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# Research hotspots and trends in heritage building information modeling: A review based on CiteSpace analysis

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The year 2022 marks the 50th anniversary of the signing of the Convention Concerning the Protection of World Cultural and Natural Heritage. Heritage building information modeling (HBIM), which is a digital method of conserving architectural heritage, has recently received a great deal of attention from researchers, planners, and policy-makers in related fields around the world. However, there is not yet a complete analysis of the hot spots and trends in this area of research, nor has a complete workflow based on the practical application of HBIM been developed. In this article, we analyzed the research progress, hot spots, and trends in HBIM since 2010. We used the CiteSpace scientometric analysis tool to analyze 372 documents with high relevance to HBIM from the Web of Science core database using literature co-citation analysis, keyword co-occurrence analysis, cluster analysis, and keyword emergence detection. The findings show that research in the field of HBIM was still in the conceptualization stage during 2010–2017, and with the continuous development of various technologies, attention to HBIM has gradually accelerated since 2017 by expanding its uses to multidisciplinary fields such as artificial intelligence. In the cluster analysis of literature co-citations, 14 clusters were generated, and four clusters, semiautomatic 3D modeling, heritage information system, pilot study, and virtual reality, which have high rates of citation, are discussed in this paper. These clusters reflect the hot spots and frontiers of research in HBIM to a certain extent. In the "Discussion" section, a systematic and complete workflow of HBIM application to heritage architecture is proposed for three levels: modeling, data exchange, and auxiliary management. On this basis, the development of the field of heritage building conservation and sustainable development is analyzed to provide valuable theoretical and practical references to propose future research directions.

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## Introduction

The Convention concerning the Protection of the World Cultural and Natural Heritage (hereinafter referred to as "Convention") was formally adopted by the General Conference of UNESCO in 1972 (United Nations Conventions and Declarations, 1972). The year 2022 marks the 50th anniversary of the Convention, which triggered a new round of global reflection and foresight in the international community. The United Nations Educational, Scientific and Cultural Organization (UNESCO) believes that the 50th anniversary of the Convention should be used as an opportunity for interdisciplinary reflection on the future of World Heritage and proposes to focus on the digital transformation of heritage conservation with a focus on the "next 50 years" (China Association for the Protection of Monuments and Sites, 2022). The next 50th anniversary should be the focus of the digital transformation of heritage conservation.

Heritage building information modeling (HBIM) is a new paradigm for digital design and management (also referred to by some scholars as historic building information modeling, but there is no essential difference between these two concepts, considering that the context of this article is the 50th anniversary of the signing of the World Heritage Convention, which adopts the first term). In 2009, Murphy et al. of the University of Dublin introduced the term HBIM to scholars for the first time (Murphy et al., 2009), specifying the application of HBIM technology to historical scenes and defining HBIM as a prototype library of parametric objects based on historical architectural data (COŞGUN et al., 2021). With the continuous turnover of related technologies, the HBIM has long since moved beyond modeling to the full lifecycle of sustainable preservation. Combined with the UK government's definition of BIM (Arayici, 2017; UK Government, 2015) and the explication of HBIM by several scholars (N. Bruno and Roncella, 2019; S. Bruno et al., 2021; COŞGUN et al., 2021; Jordan-Palomar et al., 2018; Nik Kamaruzaman, 2019), we redefine it as "a collaborative approach based on digital technology that embeds heritage asset data in 3D computer models throughout the lifecycle of its conservation."

Related research in the field of HBIM has a history of nearly 13 years; this technology is constantly innovating and evolving and has contributed greatly to the field of heritage conservation. It is important for the contemporary planned conservation of historic buildings because of its powerful ability to organize and archive architectural information. It contains specific geometric and semantic data that are extremely important to support the decision-making and workflow of historic building research. Applying HBIM to heritage building conservation can allow most resources to be recorded or saved and has good feasibility and broad prospects for application.

The emergence of HBIM represents a new concept in the Architecture, Engineering & Construction (AEC) industry, and many related studies have shown the successful application of HBIM to historic buildings. Fassi et al. (2015) proposed the application of HBIM to facilities management, using its deployment in all work phases and restoration activities of the Milan Cathedral as an example. This system would manage rapid changes to the structure, permit increased time spent in fieldwork and organize real-time communication between offices (Nik Kamaruzaman, 2019). Frosini et al. (2016) proposed an automated program based on the HBIM process to analyze fire safety systems and used the Solibre model checker for the "Command Building" of the School of Air Warfare in Florence (SMC), which was tested and analyzed. In addition, the system was able to identify and analyze possible escape routes and fire compartments in the building (Nik Kamaruzaman, 2019). Y. C. Lin (2017) studied the importance of VR in the construction industry (e.g., defect inspection) and in education (VR learning environment), using a complex structural Han-style building, the Confucius Temple in Tainan, as an object of study.

Currently, many new technologies are emerging that bring great value to the practical application of HBIM, such as the Microsoft SQL Server, artificial intelligence, the Internet of Things, Web-GIS, and virtual reality/augmented reality technologies. The combination with Microsoft SQL Server allows the creation of a database of historic buildings. The target building is associated with a 3D model of the asset, which is highly adaptable to different software platforms and can be accessed both through a developed desktop application (as a plug-in to the BIM software) and through a web interface to ensure data sharing and ease of use for both skilled and unskilled users (N. Bruno, 2018; N. Bruno and Roncella, 2019; Saygi and Remondino, 2013). In conjunction with artificial intelligence, automated diagnosis can be performed within a machine-driven platform through deep learning algorithms for preliminary knowledge analysis and identification of pathologies and cracks in ancient buildings. In addition, visual recognition of images through convolutional neural networks can help map pathologies and crack patterns and identify building settlements faster from acquired images or 3D models. The same techniques can be used to analyze thermal and radar imaging to support the structural characterization of materials (S. Bruno et al., 2018; Hatir et al., 2020; Mansuri and Patel, 2021). The combination of the Internet of Things (IoT) and Web-GIS, which links the physical and digital worlds, can transfer data from real-time diagnostics to BIM models, alerting experts and users to hazardous conditions in time to properly document and manage cultural heritage (S. Bruno et al., 2018; Javier Sanchez-Aparicio et al., 2020; W. Lee and Lee, 2019). The combination of virtual reality/augmented reality technology allows context-aware risk management of heritage buildings, linking HBIM with VR environments in a framework that can share and retrieve risk management information.

A systematic review of HBIM has also been discussed in recent years by scholars. D. P. Pocobelli et al. (2018) focused on the application of HBIM in the initial stages of the conservation of historic buildings, emphasizing the issues related to digitization and automation. F. J. López et al. (2018) reviewed the literature on HBIM and its effective implementation in the field of cultural heritage, exploring the effectiveness and usefulness of the different approaches developed for modeling a family of historic buildings. Xicheng Yang et al. (2020) discussed the integration of HBIM with other information technologies in practical applications, considering techniques such as computer graphics, photogrammetry, GIS, and ontology. After analyzing and summarizing the previous literature, the author believes that research on HBIM still needs to be discussed in the following aspects:

- A systematic analysis of the current status of research on HBIM is needed, covering annual publication volume, funding agencies, countries/regions, publication sources, and institutions, to help researchers grasp global research interest in the field of HBIM from a holistic perspective, including the identification of national funding policy support and other matters.
- Cocitation network analysis of journals and literature is needed to see the correlation between various journals and types of research and to obtain collective knowledge in certain research areas.
- A discussion of HBIM research trends in conjunction with keyword co-word analysis and cluster analysis would reveal the research hotspots and evolutionary trends in HBIM-related fields from the beginning to the current period.
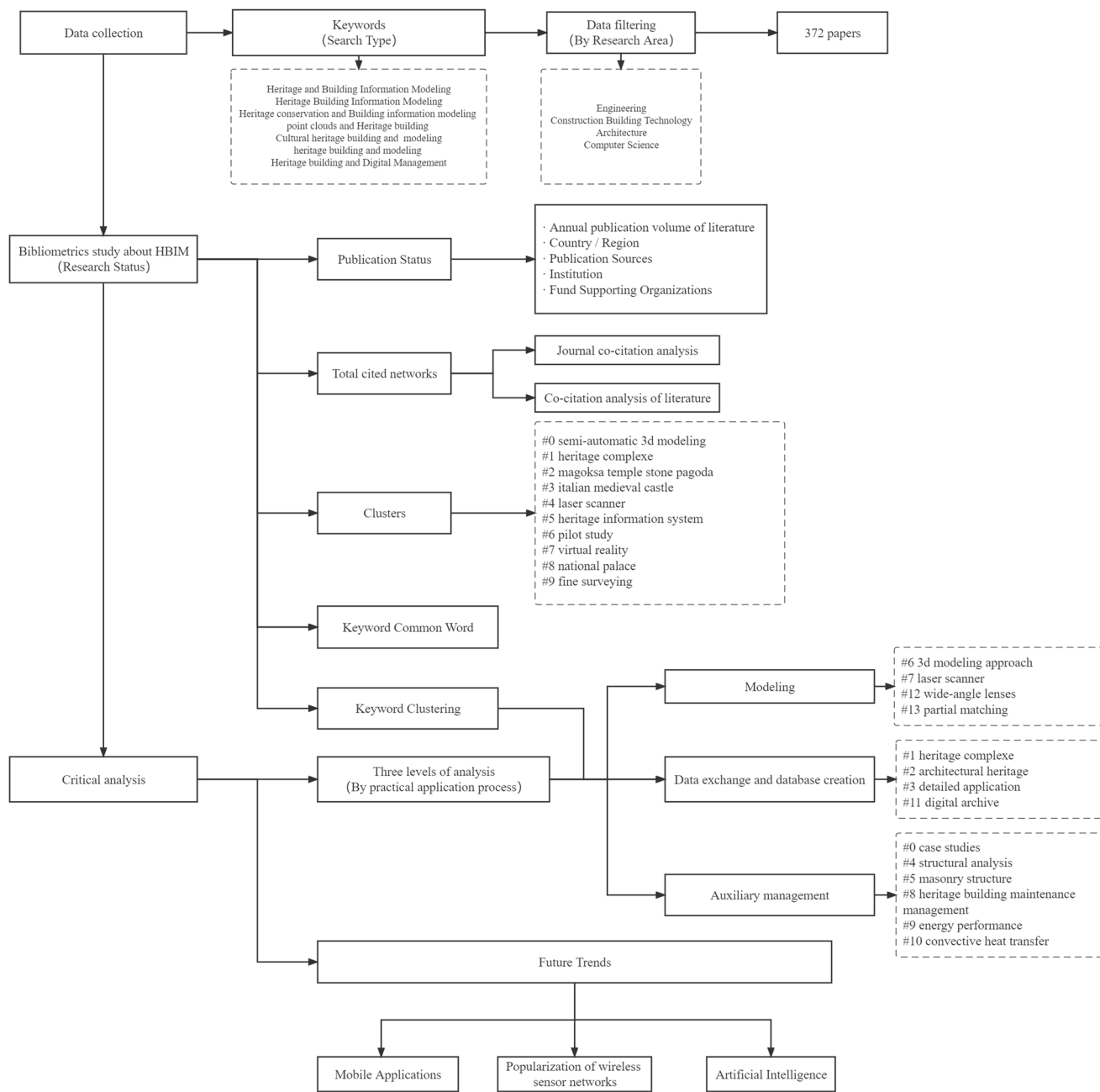
**Fig. 1 Article structure diagram.** The research framework of the article is presented in the form of a technology roadmap.

