Heritage Science

REVIEW

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Bibliometric analysis and visualisation of heritage buildings preservation

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Abstract

Heritage buildings are considered a source of pride for countries, and their preservation is an important pursuit. Different techniques have been adopted in this regard, and many review papers have addressed them either qualitatively or quantitatively through bibliometric analysis. Nevertheless, none of these review studies conducted a general dynamic quantitative analysis of the vast amount of scientific literature about heritage buildings preservation (HBP) research domain over time. Therefore, the current study performs a bibliometric analysis of the relevant literature considering a time of two decades (2002–2022). A total of 863 peer-reviewed journal articles were extracted from the Web of Science Core Collection database. A five-step methodology was followed employing VOSviewer, CiteSpace, and Biblioshiny as the bibliometric software tools. The main findings revealed the annual publication trends and the most prominent articles. It was also found that 60% of the literature publications were published in journals, and only 2.4% corresponded to review studies. The scientific collaboration networks showed the most prolific researchers and countries. Further, the citation analysis of journals identified the most reliable information sources for academic researchers. Finally, the conceptual and intellectual knowledge structures were visualised and studied via science mapping analysis to map the research domain evolution and determine its trending patterns and promising areas for future exploration. The conducted review provides fellow researchers with a systematic summarised database to be familiarized with the HBP literature and identify potential research opportunities to conduct state-of-the-art research with the top contributors in the field (researchers, journals, and countries). In addition, policymakers can utilize the results from this research to find expert authors and academic support to facilitate forming partnerships to plan and fund relevant research and address the practical implications of preserving valuable heritage buildings.

Keywords Heritage buildings, Historic buildings, Preservation, Conservation, Bibliometric analysis, Visualisation, Science mapping

Introduction

Cultural heritage buildings are considered valued, unique, limited, and irreplaceable resources for a country's wealth and historic stance [1]. The United Nation Educational, Scientific, and Cultural Organization (UNESCO) categorizes cultural heritage as tangible and intangible. The latter refers to traditions and rituals expressing local identities [2]. The former consists of movable (e.g., paintings, furniture, etc.), immovable (e.g., monuments and architectural works, etc.), and underwater (e.g., shipwrecks and underwater cities, etc.) [2]. The immovable architectural works are sub-categorized into historic and historical buildings [3]. Historic buildings are characterized by having historic significance, being more than 50–70 years of age, and having an influential role in history (such as castles and churches). On the other hand, historical buildings are traditional constructions with no distinct artistic significance (such as vernacular buildings or historical towns). The terms "historic buildings" and "heritage buildings" are often used interchangeably in the

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literature [4]. Thus, for the sake of consistency, the term "heritage buildings" will be used throughout the present study when referring to these valuable buildings.

Cultural heritage requires timely interventions to prevent losses [1]. One of the targets of the 11th goal of the United Nations [5] Sustainable Development Goals (SDGs), stated in the 2030 Agenda for Sustainable Development, is to "strengthen efforts to protect and safeguard the world's cultural and natural heritage." This is not an easy undertaking, given the multiple stakeholders involved and the multiple values associated with these buildings during the decision-making process. There are tangible values of architecture and aesthetics and intangible values like cultural and social [6]. This protection is referred to as "preservation" as a USA English Term, and "conservation/preservation" interchangeably in British English [7]. In fact, Antonopoulou and Bryan [4] defines conservation as "the process of maintaining and managing change to a heritage asset in a way that sustains and where appropriate enhances its significance". In the interests of coherence, the term "preservation" will be used in the current research study. Heritage Buildings Preservation (HBP) involves many aspects related to construction materials, asset management, structural health monitoring, deterioration and damage detection, energy, thermal performance, and environmental impacts. Different techniques and technologies have been employed in the literature to deal with these aspects, such as multi-criteria decision-making [1], non-destructive testing [2], Heritage-Building Information Modelling (HBIM) and laser scanning [8, 9], machine learning [10], energy retrofitting [11], and thermography [12].

Accordingly, many researchers have conducted state-of-the-art review studies on HBP with significant contributions, especially with respect to their average citations per year. For instance, Mishra [10] performed a literature review about the use of Machine Learning for assessing the health condition of heritage buildings as well as its different applications, such as possible damage scenarios or predicting the compressive strength of materials. It was concluded that machine learning could be useful for valuable heritage buildings where core sampling is prohibited to ensure timely retrofitting techniques. Further, Paschoalin and Isaacs [13] reviewed existing guidelines, methods, and criteria for the holistic renovation of historic buildings, involving multiple parties with conflicting needs. This holistic multi-criteria decision-making approach covers all aspects of the problem to reach the best balance between all competing criteria, including conserving heritage significance, achieving energy savings, ensuring indoor thermal comfort, reducing carbon footprint, and minimising environmental impact and required costs. Lopez [8] provided a comprehensive literature review about using H-BIM with other methodologies (such as GIS and point clouds) to accommodate the complex modeling of heritage buildings and their elements. Hence, parametric libraries of the modeled architectural components can be constructed, where such components can be adapted to other landmarks belonging to the same period or architectural style. Moreover, Lidelöw et al. [14] provided review of how energy efficiency measures and heritage conservation are being approached in the literature. They also concluded that previous studies advocate non-invasive measures to respect the building's unique cultural values. Nevertheless, these studies have adopted a qualitative approach subject to biases, judgments, and/or cognitive perceptions in interpreting findings and results. They also lack a general dynamic quantitative analysis of the HBP research domain over a while. On that account, there is a need for an objective quantitative method for reviewing the literature of HBP.

