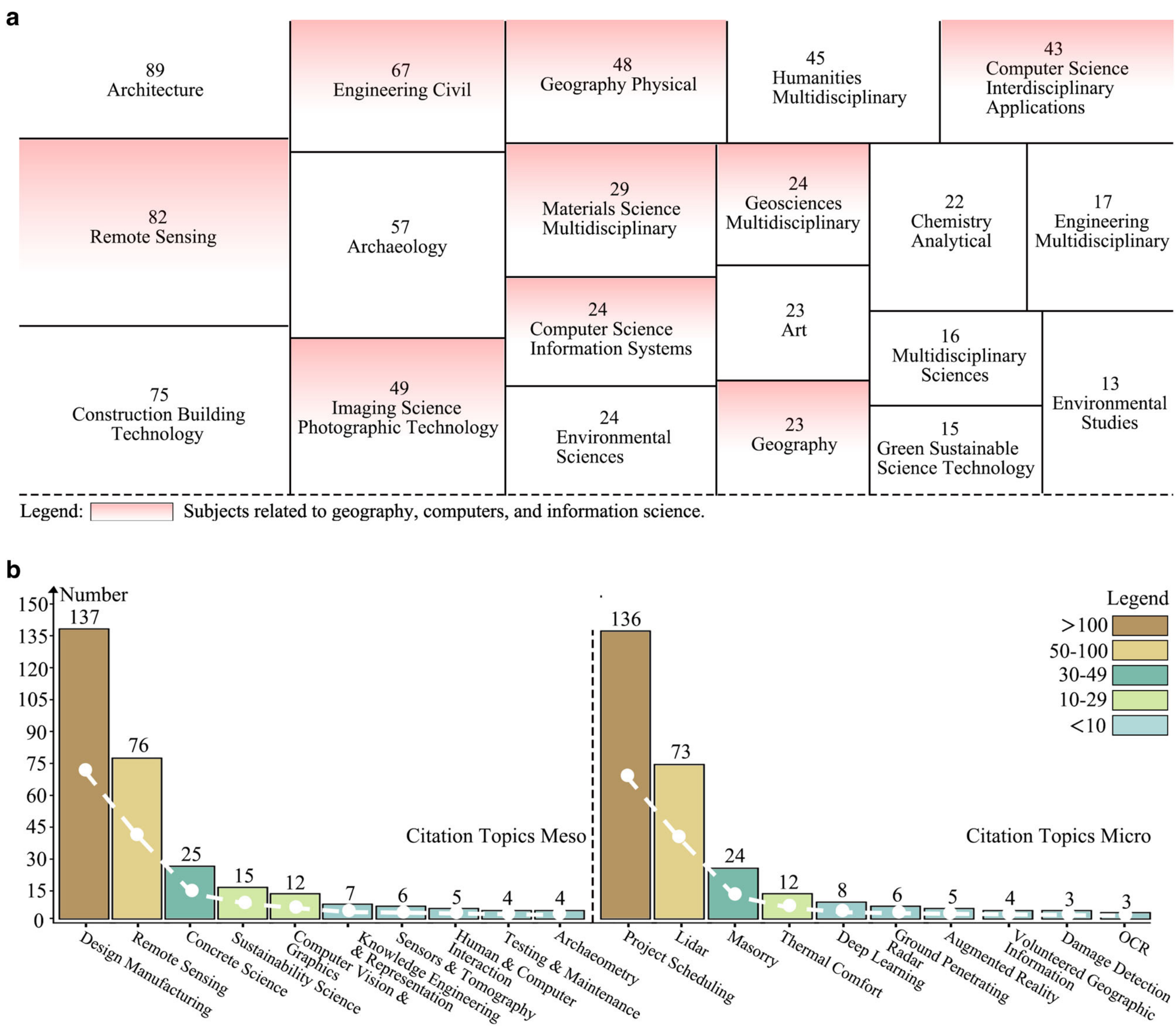


Fig. 5 | Disciplinary distribution of subject articles. a The number of subject classification of 345 articles. **b** The number of subject classification in Citation Topics Meso and Micro.

Table 3 | Top 50 keywords word frequency.