- Combining HBIM-related research with practical applications, we propose a systematic and complete workflow.

Based on this summary of gaps in the literature, this article systematically reviews the literature related to HBIM since 2010, using 372 papers from the core collection of Web of Science and CiteSpace knowledge graph analysis software to conduct a visual analysis and interpretation of the current status of research trends by combining the abovementioned contents. The structure of the article is shown in Fig. 1.

## Methods
### Research methods
*Scientometrics.* In the early 1960s, D. Price and others (Price, 1965) advocated and adopted quantitative research methods to study science itself, and E. Garfield created the large SCI database

(Garfield, 1955), which was the genesis of scientometrics. Scientometrics is the emerging discipline of a quantitative study of science itself, which uses quantitative methods to study inputs (e.g., researchers, research funding, etc.), processes (e.g., information dissemination, etc.), and outputs (e.g., number of papers, citations, etc.) to find the laws or quasi-laws governing scientific activities and provide guidance for more effective scientific activities in the future (Fu, 1982).

Compared to bibliometrics, scientometrics analysis involves not only literature metrics but also scientific talent, research funding, and the scientific community, and the results are more objective (Glänzel, 2015). Scientometrics is more closely related to the development of science, and the use of scientometrics to analyze a disciplinary research field helps scholars deepen their understanding of the inner laws guiding the development of the field, thus providing reference and guidance for the management

of future projects and the formulation of science and technology policies. This knowledge is useful for decision-makers entering into the guidance of science and technology (Fang, 2006; Liang and Wuyishan, 2006). Based on scientometrics, this article takes a quantitative approach to review and analyze the intrinsic laws governing the overall development of HBIM research as a field and discusses its future trends.

**Scientific knowledge mapping**. The concept of scientific knowledge mapping first originated from a workshop organized by the National Academy of Sciences in 2003, which pointed out that with the development of information visualization, there would be a major trend to analyze the development of scientific fields by drawing scientific knowledge maps (Chen et al., 2008).

So-called knowledge mapping is a graphic depiction showing the developmental process and structural relationship of scientific knowledge within a specific knowledge domain. Knowledge mapping has the dual characteristics of "diagram" and "spectrum": it is both a visual knowledge graph and a sequential genealogy of knowledge, showing many implicit complex relationships such as network, structure, interaction, intersection, evolution, or derivation among knowledge units or groups, and behind these complex relationships is the birth of new knowledge (Chen, 2014). The CiteSpace analysis tool used in this article, combined with the analyzed data, generates two major types of views, which are cluster view and timeline view, with the following meanings.

Clustered views include default views (Figs. 4–7 and 10) and the automatic clustering label view (Figs. 8 and 11). The nodes in the default view represent the analyzed objects, and the size of the nodes indicates the frequency of occurrence (or citation); the color and thickness of the inner circle of the nodes indicate the frequency of occurrence (or citation) in different periods; the lines between the nodes indicate the co-occurrence (or citation) relationships, and their thickness indicates the intensity of co-occurrence (or citation); node colors ranging from cool to warm tones represent the change in time from early to recent for the object being analyzed. The index of betweenness centrality, which is a measure of the importance of nodes in the network, is also generated in the cluster view analysis and is used in CiteSpace to discover and measure the importance of the literature. The importance is highlighted with purple circles for that type of literature (or author, journal, institution, etc.). The higher the betweenness centrality is, the greater the influence and importance of the node.

The timeline view (Figs. 9 and 12) mainly focuses on delineating the relationship between clusters and the historical span of documents in a cluster. Nodes in the same cluster are arranged on the same horizontal line in chronological order. The cluster view focuses on internal interrelationships, and the timeline view focuses more on the interrelationships and interactions between clusters.

The stage of interpreting scientific knowledge mapping can help us analyze the following aspects:

- Which literature is groundbreaking or represents a landmark study in a particular field?
- What literature plays a key role in the evolution of a research field?
- Which topics dominate the overall field of study?
- How are different fields of study interrelated?
- How have research frontiers based on a certain knowledge base evolved?

*Selection of scientometric tools*. The main international bibliometric tools are CiteSpace, Vosviewer, Sci2, SciMAT, Bicomb, Pajek, SATI, etc. (Li, 2018) Some of the mainstream international scientific measurement tools are listed and compared in Table 1 (Cobo et al., 2011; Li et al., 2015). Among many scientometric tools, CiteSpace is selected as the data analysis tool at this research stage because it reflects the characteristics of Ronald S. Burt′s structural hole idea, Kuhn's paradigm shift, and Kleinberg′s algorithm for detecting sudden increases in frequency (ScienceNet—Chen Chaomei′s Blog Post, 2022). These features are of great importance for developing the analysis of a certain field of scientific research.

Structural hole ideas from Ronald S. Burt at the University of Chicago were described in his study of social networks and social values (Lazega and Burt, 1995). The idea of structural holes embodied in CiteSpace is to find the midpoint of different degrees of betweenness centrality so that we do not stick to the local contributions of specific papers in the literature but focus on the role in the overall development of the academic field. This overview is precisely the forward leap needed for systematic scholarly review.

Thomas Samuel Kuhn′s (Kuhn) structural theory of scientific revolutions (Kuhn, 1970) argues that the advancement of science is an endless reciprocating process based on the scientific revolution, that is, the alternation of old and new scientific paradigms or their rise and fall. CiteSpace reflects clusters of different time periods; the dominant colors of the clusters reveal years that were particularly active, and the structural holes of Ronald S. Burt connect different clusters. We can see in the scientometric analysis how one cluster connects to another almost completely independent cluster in which the literature played a key role in a paradigm shift.

Kleinberg proposed an algorithm for detecting frequency bursts in 2002 (Kleinberg, 2004). If the citation frequency of a paper suddenly increases rapidly, then the safest explanation is that the paper hits a key part of the complex system of the academic field. The embodiment in CiteSpace is that such nodes in the knowledge network usually reveal an A job with great potential or interest.

*Data collection and processing*. Most countries in the world now have their own data resources, and the tendencies of databases to collect different kinds of knowledge vary according to the native language of each country. The authoritative international databases are the Web of Science (WoS) database, PubMed database, Derwent Innovation Index (DII) database, CNKI database, Scopus database, Google Scholar database, ADS database, etc. (Chen, 2014) To ensure reliability and authority of the data, the Web of Science Core Collection (WoS Core Collection) was used as the data source for this study.

The phase for the data collection of scientific literature is mainly based on the research of published literature through keywords, such as "Heritage Building Information Modeling", "Heritage conservation", "Historic Building Information Modeling", "point clouds", "heritage building", and "Digital Management", which is a combination of subject terms. All journal articles published from 2010 to March 2022 were retrieved, and 577 articles were initially screened.

Some studies emerged because terms with the same abbreviations have different meanings in different scientific fields; for example, in the search interface (Heidarizadeh and Zarei, 2012), HBIM is a term in chemistry, which is not consistent with the direction of this study. On this basis, we used the function to filter research categories in the Web of Science database to narrow the results to engineering or construction building technology or architecture, or computer science.

To improve the accuracy and reliability of the data analysis, the Web of Science core database was selected. The records that were

**Table 1 Comparison of scientometric tools.**

| Tool name | Development organization | Development year | Bibliometric indicators | Analysis method | Visualization mapping |
|---|---|---|---|---|---|
| CiteSpace | Drexel University, USA | 2004 | Frequency/Centrality, Year of first appearance, Burst value, ∑ value, PageRank, Half-life | Mutation detection, clustering analysis, geospatial analysis, network analysis, time series analysis | Auto-clustering tag view, timeline view, time zone view, fish eye view |
| Vosviewer | Leiden University, the Netherlands | 2010 | None | Network analysis, theme analysis | Network visualization view, entry density view, clustering density view |
| Sci2 | Indiana University Katy Bornor | 2009 | None | Mutation detection, clustering analysis, geospatial analysis, network analysis, time series analysis | horizontal bar graphs, contour maps, and scale symbol maps. |
| SciMAT | University of Gnanada, Spain | 2011 | Callon's density and centrality, average number of citations, maximum number of citations, minimum number of citations | Basic data statistical analysis, network analysis, time series analysis | Entry overlay maps, evolution maps, strategy maps, clustering networks |
| Bicomb | China Medical University | 2009 | Frequency, percentage, cumulative percentage | Cluster Analysis | Imported into SPSS, Gclute for clustering analysis |
| Pajek | A. Mrava, V. Batagelj | 1996 | Centrality, density | Network analysis, time series analysis | 2D, 3D, or dynamic community maps |
| SATI | Department of Information Management, Zhejiang University | 2011 | Frequency | Cluster Analysis | Embedded Netdraw visualization tool |

not related to the digital conservation of architectural heritage, as noted in the title, keywords, abstract, and text, were manually screened out, leaving 372 documents with high relevance for analysis. These were exported as a text file, "download_1-372.txt", in plain text form, and then R3 internal processing was used to find duplicates and convert the format, leaving 372 documents. The time slice in CiteSpace was set to 2010–2022, and the individual time slice was set to 1 year, with the remaining default values as parameters.

It should be noted that the data in the review category are limited by the search source and the conforming query used. The year of database purchase is different for different institutions, so it can lead to small differences in the web query results at different institutions. This study was analyzed based on the Web of Science database of Hubei University of Technology Library, dated March 17, 2022.

## Results
**Analysis of the current status of the publication**. Kuhn's paradigm theory considers the nature of scientific development as a process of alternating movement between normal science and scientific revolution, an accumulation paradigm, and a transformation paradigm (Fig. 2) (Chen, 2014). This study, as an expression of scientific theory development, can elaborate profoundly on the process of formation, accumulation, diffusion, and transformation of citation clusters on the CiteSpace knowledge graph and reveal the process of emergence and evolution of research frontiers in a knowledge field. The analysis of the annual publication volume of literature in the field of HBIM research is based on the WoS database, CNKI, and Scopus databases of the China Knowledge Network, and the analysis of publication year, country and region, authors, institutions, and funding agencies are based on the WoS database.
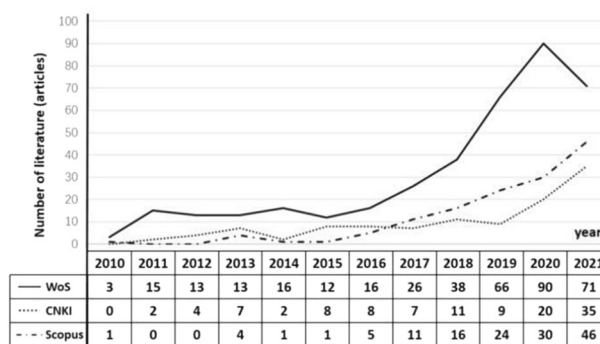


**Fig. 2 Kuhn's paradigm theory development diagram.** A summary and elaboration of the development of Kuhn's paradigm theory.