No	Words	TF	No	Words	TF
1	**HBIM**	129	26	Classification	6
2	Cultural Heritage	103	27	Parametric Modeling	6
3	BIM	78	28	Finite Element Method (FEM)	6
4	**Terrestrial Laser Scanning**	50	29	Interoperability	5
5	3D Modeling	49	30	Performance	5
6	**Point Cloud**	41	31	Monitoring	5
7	Architectural Heritage	39	32	Damage Assessment	5
8	Conservation	34	33	Grade Of Generation (GOG)	5
9	**3D Reconstruction**	32	34	Systems	5
10	**Digital Photogrammetry**	26	35	Semantic Web	5
11	**Scan-To-BIM**	19	36	**Lidar**	5
12	Management	15	37	Risk Assessment	4
13	**Virtual Reality (VR)**	15	38	Digital Survey	4
14	Historical Buildings	15	39	Reality	4
15	GIS	11	40	**Unmanned Aerial Vehicle (UAV)**	4
16	Level of Detail (LOD)	9	41	Masonry	4
17	**Digital Twin**	8	42	Pushover Analysis	4
18	Deep Learning	8	43	Algorithm	4
19	Information	8	44	Damage	4
20	Ontology	8	45	Visual Programming Languages (VPL)	4
21	Quality	7	46	Artificial Intelligence	4
22	Generation	7	47	Maintenance	4
23	Buildings	7	48	Knowledge	4
24	Vulnerability	7	49	Industry Foundation Classes (IFC)	4
25	Accuracy	7	50	Segmentation	4

the word frequency statistics panel of the COOC 6.725 tool was used, and the file was imported into the software in Excel format for keyword splitting and frequency counting. Then, based on the duplicate highlighting function in Excel, a manual review of the semantic similarities and redundancies among keywords was conducted, and similar keywords were consolidated and merged. Since COOC 6.725 is unable to automatically recognize and merge plural-singular pairs (e.g., "systems" and "system") or abbreviated forms (e.g., "three dimension" and "3D"), manual verification was a critical step. Subsequently, the keywords were sorted in descending order based on frequency, and a second round of verification was performed to ensure data accuracy. Table 3 presents the top 50 keywords by frequency. Bold text shows DTs commonly used in the CHC field. Frequently used technologies ($TF \geq 20$) include Building Information Modeling (BIM), Terrestrial Laser Scanning, Point Cloud, 3D Reconstruction, and Digital Photogrammetry. Following these are Scan-to-BIM, VR, and Digital Twins ($5 \leq TF < 20$). Less frequently used technologies ($TF < 5$) include Lidar and UAV.

This study constructs a two-dimensional matrix network based on authors and keywords using the COOC 6.725 tool. The analysis parameters are set to a publication volume of ≥3 and a keyword TF (term frequency) of ≥3, followed by the construction of a biclustering map. Figure 6 illustrates the correlation and clustering patterns of keywords and themes in studies by various authors, revealing research groups and networks of interest within the academic community. To improve the clarity of the text in the figure, the central area of the original document (the non-clustered secondary section) has been trimmed. The figure illustrates the research interests that have garnered significant attention in Group A and Group B. It reveals that over the past six years, the research trends have primarily focused on topics such as HBIM, virtual museums, GOG, and laser scanning. In addition, there has been secondary emphasis on parametric objects, GIS, Ontology, and TLS. This phenomenon reflects the increasing reliance of the academic community on advanced technologies in CHC and management, as well as the exploration of emerging technologies in practical applications. In addition, Fig. 6 shows a distribution pattern with concentrated areas at the extremes and a sparse middle, indicating a low focus on specific areas and a fragmented, dispersed clustering result. This phenomenon also indirectly reveals deficiencies in interdisciplinary collaboration, knowledge integration, and DT application integration in heritage conservation, exposing significant gaps in cross-disciplinary synergy and collaboration. This distribution pattern suggests that while DT is extensively applied in the heritage field, its application and integration levels vary significantly among different research communities and disciplines, leading to fragmented knowledge and technology applications. Banfi et al.[88–90], Previtali et al.[91], Brumana et al.[92–95] are the main groups in Group A, focusing on how to effectively combine innovative modeling methods and interactive systems to enhance the accuracy and efficiency of architectural analysis and how to enhance data sharing and multidisciplinary cooperation in the digitalization process of cultural heritage. Bruno and Roncella[96], Nieto-Julián et al.[97], Moyano et al.[70,73,98–102], Adami et al.[103] are the main groups in Group B, focusing on how to use digital means to monitor, record, manage, and analyze structural deformations of historical buildings, and how to integrate emerging technologies and explore systematic approaches in CHC.

Analysis of research directions and hot topics based on co-occurring networks and highly cited articles

This section explores the mainstream directions of DT applications in the field of heritage conservation. By organizing keywords in an Excel spreadsheet and creating a co-occurrence matrix, this study further utilized VOS Viewer software to construct a thematic co-occurrence network map. In this network, keywords related or adjacent to each other are marked in the same color to facilitate the identification of thematic clusters. A total of eight clusters were formed, with four primary clusters centered around the core keywords 'Cultural Heritage—HBIM—Photogrammetry,' 'BIM—Documentation—Point Cloud,' 'Scan-to-BIM—Conservation—Interoperability,' and 'Vulnerability-Management.' Table 4 displays the constituent elements and core themes of these clusters. Overall, these four themes can be further categorized into the following two directions: (1) the application of comprehensive digital recording and reconstruction technologies for cultural heritage; (2) strategies for risk assessment and virtualization of cultural heritage buildings.