**Annual publication volume of literature**. Figure 3 shows that during the period from 2010 to 2016, the total number of publications in the field of HBIM in all three databases is less than 100, and there is a slight fluctuation trend in rates of publication, indicating that the research on HBIM is still in the conceptualization stage, i.e., the prescience and paradigm formation stage according to paradigm theory. With the more widespread application of HBIM-related technologies in engineering and the continuous promotion of various software tools, attention to HBIM is growing daily. Since 2017, HBIM-related research has shown a gradual upward trend, with the annual volume of studies in the WoS database in 2019 exceeding 60 articles and reaching 90 articles in 2020. This increase indicates that HBIM research has entered an accelerated upward phase, i.e., the conventional science and paradigm accumulation phase. However, in 2021 compared to 2020, the volume of published literature in the WoS database shows a downward trend, but the
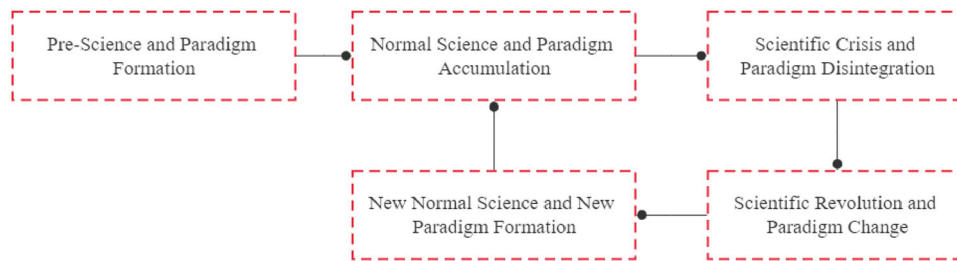
**Fig. 3 Annual publication volume of HBIM-related literature.** Annual publication volume of HBIM-related literature analyzed by CiteSpace bibliometric analysis software.



**Fig. 4 Geographical distribution of HBIM studies.** Geographical distribution of HBIM studies analyzed by CiteSpace bibliometric analysis software.

CNKI and Scopus databases have risen steadily. The general upward trend is expected to continue until it enters the third phase of paradigm theory, the scientific crisis and paradigm unraveling phase, and before this phase arrives, those involved should respond well in advance.

**Country/region analysis**. This study shows that nearly 60 major countries or regions are engaged in HBIM research, with Italy having the highest number of publications. The first publication in Italy was in 2011, and the total number of Italian publications was 115, accounting for 23.4% of the total literature, with a high intermediary center of 0.38. The next country with the highest number of publications in Spain, with a total number of 62 publications, accounting for 12.6% of the literature. Following this are Portugal, China, the United States, and others. The top 15 countries/regions and the related number of publications on HBIM research are analyzed in Fig. 4 and Table 2. It should be noted that although the total number of publications in the UK is small, it has a mediated centrality of 0.25, second only to Italy, indicating that the UK has received much attention in the field of HBIM-related research.

**Analysis of publication sources**. When the sources of publications were analyzed, it was found that the *Journal of Cultural Heritage* published more literature related to research in the field of HBIM, with a total number of 41 articles, followed by *Applied Sciences*, *International Journal of Architectural Heritage* and other journals. Table 3 lists the sources and number of publications with a total number of publications greater than 10. These journals represent the frontier of development of HBIM to a certain extent.

**Institutional analysis**. CiteSpace has analyzed the institutions to which the documents belong. Figure 5 shows the results of the

analysis. It can be seen from the figure that the connections between institutions are generally scattered, and the Polytechnic University of Milan has more achievements and is closely connected with other institutions. Although the first publication of Polytechnic is relatively late compared to other institutions, they rank first among institutions in terms of publication volume, with a total number of publications at 21 and an annual publication rate of 3.0. When analyzing the annual publication rate, we found that although the University of Seville's research on HBIM is relatively late, with the first study on HBIM published in only 2018, the subsequent annual publication rate is as high as 2.75, second only to the Polytechnic University of Milan. After the Polytechnic University of Milan are the University of Minho, the University of Seville and the Polytechnic University of Turin, and others. Table 4 lists the top 8 institutions by frequency, first publication year, and annual publication rate.

**Fund supporting organizations**. Among funding agencies for HBIM research, the European Commission has supported the highest number of publications with 44, which is much larger than the next largest funder, the Spanish government. Overall, this pattern of funding indicates that the European Union pays more attention to HBIM research and invests more in it. This is followed by the National Natural Science Foundation of China, the Ministry of Education Universities and Research, and the Portuguese Foundation for Science and Technology, among others. Table 5 shows the names and numbers of the top 10 funding agencies.

**Co-citation network analysis**. The main purpose of co-citation analysis is to express the relationship between documents through the frequency with which they are cited by other documents at the same time. That is, if two documents are cited by other documents at the same time, the higher the citation frequency is, the closer the relationship. By analyzing the clustering and key nodes in the co-citation network, the knowledge structure, research frontiers, and documents that play a key role in the development of a certain research field can be obtained (Chen, 2014).

**Journal co-citation analysis**. Journal co-citation analysis was carried out on HBIM-related literature, and the minimum spanning tree algorithm was selected. A total of 495 nodes and 849 links were generated on the knowledge map. The result of pruning the map is shown in Fig. 6. The citation history of a node is described as a number of tree rings, with each ring representing the number of citations received in the corresponding publication year. The common annual ring is a spectrum of cool to warm colors. If cited references are detected as citation bursts within a certain period, the corresponding tree ring will be displayed in red. In the figure, the thickness of the annual rings is positively correlated with the citation frequency, and the lines represent the

**Table 2 Geographical distribution of HBIM studies.**

| Country | Quantity | Intermediary Centrality | Issuance percentage | Country | Quantity | Intermediary centrality | Issuance percentage |
|---|---|---|---|---|---|---|---|
| Italy | 115 | 0.38 | 23.4 | Turkey | 15 | 0 | 3.1 |
| Spain | 62 | 0.1 | 12.6 | Germany | 12 | 0.06 | 2.4 |
| Portugal | 34 | 0.18 | 6.9 | Poland | 11 | 0 | 2.2 |
| People's Republic of China | 31 | 0.02 | 6.3 | Greece | 11 | 0.05 | 2.2 |
| USA | 20 | 0.3 | 4.1 | South Korea | 9 | 0 | 1.8 |
| England | 18 | 0.25 | 3.7 | Canada | 9 | 0.06 | 1.8 |
| France | 18 | 0.16 | 3.7 | The Netherlands | 8 | 0.09 | 1.6 |

**Table 3 Publication sources and number of publications.**

| Publication source (abbreviation) | Number of articles issued |
|---|---|
| *Journal of Cultural Heritage* | 41 |
| *Applied Sciences Basel* | 37 |
| *International Journal of Architectural Heritage* | 34 |
| *ISPRS International Journal of Geo Information* | 31 |
| *Remote Sensing* | 21 |
| *Applied Sciences* | 20 |
| *Sustainability* | 16 |
| *Buildings* | 15 |
| *Automation In Construction* | 13 |
| *Sensors* | 13 |
| *Sensors Basel Switzerland* | 13 |

co-citation relationship between journals. The journals with a citation frequency >50 are shown in Table 6.

As seen, the journal with the highest total citation frequency is the *Journal of Cultural Heritage* (the journal name is appropriately abbreviated in the analysis of journal co-citations in CiteSpace), which has a much higher number of citations than other journals, with a mediated centrality >0.1, indicating that this journal has high authority and influence in the field of HBIM. The journals that follow the Journal of Cultural Heritage are as follows: ISPRS—The International Archives of the Photogrammetry, Automation in Construction, and the International Journal of Architectural Heritage". The frequency of these three journals is greater than 100, and the centrality of mediation is >0.1, indicating a greater contribution to research in the field of HBIM.

**Literature co-citation analysis.** In the literature co-citation analysis of HBIM-related literature, there are 457 nodes and 1425 connections before pruning. This result is left after the minimum spanning tree algorithm and manual screening have been performed, as shown in the figure. In Fig. 7, the nodes represent articles, and the size of the nodes represents the citation frequency of the article. The larger the node is, the higher the frequency, which indicates that the article is cited more frequently and has a higher influence in the field. The journals with a frequency of occurrence greater than or equal to 10 were analyzed, as shown in Table 7. The most cited article was the review article *A review of Heritage Building Information Modeling (H-BIM)* published by LOPEZ SG in the journal *Multimodal Technologies and Interaction* in 2018, which reviews the literature on HBIM and its effective application in the cultural heritage field and discusses the effectiveness of different modeling approaches (Lopez et al., 2018).

Roncella's article "*A Restoration Oriented HBIM System for Cultural Heritage Documentation: The Case Study of Parma Cathedral*" published in 2018, although ranked fourth in the literature, has the highest betweenness centrality among all studies. Taking the Cathedral of Parma in Italy as an example, Roncella expounds on the study of the HBIM system, the main goal of which is to provide concrete answers to the lack of concrete tools required for cultural heritage documentation—organized and coordinated storage and management of historical data (N. Bruno and Roncella, 2018).

An analysis of this literature, which is highly cited in total, shows that the central point of research on HBIM focuses on practical case applications (Brumana et al., 2018; N. Bruno and Roncella, 2018). Overall, the research hotspots in the most cited literature focus on the creation of high-quality models for HBIM (Anton et al., 2018; Barazzetti et al., 2015; Macher et al., 2017; Quattrini et al., 2015, 2017) and assisted management (S. Bruno et al., 2018).

**Cluster analysis.** The clustering view in CiteSpace is divided into the default view and the automatic clustering label view. The automatic clustering label view is generated by the spectral clustering algorithm (Zhao, 2012) on the basis of the default view, and the clustering label is based on the algorithm extracted by the TF*IDF. The citing documents are analyzed by the algorithm, and the label words are extracted to represent the research frontier applied to a certain knowledge base.

As Fig. 8 shows, the clustering analysis based on the cocitations of HBIM literature leaves ten clusters: semiautomatic 3D modeling, heritage complex, Magoksa temple stone pagoda, Italian medieval castle, laser scanner, heritage information system, pilot study, virtual reality, National Palace, and fine surveying.

In CiteSpace analysis, there is another type of view mode, shown in Fig. 9: timeline view According to the timeline view of keywords, the origin and development of research topics and the corresponding research time limit can be seen. The following four types of hotspot clusters are analyzed, and the specific analysis is as follows.

*#0 Semiautomatic 3D modeling.* The main focus of this cluster is on the 3D modeling of HBIM. The analysis of information mapped by this cluster leads to the main research results of HBIM in the field of semiautomatic 3D modeling using terrestrial laser scanner (TLS) and 3D Time-of-Flight (TOF) technology for digital documentation of historical buildings and 3D model creation of complex structures (Altuntas et al., 2016; Croce et al., 2021; Jose Lopez et al., 2017; Masciotta et al., 2022; Noor et al., 2020). The ground-based laser scanner (TLS) and UAV unmanned aerial system (Xu et al., 2014, 2016) capture 3D point clouds and use camera networks to modify image-based 3D reconstructions or structures in motion (SFM) (Plata et al., 2021). Overlapping UAV image sets are processed to create high-quality 3D models; BIM platforms and semantic web technologies

**Fig. 5 Institutional distribution of HBIM research.** Institutional distribution of HBIM research analyzed by CiteSpace bibliometric analysis software.

| Table 4 Institutional distribution of HBIM research. | | | |
|---|---|---|---|
| **Frequency** | **Institution name (abbreviation)** | **Year of first publication** | **Annual issuance rate** |
| 21 | Polytechnic University of Milan | 2015 | 3.0 |
| 16 | University of Minho | 2013 | 1.78 |
| 11 | University of Seville | 2018 | 2.75 |
| 11 | Polytechnic University of Turin | 2012 | 1.1 |
| 9 | University of Lisbon | 2016 | 1.5 |
| 7 | University of Naples Federico II | 2015 | 1.0 |
| 6 | University of Florence | 2011 | 0.60 |
| 5 | University of Bologna | 2011 | 0.50 |

| Table 5 Funders of HBIM research. | |
|---|---|
| **Name of the funding agency (abbreviation)** | **Total number of grants** |
| European Commission | 44 |
| Spanish Government | 18 |
| National Natural Science Foundation of China | 16 |
| Ministry of Education Universities and Research | 10 |
| Portuguese Foundation for Science and Technology | 10 |
| European Commission Joint Research Centre | 8 |
| UK Research and Innovation | 8 |
| Natural Sciences and Engineering Research Council of Canada | 6 |
| Board of Wales | 5 |

(Quattrini et al., 2017) link 3D models with databases to form a repository where users can directly query the semantic structure of historic buildings and HBIM data. LOD can be used to pre-define measurement accuracy and modeling detail when creating complex historic building models (Biagini et al., 2016; Liu et al., 2019a, 2019b).

*#5 Heritage information system.* The focus of this cluster is on the construction of information systems for historic buildings. The analysis of the information mapped by this clustering leads to the following main research aggregation points for HBIM in the field of heritage information systems. Florent Poux et al. (2020) in 2020 proposed a framework for a generic system for the digital management of historic buildings, jointly developed by multi-modal users (managers, visitors, and curators) and development teams (designers, developers, and architects), containing spatial
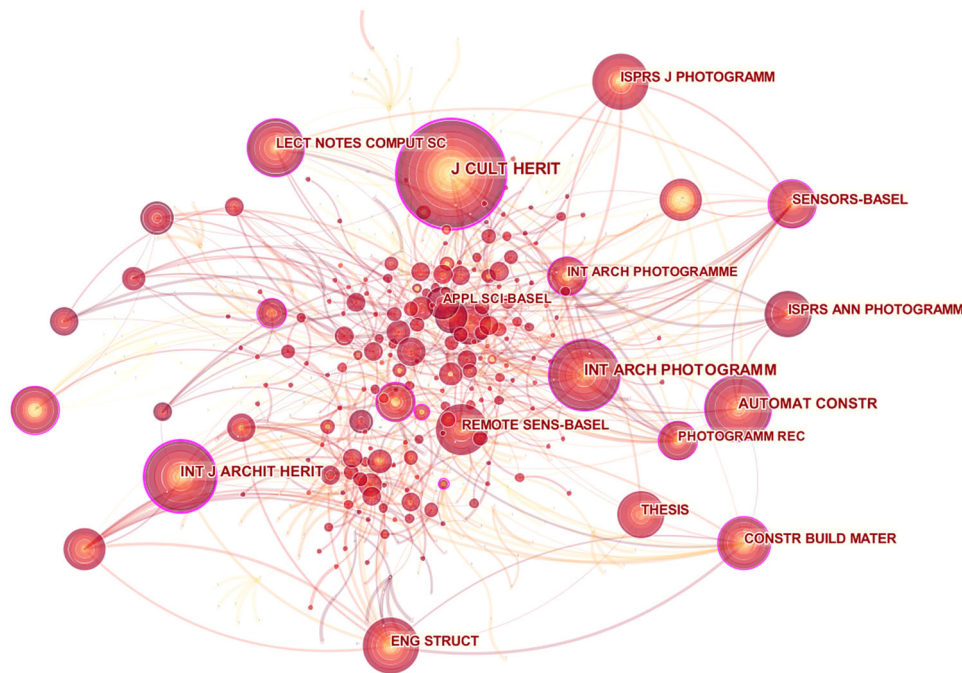
**Fig. 6 Analysis of journal co-citations for HBIM research.** Analysis of journal co-citations for HBIM research analyzed by CiteSpace bibliometric analysis software.

**Table 6 Analysis of journal co-citations for HBIM research.**

| Frequency of occurrence | Journal name (abbreviation) | Intermediary centrality | Frequency of occurrence | Journal name (abbreviation) | Intermediary centrality |
|---|---|---|---|---|---|
| 190 | Journal of Cultural Heritage | 0.2 | 54 | Applied Sciences-Basel | 0 |
| 143 | ISPRS - The International Archives of the Photogrammetry | 0.18 | 51 | Photogrammetric Record | 0.15 |
| 106 | Automation In Construction | 0.16 | 50 | The International Archives of the Photogrammetry | 0.1 |
| 101 | International Journal of Architectural Heritage | 0.21 | 49 | Sustainability | 0.06 |
| 86 | Remote Sensing | 0.03 | 48 | ISPRS International Journal of Geo-Information | 0.05 |
| 85 | ISPRS Journal of Photogrammetry and Remote Sensing | 0.03 | 47 | Journal of Archeological Science | 0.13 |
| 81 | Construction and Building Materials | 0.14 | 47 | Bulletin of Earthquake Engineering | 0.08 |
| 81 | Engineering Structures | 0.07 | 46 | Structural Survey | 0.05 |
| 75 | Lecture Notes in Computer Science | 0.18 | 40 | Building and Environment | 0.13 |
| 72 | Thesis | 0 | 36 | IEEE Transactions on Pattern Analysis and Machine Intelligence | 0.04 |
| 68 | Sensors | 0.11 | 34 | Applied Geomatics | 0.08 |
| 65 | ISPRS Journal of Photogrammetry and Remote Sensing | 0.05 | 30 | Procedia Engineering | 0.01 |

and temporal information on historic buildings, all managed by a central database and visualized in 3D. Roque Angulo-Fornos et al. (Angulo-Fornos and Castellano-Roman, 2020) in 2020 discussed the generation of HBIM for the preventive conservation of historic buildings, presenting the information for historic buildings in their current state of conservation in the form of images and data tables and containing the corresponding treatment for preventive conservation. Alvaro Mol et al. (2020) in 2020 proposed a software-based HBIM that combines the results of nondestructive testing and geometric measurements for the management and maintenance of historic wooden buildings, which can model, analyze, and store geometric data, decay levels, and materials of wooden buildings. Pin-Chan Lee et al. (2019) in 2019 proposed a method to connect ontology and BIM using FMEA (failure mode and effects analysis) to facilitate research on building knowledge management (BKM), with the aim of better handling uncertain information and improving reliability when managing the maintenance of historic buildings. Pierre Jouan et al. (Jouan and Hallot, 2020) in 2020 proposed the application of a digital twin (DT) to the management planning process for preventive
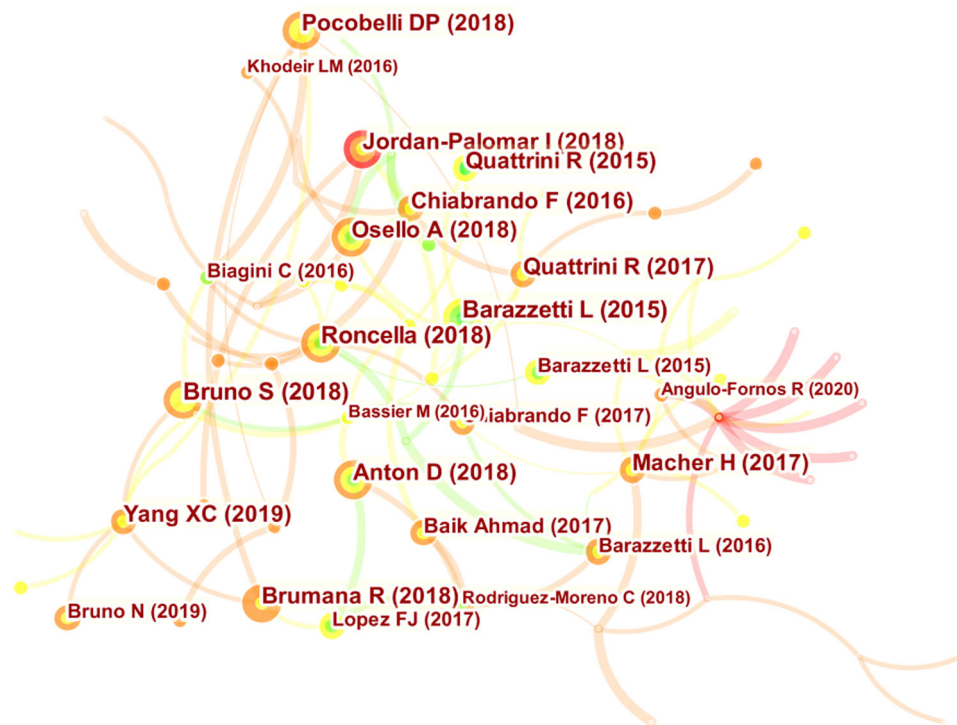
**Fig. 7 Co-citation analysis of literature.** Co-citation analysis of literature analyzed by CiteSpace bibliometric analysis software.

conservation, i.e., using HBIM models as digital twins of historic buildings to construct data models of preventive conservation strategy information.

*#6 Pilot study*. The focus of this cluster is on pilot studies of HBIM. Pilot studies are small-scale preliminary studies designed to investigate the feasibility of key components of the main study and are smaller than full-scale studies; in other words, pilot studies are very important to improve the quality and efficiency of the main study. The analysis of the information mapped by this cluster leads to the following main research aggregation points for HBIM. Jelena Žurić et al. (2022) in 2022 presented a pilot study of HBIM-based certification of GBC historic buildings using the Open Data Interchange standard (IFC), which focuses on data interoperability and preservation. Gustavo Rocha et al. (Rocha and Mateus, 2021) in 2021 conducted a questionnaire survey of 208 industry professionals working in 78 countries that focused on the speed and effectiveness of surveying methods for modeling historic buildings using terrestrial 3D laser scanning and digital photogrammetry. Arnadi et al. (Murtiyoso and Grussenmeyer, 2020) in 2020 proposed an approach to the semantic annotation of point clouds, i.e., an algorithmic approach in the form of a toolbox to semantically segment large point clouds into smaller, more manageable and semantically labeled clusters. They tested it on historic buildings, showing results in line with expectations. Cristina et al. (Piselli et al., 2020) in 2020 selected a central Italian building as a representative of European rural offshore ancient architecture as a pilot study with a view of retrofitting historic building complexes with renewable energy in the form of geothermal HVAC systems.

*#7 Virtual reality (virtual reality)*. The focus of this cluster focuses on the virtual reality of HBIM. Analysis of the information mapped by this cluster yields the following major research aggregation points for HBIM. Jongwook Lee et al. (2019) in 2019 proposed a context-aware metadata structure based on the 5W1H (what, when, where who, why, and how) model for situational awareness

risk management of architectural heritage using HBIM and virtual reality (VR) and created two prototypes: an on-site VR application for heritage managers and a remote VR application for conservators. Eva Savina Malinverni et al. (Banfi, 2021) in 2021 investigated a technology flow based on the visual programming language (VPL) and AR environment to investigate new forms of communication to store, record, and share HBIM models.

### Research trend analysis

**Keyword co-occurrence analysis**. Co-occurrence analysis was first proposed in 1986 by scientists from the French National Center for Scientific Research and other scholars (Cozzens et al., 1988). The principle of co-occurrence analysis is to count the number of occurrences of a set of keywords in the same document, to cluster these words based on the number of occurrences, to reflect the affinity of these words, and then to analyze the structural changes of the disciplines and topics represented by these words (Ma et al., 2000; Wu and Lu, 2012; Zhou, 2017).