Direction 1 focuses on the use of DT for documentation and dynamic 3D reconstruction of cultural heritage, providing tools for information storage and visualization to support conservation and restoration efforts. Utilizing the HBIM framework, Bruno and Roncella[96] organized, stored, and managed geometric information, and facilitated data sharing and usability through a standalone database linked to 3D models accessible via desktop applications and web interfaces, effectively addressing limitations in HBIM's user interface and data accessibility. Further, Croce et al.[69] explored a semi-automatic approach using machine learning techniques to reconstruct HBIM from point cloud data, enhancing the documentation of heritage artifacts. Additionally, Yang et al.[104] demonstrated how BIM and 3D modeling could digitally document and manage heritage, integrating geometric elements with historical knowledge. Moreover, Andriasyan et al.[105] automated the reconstruction of cultural heritage geometries using TLS and SfM technologies, along with tools such as Rhino+Grasshopper-ArchiCAD. Bianchini and Potestà[106] focus on the challenges of applying 3D virtual modeling, particularly BIM systems, to historic buildings, using the Baptistery of San Giovanni as a case study to explore how semantic segmentation and connection of constructive elements can enhance the understanding of their evolutionary phases and improve the Levels of Development parameter for built heritage. Brusaporci and Maiezza[107] explor

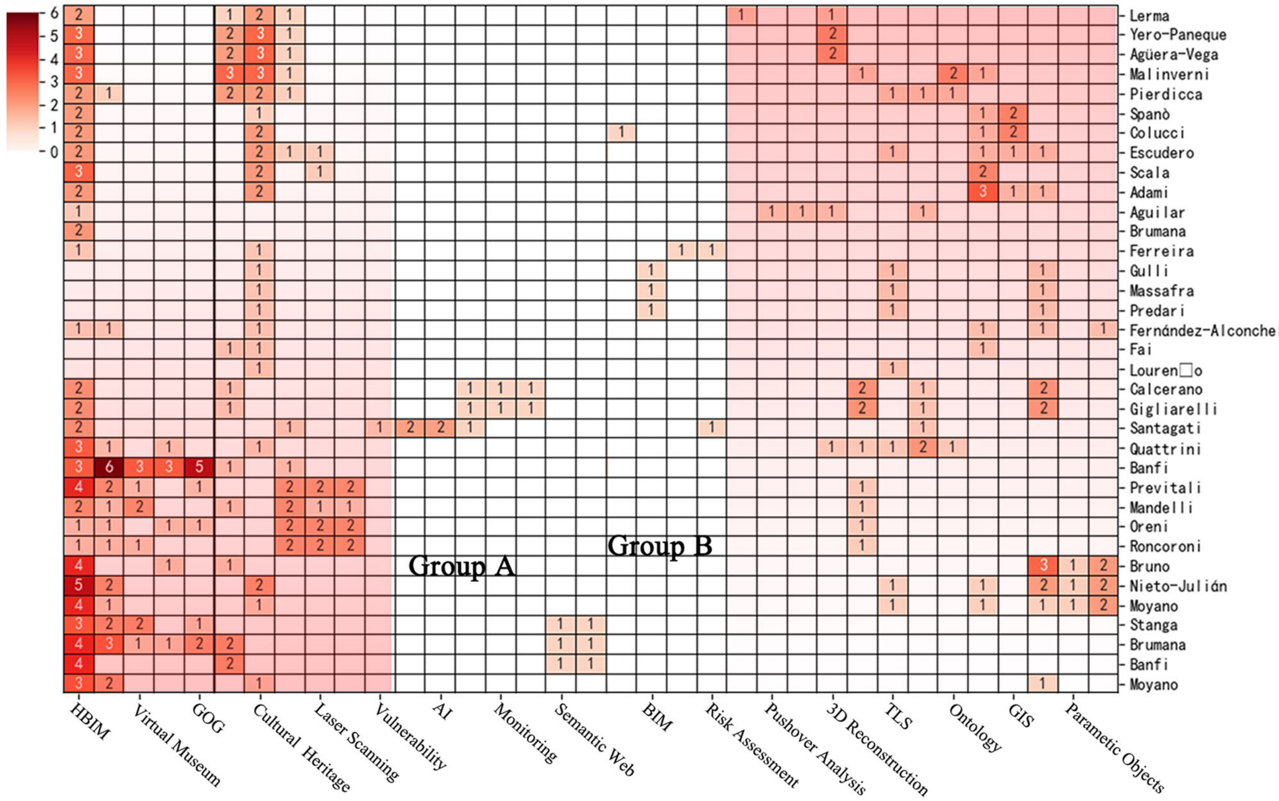


Fig. 6 | Clustering relationship map based on authors and keywords.

the use of 3D models and AR to study and communicate architectural and urban values, promoting "smart heritage" by merging digital and physical dimensions, as demonstrated through two case studies of St. Basilio Monastery and the Basilica of Collemaggio. These studies highlight the dependency of CHC on accurate initial data and complex data processing workflows.

Direction 2 centers on the potential of DT in assessing risks and structural vulnerabilities of heritage buildings, thereby enhancing the safety and management efficiency of heritage. Wang et al.[5] introduced an automated system for detecting structural damage that can precisely identify efflorescence and spalling through IP network cameras and smartphones integrated for real-time functionality, significantly improving the efficiency, reliability, and convenience of historic building conservation management. Angielu et al.[108] developed simulation models for the digital twin application in historic brick-and-stone buildings, integrating experimental physical realities to study the structural response, preventive maintenance, and reinforcement actions. Employing specific spatial and morphological filters, Galantucci and Fatiguso[67] used software tools for 3D metrology and surface topography to detect damages within 3D models, allowing for quantitative information about certain types of changes such as cracks or features caused by material loss to be derived from point clouds or polygonal meshes. Valente et al.[109] conducted advanced 3D finite element (FE) numerical simulations to investigate the seismic response of two complex historical masonry structures located in Sora, Lazio, central Italy. The study assessed their performance during earthquakes and revealed a high level of vulnerability in these structures. Common limitations in the aforementioned research include the high cost of technical implementation, the complexity of data processing and interpretation, and the applicability of the techniques in different environments.

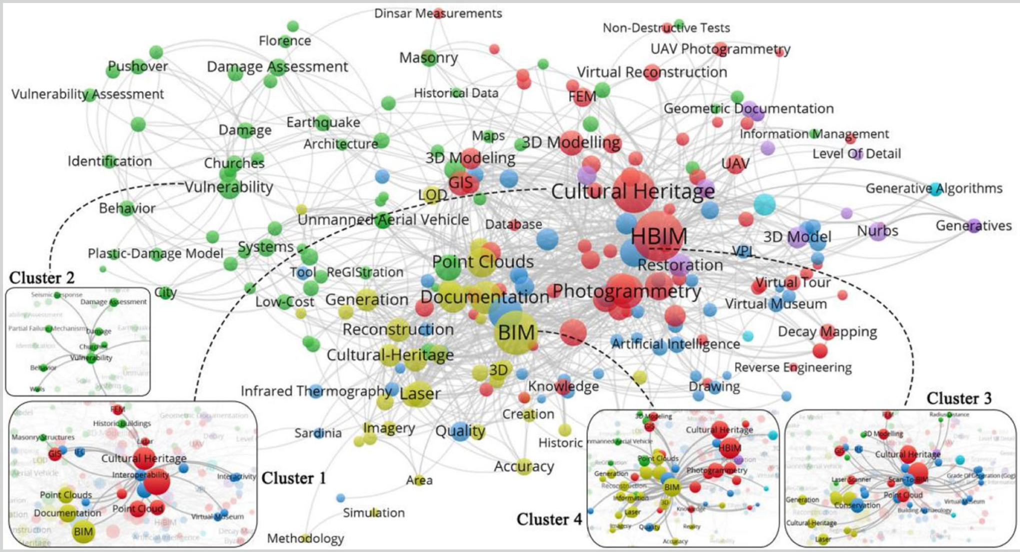
Comprehensively, the research contents of 19 hot articles in Table 5 reveal that Digital heritage management has deeply integrated into the stages of data collection, data processing and management, analysis and application, and cross-disciplinary comprehensive integration. The Digital Orthophoto Map provides precise measurements, condition assessments, and damage monitoring of heritage sites with high-altitude images free from perspective distortion[110]. Laser scanners capture the geometric shapes of complex surfaces by recognizing the surrounding geographical environment, thus generating 3D point cloud data[111]. Secondly, some scholars have explored how to analyze building structures using digital twins to address natural disasters. This includes simulating seismic responses[109], three-dimensional monitoring and quantification of building damage[67], and automated modeling[105]. From multi-angle to array-based, utilizing geometric principles to distributed collaboration, Milosz et al.[112] detailed the processes and technical descriptions for 3D scanning of 213 wooden columns and automated modeling of the Juma Mosque in their work at Itchan Kala.

Discussions

Over the past 6 years, research on DT in CHC has exhibited a technology-oriented application tendency, lacking in-depth discussion on its social impacts and cultural adaptability. Based on bibliometric analysis, this paper reveals the current state of research, application advancements, and emerging trends. Previous literature reviews have revealed that DT demonstrate significant potential in enhancing cultural identity, virtual reconstruction of architecture, production construction, and automatic classification. Table 6 lists specific examples of DT in these application areas. These cases are derived from the author's compilation and summarization while reading articles. The introduction of DTs such as 3D point clouds, VR, TSL, High Resolution Digital Camera (HRDC), Digital Orthophoto Map (DOM), and HBIM has optimized the processes of data collection and visualization for CHC.