The keywords in the academic field are dynamic, and since most scholars' research is based on the research results of their predecessors, the keywords are inherited and extended (Feng and Kong, 2020). The keywords are words in natural language that express the themes and focal concepts of the literature and can reflect the research contents and core themes. The keywords were analyzed in CiteSpace, and after the minimum spanning tree algorithm was performed, 344 keyword nodes and 471 connecting lines between the nodes were left. After manual construction, the keyword co-occurrence network map shown in Fig. 10 was left. The size of each node represents the frequency of occurrence of the keyword. The more frequent the occurrence of the keyword, the larger the node. The darker the color of the connecting line between the nodes, the higher the degree of association between the nodes.

Due to space limitations, only the keywords with frequencies greater than or equal to 10 are listed in Table 8. The top ranking keywords are "cultural heritage", "building", "model", "documentation", "point cloud" and "bim". These words are the hotspots of

**Table 7 Co-citation analysis of literature.**

| Frequency of occurrence | Intermediary centrality | Literature name | First author | Year of publication | Journal source | Affiliated clusters |
|---|---|---|---|---|---|---|
| 21 | 0.06 | *A Review of Heritage Building Information Modeling (H-BIM)* | Lopez Sg | 2018 | *Multimodal Technologies and Interaction* | 4 |
| 14 | 0.01 | *Historic Building Information Modeling: Performance Assessment for Diagnosis-Aided Information Modeling and Management* | Bruno S | 2018 | *Automation in Construction* | 5 |
| 13 | 0.03 | *Cloud-to-BIM-to-FEM: Structural Simulation with Accurate Historic BIM From Laser Scans* | Barazzetti L | 2015 | *Simulation Modeling Practice and Theory* | 5 |
| 13 | 0.11 | *A Restoration Oriented Hbim System for Cultural Heritage Documentation: The Case Study of Parma Cathedral* | Bruno | 2018 | *The International Archives of the Photogrammetry* | 5 |
| 12 | 0.02 | *Knowledge-Based Data Enrichment for HBIM: Exploring High-Quality Models Using The Semantic-Web* | Quattrini R | 2017 | *Journal of Cultural Heritage* | 7 |
| 12 | 0.01 | *Accuracy Evaluation of The Semi-Automatic 3D Modeling for Historical Building Information Models* | Anton D | 2018 | *International Journal of Architectural Heritage* | 5 |
| 11 | 0.02 | *HBIM and Virtual Tools: A New Chance to Preserve Architectural Heritage* | Osello A | 2018 | *Buildings* | 7 |
| 11 | 0.02 | *Protocol to Manage Heritage-Building Interventions Using Heritage Building Information Modeling (HBIM)* | Jordan-Palomar I | 2018 | *Sustainability* | 7 |
| 11 | 0 | *Generative HBIM modeling to embody complexity (LOD, LOG, LOA, LOI): surveying, preservation, site intervention—the Basilica di Collemaggio (L'Aquila)* | Brumana R | 2018 | *Applied Geomatics* | 5 |
| 11 | 0.03 | *BIM for Heritage Science: A Review* | Pocobelli DP | 2018 | *Heritage Science* | 5 |
| 11 | 0.05 | *Historical Buildings Models and Their Handling Via 3d Survey: From Points Clouds To User-Oriented Hbim* | Chiabrando F | 2016 | *The International Archives of the Photogrammetry* | 7 |
| 10 | 0.02 | *HBIM Modeling from the Surface Mesh and Its Extended Capability of Knowledge Representation* | Yang XC | 2019 | *ISPRS International Journal of Geo-Information* | 5 |
| 10 | 0.02 | *Structural Simulations and Conservation Analysis -Historic Building Information Model (HBIM)* | Dore C | 2015 | *The International Archives of the Photogrammetry* | 1 |
| 10 | 0.04 | *Implementation and Management of Structural Deformations into Historic Building Information Models* | Nieto-Julian JE | 2019 | *International Journal of Architectural Heritage* | 4 |
| 10 | 0.02 | *From Point Clouds to Building Information Models: 3D Semi-Automatic Reconstruction of Indoors of Existing Buildings* | Macher H | 2017 | *Applied Sciences-Base* | 6 |
| 10 | 0.07 | *Building Information Modeling (BIM) for existing buildings— Literature review and future needs* | Volk R | 2014 | *Automation in Construction* | 0 |
| 10 | 0.04 | *From TLS to HBIM. High quality semantically-aware 3d modeling of complex architecture* | Quattrini R | 2015 | *The International Archives of the Photogrammetry* | 5 |

current research and are closely related to each other. The purple circle around the outer ring of these words indicates a high centrality. The word "model" does not rank highest and, in fact, has only been in scholarly discussion since 2017, but its high annual frequency indicates that the word has received continuous attention and research in the last few years.

**Keyword clustering analysis.** CiteSpace was used to cluster the analysis of high-frequency keywords, which were classified into 14 categories as research hotspots and frontiers in the field of HBIM, and the results are shown in Fig. 11. The high-frequency keywords were clustered into 14 categories: #0 case studies, #1 heritage complex, #2 architectural heritage, #3 detailed application, #4 structural analysis, #5 masonry, #6 structural analysis and 3D modeling approach, #7 laser scanner, #8 heritage building maintenance management, #9 energy performance, #10 convective heat transfer, #11 digital archive, #12 wide-angle lenses, and #13 partial matching. From the timeline view of keyword clustering in Fig. 12, it can be seen that the case studies and detailed application of HBIM are relatively hot, and the clusters ranked at the bottom are wide-angle lenses and partial matching, indicating that related research is just emerging but has great potential for development.
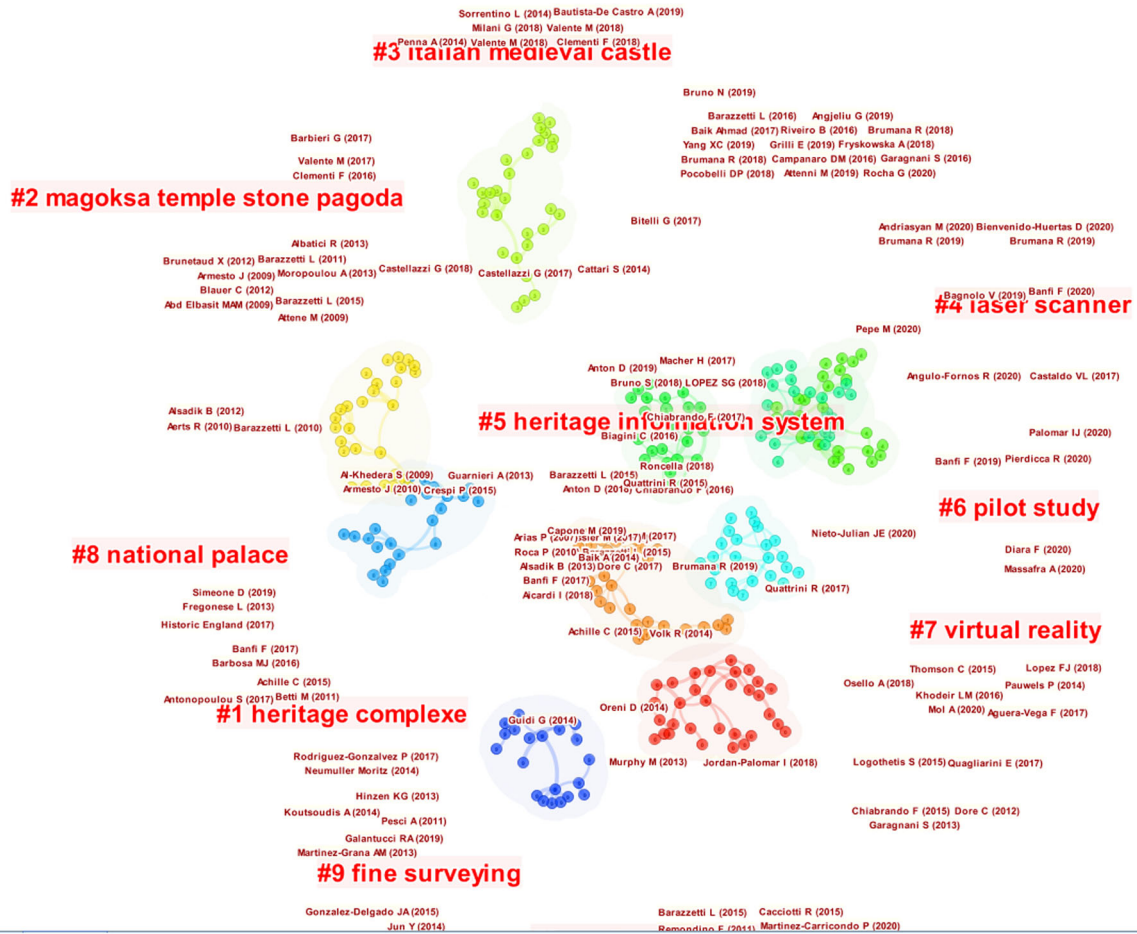
**Fig. 8 Clustered view of literature co-citations.** Clustered view of literature co-citations analyzed by CiteSpace bibliometric analysis software.
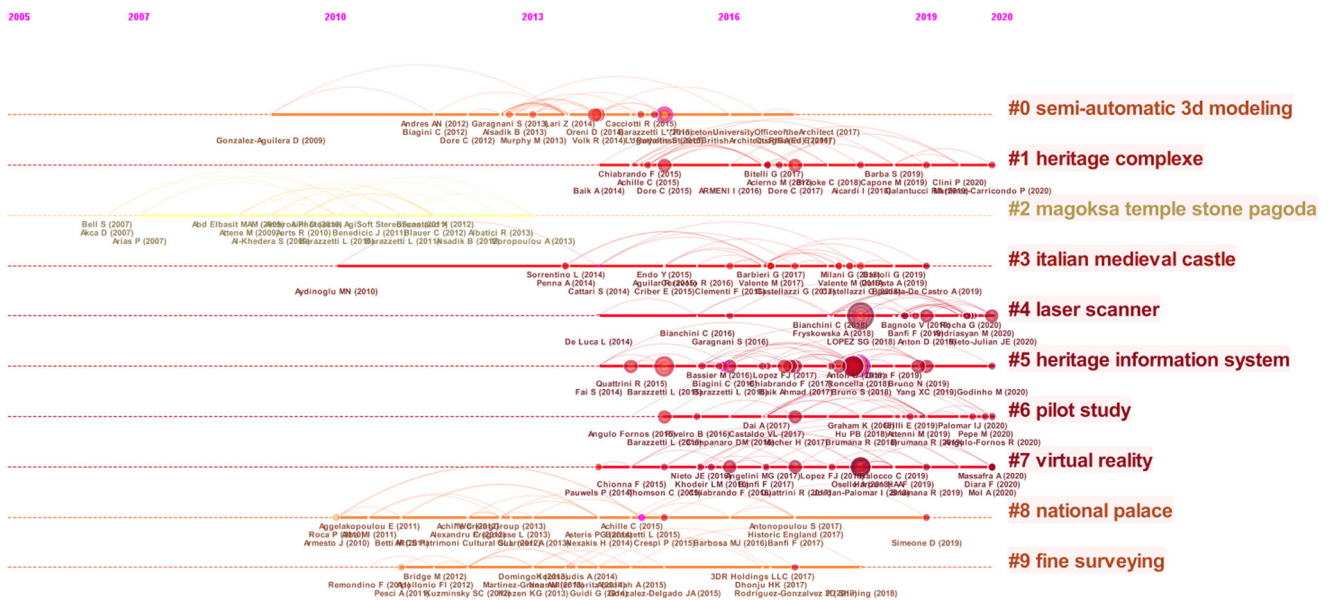


**Fig. 9 Clustered timeline view of literature co-citations.** Clustered view of literature co-citations analyzed by CiteSpace bibliometric analysis software.

There is also a detailed analysis of the origin of clusters in CiteSpace, i.e., which articles and keywords are added to a cluster, how frequent these keywords occur, and from which keyword clusters they are formed. In combination with these clusters, this article proposes a systematic and complete workflow, as described in the discussion section.
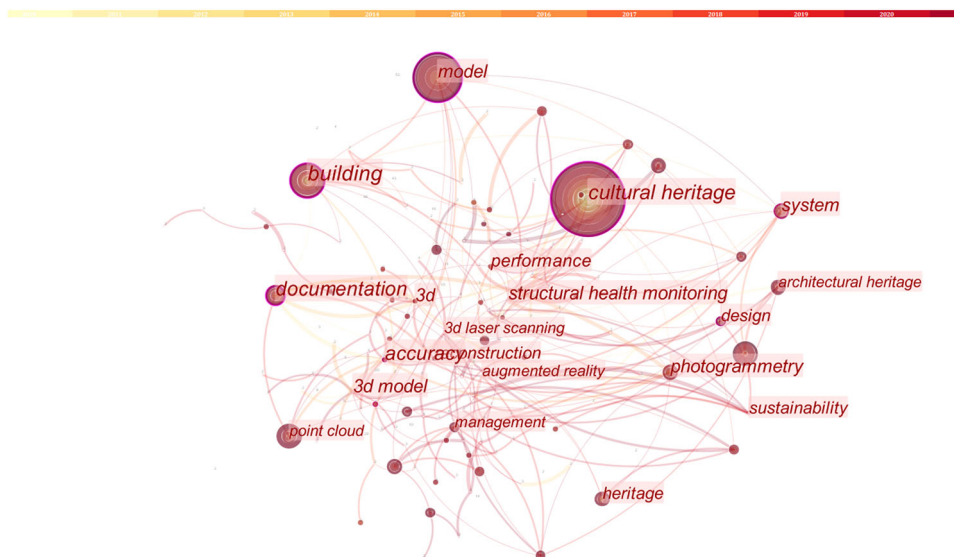
**Fig. 10 Keyword co-existence network.** Keyword co-existence network analyzed by CiteSpace bibliometric analysis software.

**Table 8 Keyword frequency.**

| Frequency | Keyword | Year of first occurrence | Annual frequency (up to 2022) | Frequency | Keyword | Year of first occurrence | Annual frequency (up to 2022) |
|---|---|---|---|---|---|---|---|
| 86 | cultural heritage | 2011 | 7.17 | 15 | architectural heritage | 2011 | 1.36 |
| 53 | model | 2017 | 10.60 | 14 | conservation | 2014 | 1.75 |
| 43 | building | 2012 | 4.30 | 14 | heritage | 2017 | 2.80 |
| 31 | documentation | 2011 | 2.81 | 12 | design | 2011 | 1.09 |
| 29 | point cloud | 2014 | 3.63 | 12 | vulnerability | 2017 | 2.40 |
| 24 | bim | 2017 | 4.80 | 12 | laser | 2018 | 3.0 |
| 20 | photogrammetry | 2014 | 2.50 | 11 | performance | 2017 | 2.20 |
| 16 | heritage building | 2012 | 1.60 | 10 | damage | 2014 | 1.67 |
| 16 | system | 2014 | 2.0 | 10 | management | 2018 | 2.50 |
| 15 | behavior | 2016 | 2.50 | 10 | earthquake | 2017 | 2.0 |
| 15 | information | 2019 | 5.0 | 10 | virtual reality | 2019 | 3.33 |
| 15 | architectural heritage | 2011 | 1.36 | 10 | terrestrial laser scanning | 2015 | 1.43 |

**Keyword surge analysis**. Surge keywords receive much attention in a short period, which can explain the development trends and frontiers of the field. The surge rate test of keywords can help identify frontier changes in the field and predict development trends. As shown in the figure, the 15 keywords with high emergence rates in the period from 2010 to 2022 are shown.

Table 9 illustrates that during the period from 2010 to 2014, the emerging keywords were close-range photogrammetry, calibration, and algorithm; that is, when the application of BIM to historical buildings had just entered the field, scholars mainly focused on the point cloud measurement and identification of historical buildings combined with related algorithms. During 2014–2018, the emerging keywords were seismic assessment, damage assessment, terrestrial laser scanning, and area. It can be speculated that during this period, the research content was mainly concentrated on the research and application of HBIM to practical cases. From 2018 to the present, the emerging keywords are laser, information, built heritage, HBIM, preventive conservation, virtual reality, and seismic vulnerability. Compared with the surge of keywords, it can be seen that the emerging keywords of HBIM in the past four years are twice those of the previous four years, which shows that in recent years, the research on HBIM at home and abroad has gone further than before. Attention has also gradually increased.

Although the research on HBIM in recent years continues to assess earthquake vulnerability as it did between 2010 and 2014 (Grazzini et al., 2020; Mondello et al., 2019; Rapone et al., 2018), it has moved from the damage assessment of historic buildings in 2014–2018 to a focus on preventive conservation (Fregonese et al., 2015; Olimpio et al., 2021; Zalamea et al., 2018). This is a major leap in the field of HBIM research. In addition, the research in the last 4 years has also focused on VR, and looking into the future, the application of HBIM to historic buildings combined with artificial intelligence (Bienvenido-Huertas et al., 2020; Mesanza-Moraza et al., 2021; Ni et al., 2021; Wang et al., 2020; Zou et al., 2019) will be a big leap forward.

**Citation surge analysis**. During the evolutionary development of the cluster, there will be a citation surge in the literature at a certain stage, and these studies have influenced or determined the development of HBIM in a certain period to some extent. References with high values in the intensity column are often milestones of scientific mapping studies, as Table 10 shows, mapping the top 20 studies with citation surges from 2011 to the present. The top three with the largest surge intensity are Historic Building Information Modeling—Adding intelligence
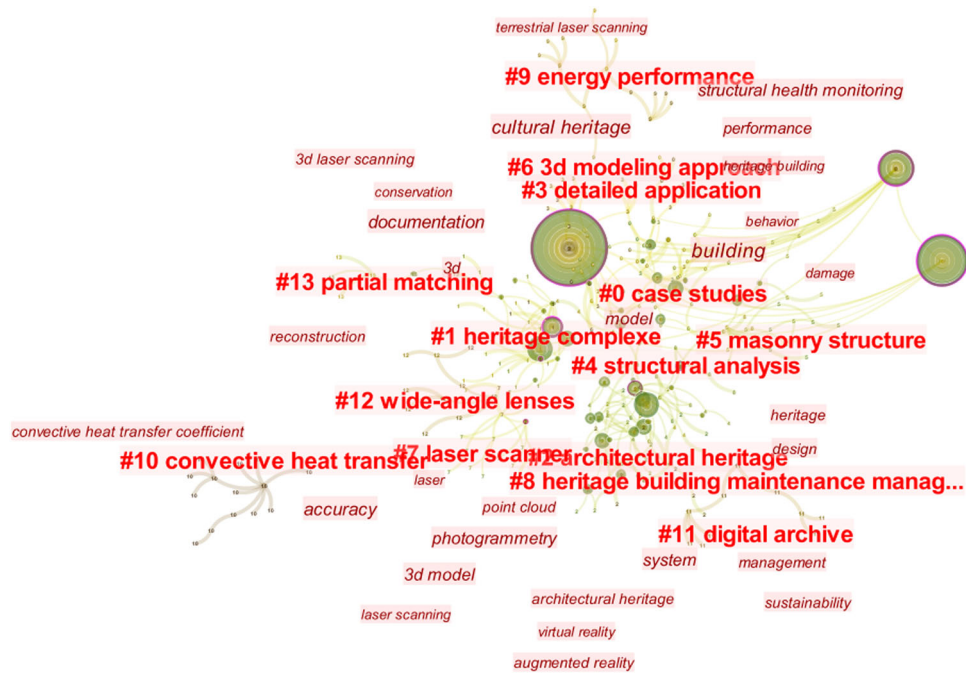
**Fig. 11 Keyword clustering.** Keyword clustering analyzed by CiteSpace bibliometric analysis software.
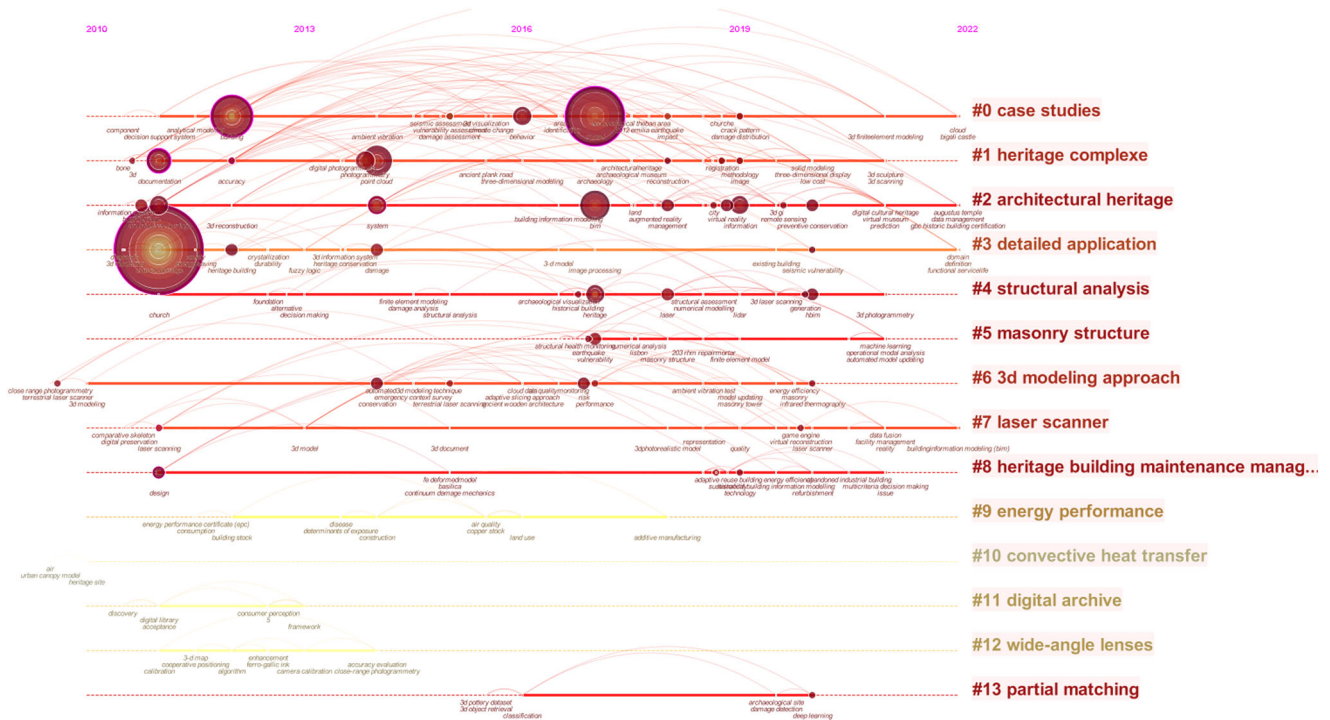


**Fig. 12 Keyword clustering timeline view.** Keyword clustering timeline view analyzed by CiteSpace bibliometric analysis software.

to laser and image-based surveys of European classical architecture (P.-C. Lee et al., 2019), Building Information Modeling (BIM) for existing buildings—literature review and future needs (Volk et al., 2014), Survey turned into HBIM: The restoration and the work involved concerning the Basilica di Collemaggio after the earthquake (L'Aquila) (Oreni et al., 2014). The focus of the literature is on the application of HBIM to real-life cases. As seen from the table, the number of citations that proliferated from 2018 to 2022 is equal to the sum of the preceding 8 years

and combined with the keyword emergence analysis, research into HBIM has received further attention since 2018.