However, many DT technologies are still in the developmental stage and face challenges related to research quality and usability[113], limited algorithm generalization capabilities[114], and ethical and cultural sensitivities[115]. The limitations of these DT technologies in terms of accuracy, data processing, and long-term maintenance still require thorough

Table 4 | Keyword-based thematic co-occurrence network analysis



Classify	Items	Representative words	Core themes
Cluster 1	71	Central word 'Cultural Heeritage-HBIM-Photogrammetry': Laser Scanning, Architectural Heritage, TLS, Deep Learning, 3D Modeling, GIS, Sementic Web, Monitoring, Virtual Reality, UAV Photogrammetry, Maintenances, Virtual Reconstruction, FEM, Data Integration, Virtual Tour, Decay Mapping, Knowledge,……, etc.	Technologies such as UAV Photogrammetry, Point Cloud and GIS are applied to 3D modeling, information recording and restoration of heritage.
Cluster 2	65	Central word 'Vulnerability-Management': Management, Point Cloud, 3D Reconstruction, Performance, Churches,Dage Assessment, Earthquake, Pushover Analysis, Modal-analysis, Partial Failure Mechanisms, Identification, Behavior, Scale, Plastic-damage Model, Vulnerability Assessment, Seiismic Response, Implementation, Systems, Images, Algorithm, Unmanned Aerial Vehicle, Damage Detection, Masony, Deep Learning, Historic Buildings,…….,etc.	Vulnerability assessment and structural analysis of historic buildings.
Cluster 3	54	Central word 'Scan-to-BIM-Conservation-Interoperability': Heritage Buildings, Digital Twin, Interoperability, Ontology, Quality, Infrared Thermography, Artificial Intelligence, Virtual Museum, Virtual Reality, Grade of Generation, Interactivity, IFC, Citygml, Rapid Mapping,…..,etc.	How to enhance the digital protection and presentation of heritage through virtual model interaction.
Cluster 4	41	Central word 'BIM-Documentation-Point Cloud': Laser, Representation, Segmentation, Accuracy, Models, Information, Imagery, Reconstruction, Buildings Model, Preservation, LOD, ArchaeoBIM, Classification, Level of Geometry, Parametric Objects, Recognition, Renovation,…..,etc.	Documentation and reconstruction of cultural heritage using LC with BIM.

exploration. Although 3D point cloud technology can provide high-precision spatial data, issues such as high resource consumption for data storage and processing, and how to effectively integrate multi-source data to enhance model usability and accuracy, remain key challenges for technological development[116]. VR significantly enhances user experience[117]; however, balancing innovative representation with historical accuracy to ensure the authenticity and appropriateness of cultural dissemination presents an essential ethical concern.

In addition to the practical applications of DT itself, its widespread adoption and promotion are also influenced by external factors. Advanced digital devices and technologies are often expensive and complex to operate, requiring specialized knowledge in related fields. Relevant articles have explored several low-cost alternative technologies, but their practical applications still need verification[118]. The complexity of historical building structures affects the accuracy of measurement data, and the natural lighting environment, which changes over time, also impacts the quality of 3D scanning[80]. Data processing and storage present challenges. The generation of large amounts of 3D point cloud data and high-resolution images requires substantial storage space and powerful computing resources for processing[89]. The complex geometries and material characteristics of artifacts may be difficult to fully capture and simulate with existing technologies[5,119].

The promotion and application of DT in CHC rely on the combined efforts of both top-down and bottom-up approaches. Although international organizations like UNESCO advocate for CHC within a global framework, these top-down strategies often struggle to meet the specific needs of local communities, which may result in the homogenization and delocalization of cultural heritage under the dominance of globalized discourse[120,121]. Government agencies, as key actors in CHC, can mobilize significant resources to carry out digital heritage initiatives, but their short-term political objectives and economic orientations may overlook long-term planning and heritage projects with higher cultural value[122]. While technology companies play a central role in DT innovation, their profit-driven nature tends to result in the short-term application of technologies, neglecting the long-term needs of CHC[123]. Experts and scholars in CHC face the risk of a disconnect between theory and practice, particularly in the context of rapid developments in the digital environment[124]. The integration of traditional preservation methods with modern technology remains a subject of significant debate. Public participation is crucial in the transmission and development of heritage, yet its role in DT applications is often