## Conclusion
Based on CiteSpace knowledge graph analysis, this study systematically reviewed the literature related to HBIM research from 2010 to 2022 and visualized and interpreted the current research and trends of 372 papers in the Web of Science core literature collection.

**Table 9 Keyword surge.**

| Keywords | Burst duration | Range (2010–2022) |
| --- | --- | --- |
| close range photogrammetry | 2010–2015 | |
| calibration | 2011–2014 | |
| algorithm | 2012–2013 | |
| construction | 2014–2018 | |
| seismic assessment | 2015–2017 | |
| damage assessment | 2015–2017 | |
| terrestrial laser scanning | 2015–2016 | |
| area | 2017–2018 | |
| laser | 2018–2019 | |
| information | 2019–2020 | |
| built heritage | 2019–2020 | |
| hbim | 2020–2022 | |
| preventive conservation | 2020–2022 | |
| virtual reality | 2020–2022 | |
| seismic vulnerability | 2020–2022 | |

**Table 10 Citation surge literature.**

| Title | Strength | Burst duration | Range (2010–2022) |
| --- | --- | --- | --- |
| Developing a documentation system for desert palaces in Jordan using 3D laser scanning and digital photogrammetry | 2.35 | 2011–2014 | |
| Orientation and 3D modeling from markerless terrestrial images: combining accuracy with automation | 1.84 | 2012–2014 | |
| Modeling masonry arches shape using terrestrial laser scanning data and nonparametric methods | 1.82 | 2013–2015 | |
| Automated camera network design for 3D modeling of cultural heritage objects | 2.13 | 2014–2017 | |
| Monitoring of complex structure for structural control using terrestrial laser scanning (TLS) and photogrammetry | 1.94 | 2015–2018 | |
| Historic building information modeling—adding intelligence to laser and image-based surveys of European classical architecture | 4.18 | 2016–2018 | |
| Survey turned into HBIM: the restoration and the work involved concerning the Basilica di Collemaggio after the earthquake (L'Aquila) | 3.19 | 2016–2019 | |
| 3D survey and virtual reconstruction of archeological sites | 2.08 | 2016–2018 | |
| Building information modeling (BIM) for existing buildings— literature review and future needs | 4.02 | 2017–2019 | |
| Building information modeling for cultural heritage: a review | 2.45 | 2017–2018 | |
| From TLS to HBIM. High-quality semantically aware 3d modeling of complex architecture | 2.19 | 2017–2018 | |
| Cloud-to-BIM-to-FEM: structural simulation with accurate historic BIM from laser scans | 2.75 | 2018–2020 | |
| Structural simulations and conservation analysis—historic building information model (HBIM) | 2.91 | 2019–2020 | |
| A framework for using point cloud data of heritage buildings toward geometry modeling in a BIM context: a case study on Santa Maria La Real De Mave Church | 2.03 | 2019–2020 | |
| Implementation of scan-to-BIM and FEM for the documentation and analysis of heritage timber roof structures | 1.74 | 2019–2020 | |
| Knowledge-based data enrichment for HBIM: exploring high-quality models using the semantic-web | 2.97 | 2020–2022 | |
| HBIM modeling from the surface mesh and its extended capability of knowledge representation | 2.47 | 2020–2022 | |
| Implementation and management of structural deformations into historic building information models | 2.47 | 2020–2022 | |
| HBIM for conservation: a new proposal for information modeling | 1.97 | 2020–2022 | |
| As-built 3D heritage city modeling to support numerical structural analysis: application to the assessment of an archeological remain | 1.72 | 2020–2022 | |

(1) Through the analysis of 372 studies, it was found that from 2010 to 2016, there were few HBIM-related studies, which is indicative of the conception stage. After 2017, the research on HBIM showed a gradual upward trend and was in the stage of paradigm accumulation. In terms of geographical distribution, Italy is the country with the largest number of publications, accounting for 23.4% of the total number of published papers. Among journals, the "Journal of Cultural Heritage" published the most HBIM-related literature, with a total number of published papers reaching 41. Regarding the analysis of institutions, although Polytechnic University of Milan started late, its annual publication rate and total frequency are the highest.

(2) From the cocitation cluster diagram, it can be concluded that the research on HBIM is still in the stage of diffusion and growth. HBIM research is mainly distributed in the following fields: semiautomatic 3D modeling, heritage complexes, Magoksa temple stone pagoda, Italian medieval castles, laser

scanners, heritage information systems, pilot studies, virtual reality, national palaces, and fine surveying. These 10 fields form the knowledge base for HBIM.

(3) The high-frequency keyword analysis found that "culture heritage", "building", "model", "documentation", "point cloud" and "bim" are the core words of HBIM research, and these words are also the hotspots of current research. From the perspective of the temporal evolution of emergent words, the development of HBIM has gone through three major stages. During the period from 2010 to 2014, the research focus was on point cloud measurement and recognition of historical buildings combined with related algorithms, and the research on close-range photogrammetry was emphasized. From 2014 to 2018, the research focus shifted to the applications of HBIM to practical cases. Since 2018, based on recent studies, HBIM research has begun to turn to preventive protection, information processing and VR for historical buildings. It is foreseeable that the development trends in HBIM will eventually include artificial intelligence to achieve the next large leap.

(4) There were 14 clusters of HBIM keywords, reflecting the hotspots and frontiers of HBIM research. Combining these clusters, a systematic HBIM practical application workflow was proposed.

## Discussion

**HBIM application workflow**. Combined with the analysis of HBIM keyword clustering, HBIM can be divided into three levels in practical application, namely, model creation, data exchange, database construction, and auxiliary management. The specific levels and subordinate clusters are shown in Fig. 13. These layers constitute the workflow of a system, as shown in Fig. 14.

**Modeling**. The level of model creation contains four clusters, #6 3D modeling approach, #7 laser scanner, #12 wide-angle lenses, and #13 partial matching, with the keywords corresponding to each cluster as shown in Fig. 12.

In the modeling phase of historic buildings, manual modeling is a complex and tedious task, and the research group proposed an idea to define HBIM as the process of creating a model starting from measurement data (Quattrini et al., 2017). BIM models are a step forward in information storage and modeling efficiency over traditional geometric models, with the addition of parametric and semantic data. Surveying is a valuable tool, and terrestrial laser scanner (TLS) technology (Anil et al., 2013; Boardman et al., 2018) has been widely used in archeology (Al-kheder et al., 2009; Lerma et al., 2010), architectural modeling (Pritchard et al., 2017), urban analysis of historic towns, and assessments of cultural heritage (Brumana et al., 2013). Photogrammetry was initially used by a small group of experts until the concept of structure in motion (SFM) emerged, and photogrammetry became widely used in the field of cultural heritage (Francisco et al., 2018).

Currently, the combination of laser scanners and photogrammetry is the most advanced technology in historic building modeling, and the combination of the two can produce accurate 3D point clouds and holistic grids to document the geometry of the heritage structure (Yang et al., 2020). As technology continues to evolve, BIM software increasingly supports the import of point clouds into software to create 3D models. While aerial photogrammetry and light detection and ranging (LiDAR) can be used to generate digital surface models (DSMs) of historic buildings (Gimenez et al., 2015; Yang et al., 2015), it is difficult to meet the needs of historic building applications in terms of accuracy and detail.

The HBIM model that corresponds to those most commonly used in CityGML is LOD3 or LOD300 in IFC, which contains a model of the complete exterior of the building, with a complete wall and roof structure, doors, and windows (Yang et al., 2019).

Lin Li et al. (2017) modeled the main buildings of the Chinese National Palace Museum using a semantic modeling approach. To improve the display efficiency of the model and ensure visual realism, three levels of detail (LOD1, LOD2, and LOD3) were used in CityGML based on semantic decomposition. It should be noted that historic buildings have unique microstructures (sculptures, archways, etc.) (Yang et al., 2020). At present, many scholars have used the following methods to model the unique microstructure of historical building facades: inverse modeling (Musialski et al., 2013), RANSAC-based segmentation (Albano, 2019; Cao and Scaioni, 2021; Serna et al., 2016), the region growth method (Pu and Vosselman, 2009) and the semantic-based method (Becker and Haala, 2009).

In addition, for ancient Chinese wooden buildings, due to the complexity of the structure (e.g., cascading buckets), laser scanners and photogrammetry techniques cannot scan the invisible dimensions completely, leading Yonghui Jiang et al. (2020) to propose an intelligent modeling method for the wooden structure of ancient buildings, using Dynamo to identify component types based on measurement data and deriving invisible dimensions based only on measured visible dimensions. From this study, scholars were able to successfully build a complex Dougong in 5 min.

**Data exchange and database creation**. This level contains four clusters, namely, the #1 heritage complex, #2 architectural heritage, #3 detailed application (specific application), and #11 digital archive. The keywords are shown in Fig. 12.

HBIM contains specific geometric and semantic data, and one of the main problems it faces in practical applications is the interoperability of historical building data models, a point first made by Andreas Georgopoulos in 2013 (Georgopoulos et al., 2013) and echoed by Laurens Jozef in 2022 (Oostwegel et al., 2022). The specific data exchange scenario can be supported by first developing an information delivery manual (IDM) and later filtering a part of the IFC schema and creating a specialized model view definition (MVD). IFC is a standard for the building industry defined through the EXPRESS architecture, and the connection point between semantic web technologies and IFC standards will be represented by an IFC-compliant web ontology language (OWL) called IFCOWL, which allows the continued use of the refined IFC standards for representing building data (Pauwels and Terkaj, 2016).

The HBIM model should have nongeometric information, i.e., semantic knowledge related to the historical building ontology, such as architectural style, maintenance date, renovation time, and renovation style, in addition to the relevant geometric parameters. The organized storage and management of historic building data, simple analytical queries, and flexibility are important to the design of the model. Nazarena Bruno et al. designed a stand-alone database system for HBIM in 2019, which was intended to assist with historic building conservation in collaboration with institutions to meet their specific needs, such as coordination of disciplinary participants and ease of use. The system links the 3D model of the historic building to an external database through a unique identifier (ID) that explicitly identifies each object to the BIM model, which can be accessed both through a developed desktop application (as a plug-in to the BIM software) and through the web interface to ensure data sharing and ease of use for skilled and unskilled users.