Table 5 | Research content analysis of 19 hot articles

No.	Authors	Research Content	Year published	Average per year	Total Cited
1	Fiorucci et al.[136]	From basic statistical methods to complex deep learning models, the authors reviewed the development of applications of machine learning (ML) in the field of CHC and explored the practical implications of theoretical improvements in ML algorithms.	2020	27.8	139
2	Wang et al.[5]	The authors introduced an automated damage detection system for buildings. This system can accurately identify efflorescence and spalling damage and achieves real-time functionality through the integration of IP network cameras and smartphones, significantly improving the efficiency, reliability, and convenience of historic building protection and management.	2019	21.33	128
3	Angielu et al.[108]	The paper develops a simulation model for the application of digital twins in historic masonry buildings. This model integrates experimental physical reality and is used to study structural response, preventive maintenance, and reinforcement operations of the system.	2020	20.4	102
4	Jo and Hong[137]	This study demonstrates the effectiveness of integrating terrestrial laser scanning and UAV photogrammetry for creating a high-accuracy 3D model and digital documentation of the Magoksa Temple, with laser scanning providing superior positional accuracy while UAV photogrammetry excelled in upper zone data acquisition.	2019	16.17	97
5	Yang et al.[6]	The article summarizes the applications of DT in heritage documentation, particularly in utilizing BIM, photogrammetry, laser scanning, computer graphics, GIS, and ontology tools for geometric modeling and semantic knowledge management.	2020	18.2	91
6	Pan et al.[138]	This study presents a semi-automated framework for generating 3D surface models of heritage bridges using UAV photogrammetry and point clouds, achieving high accuracy in segmentation and recognition of structural elements, with experiments on two bridges in China showing a reconstruction error as low as 0.4%.	2019	12.67	76
7	Andriasyan et al.[105]	The study explores the application of parametric modeling in HBIM by converting TLS and Structure from Motion (SfM) point cloud data into BIM objects using a Rhino+Grasshopper-ArchiCAD workflow, demonstrating an accuracy that, while slightly lower than other methods, is sufficient for the case study.	2020	15	75
8	Bruno and Roncella[96]	The paper organizes, stores, and manages geometric information based on HBIM and designs an independent database connected to the 3D model. It achieves data sharing and usability through desktop applications and web interfaces to overcome limitations of HBIM in practical conservation work.	2019	12.33	74
9	Banfi et al.[139]	Authors explore how integrating 3D survey, 3D modeling, BIM, and XR technologies enhances the dissemination and awareness of architectural heritage, using the Basilica of Sant'Ambrogio as a case study, and demonstrates the creation of an interactive XR experience accessible across various devices and user types.	2019	11.83	71
10	Pepe et al.[68]	The authors established an efficient process to construct HBIM and create digital models for structural analysis.	2020	12.6	63
11	Galantucci and Fatiguso[67]	Based on specific spatial and morphological filter sets, the authors used three-dimensional metrology and surface topography software tools to detect damage in 3D models. From this, quantitative information on certain types of changes (such as cracks or features caused by material loss) can be extracted from point clouds or polygon meshes.	2019	10.5	63
12	Valente et al.[109]	The authors conducted advanced numerical simulations using the 3D finite element method to study the seismic response of two complex historical masonry structures in Sora, Lazio, Central Italy. The evaluation of their performance during earthquakes showed a high level of vulnerability of these structures.	2019	10.17	61
13	Croce et al.[69]	The paper introduces a semi-automated method for reconstructing cultural heritage HBIM from point cloud data using machine learning techniques. The application of such a digital information system is increasingly used in the documentation and analysis of architectural heritage.	2021	13.75	55
14	Yang et al.[104]	The authors utilized BIM and 3D models for the digital documentation and management of heritage and developed new methods for converting meshes to HBIM, demonstrating how to integrate geometric elements with historical knowledge.	2019	8.67	52
15	Mora et al.[140]	This study introduces an approach for preventive conservation of historical buildings using HBIM strategies, integrating advanced inspection protocols, digitalization tools, and wireless monitoring networks, validated in the General Historical Library of the University of Salamanca, Spain.	2021	12.75	51
16	Moyano et al.[70]	The study presents a methodology using digital twins and 3D reconstruction techniques, supported by BIM and parametric modeling, to accurately assess and monitor structural deviations in historical buildings, with results showing minimal deviation between different data acquisition methods, confirming their effectiveness for preserving architectural heritage.	2022	11	44
17	Nieto-Julián et al.[97]	The study presents two modeling procedures for creating a structural HBIM for the Pavilion of Carlos V, demonstrating significant geometric discrepancies between the theoretical-HBIM and the as-built-HBIM generated from terrestrial laser scanning and photogrammetry, highlighting the need for improved modeling processes in conservation efforts.	2020	8.4	42
18	Moyano et al.[141]	This paper reviews the scientific literature on integrating TLS and Structure-from-Motion/Multi-View Stereo (SfM/MVS) data into HBIM, highlighting the need for a more structured methodology for point cloud data integration.	2022	7.5	30
19	Bruno et al.[142]	This study explores the potential of digital technologies, such as AR and VR, to enhance accessibility and user experience at underwater cultural and natural heritage sites, proposing a multidisciplinary plan to support sustainable tourism and innovation in the diving industry in the Mediterranean.	2020	3	15

marginalized. Decision-making in heritage planning is frequently dominated by elites and experts, overlooking the participation and interests of local communities[125]. This can lead to conflicts between the commercialization of heritage and the public interest.

How to effectively integrate multi-source data in the application of DT technology to improve the accuracy and efficiency of CHC and management. Vincent et al.[126] indicate that a single data source often fails to comprehensively capture heritage information. The integration of multi-source

Table 6 | Cases and potentials of DT applied to CHC

Cases	Application	Author
Cultural heritage and identity	1) International Environmental Education Foundation's (IEEF) Urban Heritage and Center for the Protection of Cultural Heritage and Identity (CPCHI) used 3D scanning and printing, and VR to develop the first roadmap for the protection of Iraqi's cultural heritage identity; 2) This work aims to raise awareness of cultural heritage issues in the Holy City of Najaf by identifying those heritage sites, monuments, ruins and important artifacts.	Al-Baghdadi[143]
Virtual reconstruction of buildings	1) Measurement of Santa Maria Church in Portonovo, Italian using TSL and modeling in Revit software; 2) Quality assessment of the BIM model by comparison with 3D point cloud.	Quattrini et al.[144]
Reproduction of decorative elements of historical buildings	1) Measurement of dimensional data of historic building components using a hand-held structured 3D scanner; 2) Formatting the solid model as a STereo Lithography (STL) file and inputting it into a 3D printing program; and 3) Controlling the printing program and coordinating the machine movements in order to build the components in layers for eventual 3D printing.	Xu et al.[145]
A novel network architecture for 3D point cloud semantic segmentation in indoor scenes	A multi-layer perceptron (MLP) composed of multiple layers of neurons with a nonlinear activation function is used to independently encode each point, capturing the features of each point in high-dimensional space; 2) Multi-scale ring grouping learning, inspired by atrous convolution, is employed to extract multi-scale information from the better-performing point encoding, aiming to learn the local features of each representative point; 3) The inverse distance weighted method is used to integrate independent features and neighborhood features at different scales, while a channel attention module is introduced to improve segmentation results. Through these steps, the ring grouping neural network with attention module (RGAM) enhances the recognition capability of 3D point cloud semantic segmentation tasks.	Chen et al.[146]
Classification of types of architectural roofs	The point cloud is first segmented to determine the roof type related to the number of segments, followed by estimating the roof plane parameters; 2) A roof extraction method is applied to segment the point cloud into facade points and roof points, thereby obtaining the feature NoRE. If NoREs=1, the roof of the Ming and Qing official-style buildings is classified as a single-eave roof; otherwise, the roof is classified as a multiple-eaves roof; 3) Ridge points are extracted from the roof points, and the feature SoRs is generated using these ridge points. Based on this parameter, the single-eave roof is further classified as a hip roof, pyramidal roof, unclassified gable and hip roof, or unclassified roof, while the multiple-eaves roof is classified as a hip roof, pyramidal roof, or unclassified gable and hip roof.	Dong et al.[119]

data can provide more comprehensive and accurate heritage information, aiding in the formulation of more scientific protection strategies. In addition, how to balance the tension between technological innovation and historical authenticity in the virtual display of cultural heritage using DT technology. The rapid development of technology has made virtual displays possible, but it also brings challenges to historical authenticity[127]. Finding a balance between these two aspects is of significant importance.

Grazianova and Mesaros[128] state that the essence of DT is to enhance the efficiency of CHC and management through digital means. Shim et al.[129] argue that the application of DT aims to explore the potential value of cultural heritage and to facilitate its broader dissemination and understanding. Selim et al.[130] suggest that studying the past is to better understand and face future challenges, ensuring the continuity and sustainability of cultural heritage. By analyzing research trends, regional impacts, academic disciplines, frontier directions, and thematic inquiries, this paper reviews the latest advancements in the application of DT in heritage protection from 2019 to 2024, thus revealing the problems, opportunities, and challenges. From a cultural perspective, the inherent innovative potential of technology has driven progress in heritage protection. In the context of globalization, how to utilize DT technology to protect and transmit cultural heritage has become a current research focus.

The application of DT in heritage should not only focus on technological drive but also consider the historical value, structural integrity, and community significance of material heritage. Misguided algorithmic decisions could lead to irreversible damage to ancient buildings, representing not only technological failures but also irrevocable losses to CHC[114]. Additionally, ethical considerations, cultural sensitivity, and commercial issues surrounding heritage buildings warrant attention. Driven by commercialization, heritage buildings may be over-exploited to the detriment of their cultural and historical values[131].