**Fig. 13 Hierarchy of keyword clustering.** Hierarchy in keyword clustering obtained after analysis of HBIM literature.

It is important to mention that ontology-based information models and HBIM-based geometric models can be linked to some extent, extending the ability of HBIM to attach heterogeneous knowledge. Xiucheng Yang et al. (2019) proposed that instead of creating HBIM and ontology models separately, the corresponding entities in the two modeling environments can be linked by placing the same identifier. To date, scholars have proposed the IFC language for the ontology of RDF/PWL conversion procedures for BIM. Pauwels et al. (Yang et al. 2019) developed an IFC-to-RDF conversion tool in 2016 that can automatically map IFC extensible
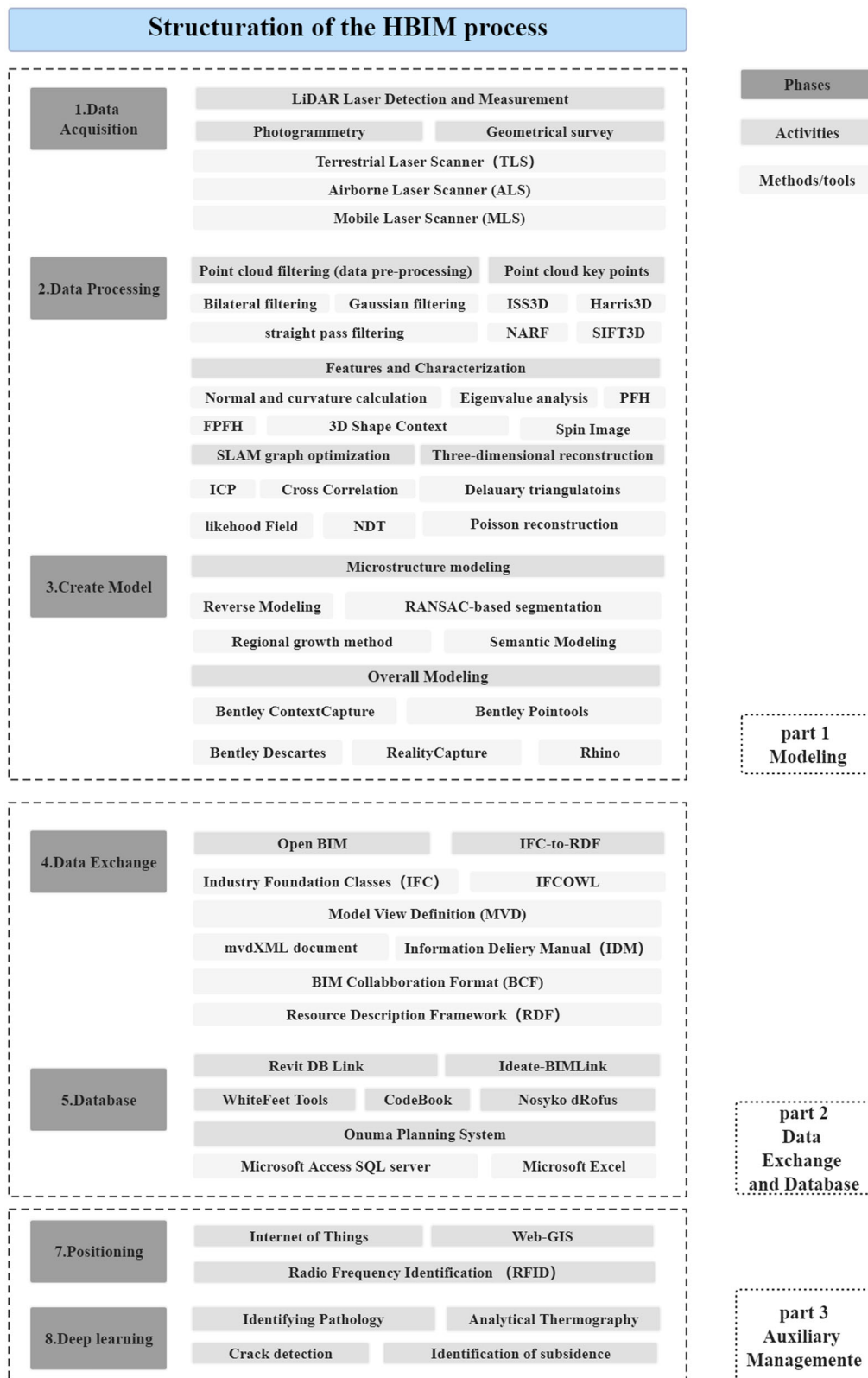
**Structuration of the HBIM process**

| | | |
|---|---|---|
| | Phases | |
| | Activities | |
| | Methods/tools | |

**1. Data Acquisition**
- LiDAR Laser Detection and Measurement
- Photogrammetry | Geometrical survey
- Terrestrial Laser Scanner (TLS)
- Airborne Laser Scanner (ALS)
- Mobile Laser Scanner (MLS)

**2. Data Processing**
- Point cloud filtering (data pre-processing) | Point cloud key points
- Bilateral filtering | Gaussian filtering | ISS3D | Harris3D
- straight pass filtering | NARF | SIFT3D
- Features and Characterization
- Normal and curvature calculation | Eigenvalue analysis | PFH
- FPFH | 3D Shape Context | Spin Image
- SLAM graph optimization | Three-dimensional reconstruction
- ICP | Cross Correlation | Delauary triangulatoins
- likehood Field | NDT | Poisson reconstruction

**3. Create Model**
- Microstructure modeling
- Reverse Modeling | RANSAC-based segmentation
- Regional growth method | Semantic Modeling
- Overall Modeling
- Bentley ContextCapture | Bentley Pointools
- Bentley Descartes | RealityCapture | Rhino

**part 1 Modeling**

**4. Data Exchange**
- Open BIM | IFC-to-RDF
- Industry Foundation Classes (IFC) | IFCOWL
- Model View Definition (MVD)
- mvdXML document | Information Deliery Manual (IDM)
- BIM Collabboration Format (BCF)
- Resource Description Framework (RDF)

**5. Database**
- Revit DB Link | Ideate-BIMLink
- WhiteFeet Tools | CodeBook | Nosyko dRofus
- Onuma Planning System
- Microsoft Access SQL server | Microsoft Excel

**part 2 Data Exchange and Database**

**7. Positioning**
- Internet of Things | Web-GIS
- Radio Frequency Identification (RFID)

**8. Deep learning**
- Identifying Pathology | Analytical Thermography
- Crack detection | Identification of subsidence

**part 3 Auxiliary Managemente**

**Fig. 14 Structuration of the HBIM process.** HBIM application routes are obtained in combination with practical applications.

attributes to RDF data based on the IFCOWL ontology. Once the HBIM model is created in the BIM environment, the geometric element-based model can be directly exported to the IFC format and converted to ontology RDF by using the IFC-to-RDF conversion tool. After conversion, general "classes" and individual entities are preserved by unique identifiers (IDs). Simeone et al. worked on developing semantically rich HBIM models that integrate HBIM and knowledge bases through ontology as a way to enhance knowledge representation and management (Acierno et al., 2017; Simeone et al., 2014, 2019).

**Auxiliary management**. As mentioned above, this level contains six clusters, namely, #0 case studies, #4 structural analysis, #5 masonry structure, #8 heritage building maintenance management, #9 energy performance, and #10 convective heat transfer. The keywords for each cluster are shown in Fig. 12.

Recently, a new approach to HBIM oriented toward diagnosis-aided management has been proposed (S. Bruno et al., 2018), namely, diagnosis-aided historic building information modeling and management (DA-HBIMM), where the connection of HBIM with RFID and IoT is specifically proposed. R. Volk et al. in 2014 (Volk et al., 2014) initially analyzed the integration of RFID and BIM applications, followed by Pavan Meadati et al. (Meadati et al., 2022) who investigated the use of RFID devices for facility management and operation of historic buildings in a pilot project. The inheritance of BIM and RFID technology allows for the automatic identification and selection of real-world components with corresponding 3D model elements. Y. Zhang and Bai (2015) proposed that the combination of BIM and RFID technology could enable contactless scanning of structures to detect the exceedance of a preset strain threshold corresponding to structural damage conditions such as yielding or buckling. This system can quickly identify the location where the preset strain threshold is exceeded and highlight the corresponding structural elements in the BIM to provide an alert signal to engineers and decision-makers. This research will help the application of HBIM in the future.

### Limitations

There are still deficiencies in this study. The source of data and the selection of samples may bring certain limitations to this study, which are mainly manifested in the following two points.

First, there are limitations to the data sources. The data source is the WoS core database, which contains the largest number of documents in the world, but libraries such as PubMed and Google Scholar also contain HBIM-related studies. Although they are not key nodes, they have a certain impact on the research results. At the same time, because CiteSpace software itself cannot acquire and merge mutual citations between different databases, it is difficult to integrate the retrieval records and citation records between different databases. This limitation can be alleviated with the continuous improvement of tools in the future.

Second, there were limitations in sample selection. The samples in the WoS database were selected by a subject-word search, but research in the HBIM field has only been conducted in the past ten years, and no complete and unified conceptual terms have been formed, as expressed in the diversity of language used with heritage buildings, historical buildings, and cultural buildings, all referring to the same concept. All subject terms refer to the HBIM subjects of the study but have a variety of descriptions. At the same time, the last step of sample processing is to manually screen out the literature that is irrelevant to the research field after manually browsing the title, abstract and full text. This technique is susceptible to distortions from differences in personal understanding of concepts, which will lead to the limitation of sample selection. This study is also not a complete and exhaustive consideration of all that has surfaced on this topic over a period of time. In the future, with the continuous development and maturity of this field, relevant concepts will be clarified and defined one by one, and the selection of HBIM samples will be more precise and detailed.

**Outlook**. Looking ahead, research in the field of HBIM still needs attention in the following three areas.

- Integration with artificial intelligence
- Popularization of wireless sensor networks
- Mobile applications

Heritage buildings have high cultural and historical values, and rapid surveys and damage assessments are crucial to their preservation; however, routine inspections and statistical measurements of historic buildings are currently conducted almost exclusively by sight, and each inspection takes considerable time and effort. The combination with artificial intelligence (Hatir et al., 2020; Mansuri and Patel, 2021; Mishra, 2021) can promote the intelligent development of routine inspection of historical buildings. Using drone scanning and deep learning of convolutional neural networks, the material loss and component loss of historical buildings can be quickly detected (Zou et al., 2019), including weathering (Hatir et al., 2020) and structural damage (Gao and Mosalam, 2018; Masrour et al., 2020; Wang et al., 2020, 2019; Xiaowei et al., 2019), which saves considerable time and improves efficiency.

The mobile application can be combined with mobile crowd sensing (MCS) technology, which is suitable for rapid survey and damage assessment of large historical buildings (Marra and Fabbrocino, 2021; Wang et al., 2019). For example, at the ancient Great Wall of China, due to its large scope and many visitors, a complete inspection would take as long as 6 months. Smartphone mobile devices can be used to sense, collect, upload and analyze data on a large scale to establish a database of historical buildings. Visitors can simply take photos and upload them to the app, and by extracting GPS data combined with deep learning, the app can quickly identify and locate the damaged parts of large historical buildings.

At the same time, combined with the Internet of Things and wireless sensor networks such as RFID technology (Krommyda et al., 2022; Mitro et al., 2022), remote data detection of historical buildings is improving, especially the more serious loss of the building a whole or critical part. Real-time detection of the historical building itself, using cues from illumination level, surrounding humidity, and temperature, can be used as early warning system and reveal abnormal analysis or security management. In the future, when drones, artificial intelligence, and wireless sensor networks are connected, regular data transmission to the network can be achieved without human intervention, and the deep learning of artificial intelligence combined with wireless sensor networks can analyze the loss of historical buildings.

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## Competing interests

The authors declare no competing interests.

## Ethical approval

No human participants were studied for this article.

## Informed consent

No human participants were studied for this article.

## Additional information