In the context of AI-driven technological transformation, the vulnerability of cultural heritage and the increasing pressures on its preservation have become more pronounced, prompting scholars to critically reassess the role of DT in heritage management. Traditional CHC methods struggle to address the complex demands of management, necessitating a reevaluation of the practicalities and significance of embedding DT into CHC processes. The integration of DT is not merely a straightforward replacement of traditional restoration methods. Instead, it seeks to establish an interdisciplinary and collaborative protection system, offering new pathways to achieve the sustainable development goals set by UNESCO. Based on this, scholars are currently reflecting on two key dimensions: 1) How can DT maintain the authenticity and integrity of heritage, avoiding distortion of its cultural significance? 2) What is the applicability and feasibility of DT in heritage management? Proponents of symbol interaction and cultural capital theories are attempting to bridge DT with cultural authenticity. Chhabra[127] proposed the concept of "digital authenticity," providing a theoretical foundation for this approach, yet the analytical framework combining DT and cultural theory remains underdeveloped. This issue largely stems from an overemphasis on the technological-driven aspects in existing research, while overlooking the cultural relationships underpinning heritage. Can DT enhance the readability and dissemination of cultural heritage while preserving its cultural essence? Is DT merely a tool in cultural preservation, or does it act as a cultural constructor? How can we balance the representation and innovation of culture in a digital environment? These questions raised in this paper challenge the simplified understanding of DT's role in CHC.

The works of Lovell et al.[132], Arteaga et al.[133], and Mendoza et al.[134] indicate future research trends. Multidisciplinary integration will further deepen, particularly in the cross-application of remote sensing, VR, and AI technologies with CHC, thereby improving management efficiency and precision[6]. The widespread use of digital recording and virtual reconstruction technologies will drive the development of digital heritage archives, offering innovative models for presentation and education[135]. Risk assessment systems driven by big data and machine learning will gradually mature, aiding the preventive protection and maintenance of CHC. Although the effectiveness of DT compared to traditional restoration methods remains a subject of debate, it undoubtedly presents diversified development potential for CHC.

This study proposes three levels for achieving the application paths of CHC and DT. The first level provides the necessary hardware and software support, ensuring secure storage and efficient processing of data, including high-performance computing equipment and cloud storage solutions. The second level is to enhance the usability and accuracy of data through advanced algorithms and analytical tools, involving technologies such as machine learning and image processing. The third level is to increase public awareness and participation in CHC through effective dissemination and educational means, including virtual reality displays and educational projects. Previous studies have focused on the first two levels, however, this study emphasizes that the application and promotion of CHC work are equally important.

The limitations of this study are primarily reflected in the constraints of the literature time span and data sources. The selection of literature only covers the period from 2019 to 2024. While this highlights recent trends in the development of DT in the context of CHC, it fails to capture long-term development patterns. Additionally, the literature search was restricted to the Web of Science Core Collection, excluding other significant databases such as Scopus and Engineering Village, thereby limiting the comprehensiveness of the research. Furthermore, the analysis was confined to English-language publications, overlooking studies in other languages. Future research should broaden the range of literature sources to enhance a multidimensional understanding of DT applications in CHC.

Conclusions

Findings: (1) The trajectory of DT in CHC has evolved through three distinct phases: an exploratory phase, a phase of diversified development, and a stage of technological integration and innovation, culminating in a multidisciplinary convergence with a notable surge in interest in 2023; (2) A substantial citation volume highlights the advanced level of DT application in European regions, such as Italy, Spain, Portugal, France, and China, with subsequent attention in Asia, South America, and North America. Conversely, regions with lower levels of urbanization experience relative marginalization; (3) Recent study has focused on four primary themes: 'DT and reconstruction technologies' and 'risk assessment and interactive displays'; (4) Over the past six years, research trends have predominantly centered on HBIM, virtual museums, GOG, and laser scanning, followed by interests in parametric objects, GIS, ontology, and TLS; (5) Despite advancements, DT in CHC shows deficiencies in interdisciplinary collaborative research, evidenced by a fragmentation in knowledge and technological application; (6) Structural forecasts and maintenance have emerged as prominent topics, particularly in the specialized study of automated damage detection and maintenance in historic buildings.

The application of DT in CHC has transitioned from a focus on structural forecasts and maintenance towards a workflow involving parametric modeling, heritage management collaboration and assessment, and the integration of technology across disciplinary areas, with a general emphasis on technology-driven research. The overarching goal of current studies is to enhance the capabilities of health monitoring, restoration, and risk management in CHC through diversified DT and system architectures. It is to be expected that DT will realize more potential in CHC with the advancement of technology.

Data availability

No datasets were generated or analysed during the current study.

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Author contributions

S.J., M.Y., J.S. and H.L. were responsible for data collection. W.L., Q.X. and J.A. were responsible for data analysis. W.L. and J.A. Wrote and revised manuscript, as well as supervised the accuracy of the experimental design. J.A. and Q.X. provided financial support.

Competing interests

The authors declare no competing interests.

Additional information

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