As a result of the exponentially growing volume of scientific documents being published in different research areas, special techniques are indispensable to enable the comprehensive understanding of such areas by identifying major scientific contributors, reliable sources, research patterns, new trends, and promising topics for future exploration [15]. Bibliometrics is a set of quantitative methods used to explore a research domain through the article metadata provided in bibliographic databases (e.g., Scopus, Web of Science Core Collection) [15]. This metadata includes a publication's title, keywords, abstract, and citation records. Two main bibliometric procedures are used for the exploration of research domains: performance analysis and science mapping. Performance analysis provides the means to quantify academic output and assess it for productivity, quality, and scientific impact by identifying major contributors (authors, countries, organizations) and finding reliable sources of academic publication [16]. Science mapping aims at detecting the conceptual and intellectual structures of a research field, recognizing its potentially insightful patterns, and visualizing significant changes over time in a large body of literature [17]. Bibliometrics has been previously used in several scientific disciplines, such as lean supply chain management [16] and construction safety management technologies [18].

Bibliometrics has been successfully used in the field of HBP. Nadkarni and Puthuvayi [1] presented a bibliometric literature analysis of 42 papers discussing the use of Multi-Criteria Decision Making methods (MCDM) for complex decision-making problems facing heritage conservation, such as selecting renovation projects, assessing building conditions, contractor selection, budget allocation, etc. They identified the research publication trend, application categories of studies, and the various MCDM methods used for determining criteria weights, ranking, and validation. Further, Tejedor et al. [2] performed a comprehensive bibliometric review of the use of quantitative and qualitative non-destructive testing and advanced modeling technologies to assess the condition of heritage buildings in Europe over the period (2001–2021) as well as their future trends in retrofit and adaptive reuse of heritage buildings. The analysis showed interoperability issues between BIM tools and NDT tools such as digital cameras, infrared cameras, and laser scanning. Nevertheless, there is a need for a general bibliometric study which addresses the research field of preserving heritage buildings to lay the academic foundation to support the exploration and development of scientific knowledge on HBP.

The objective of this research study is to conduct a quantitative and comprehensive review of the Heritage Buildings Preservation (HBP) field, which is achieved by carrying out the following activities:

- Identify annual publication trends and influential articles.
- Study the geographic distribution of the literature.
- Identify distinguished authors and eminent journals in the research domain.
- Determine the research hot spots, the evolution of its topics, and trending patterns.

The present study essentially attempts to answer the following research question: How can academic researchers and policymakers benefit from bibliometric techniques and science mapping analysis to conduct novel research and practical applications in the research domain of "Heritage Buildings Preservation"?

Aiming to address the identified limitations in the body of knowledge, this study conducts a general comprehensive review of the HBP field to provide a detailed insight into the various preservation approaches, according to the steps defined in Fig. 1. This review would provide fellow academic researchers and policymakers with a quantitative understanding of the research domain evolution, its trending patterns, and promising areas for future exploration. The remainder of this paper is organized as follows: "Analysis and results" section describes the research methodology steps, results of the bibliometric analysis for publication trends, influential articles, geographic distribution, top authors and journals, and conceptual and intellectual knowledge structures. "Research findings and contributions" section discusses the interpretation of these findings, the challenges facing the persistent issues of heritage buildings, and the research study contributions. "Conclusions" section presents a summary of the paper and its limitations.

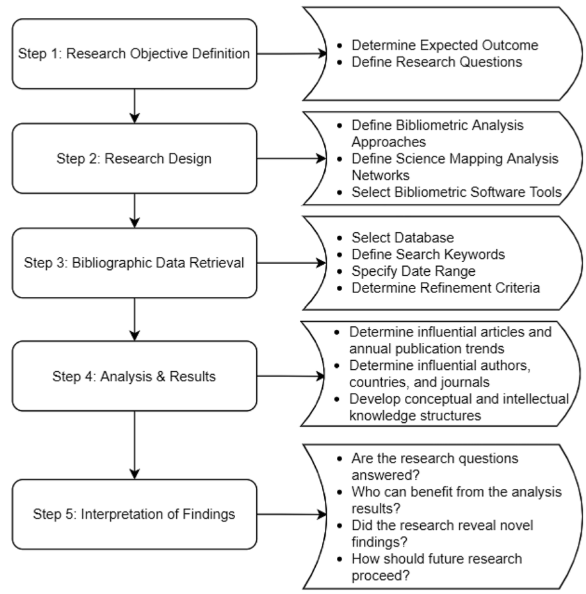

Fig. 1 Proposed research methodology

Research design

The research design step defines the approaches and software tools of bibliometric analysis. In line with the research objective and sub-objectives, the bibliometric approaches employed in this research are co-authorship, co-occurrence, citation, and co-citation analyses as well as aggregation and ranking, which are conducted to evaluate the academic output.

- Co-authorship is a quantitative analysis that examines authors and countries, their affiliations, and their collaboration patterns to establish a research field social structure according to co-authored publications [19]. This social structure is visualised in "Collaboration Networks".
- Co-occurrence is a quantitative analysis that uses the number of times a term will appear in more than one article in the database to construct the conceptual knowledge structure of a research domain and highlight its key areas [19]. This conceptual structure is visualised in "Conceptual Networks".
- Citation analysis is a quantitative analysis that uses citation counts to assess the similarity between publications, authors, organizations, or sources [19].

Co-citation analysis is a quantitative analysis that uses the number of publications in which references, authors, or sources are co-cited together to evaluate their interconnection relationships and establish the research field's intellectual knowledge structure [20, 21]. This intellectual structure is visualised in "Intellectual Networks." Two articles are said to be co-cited if both are cited in a third article [19].

Several software tools exist with varying degrees of strengths, weaknesses, and availability. In the current study, VOSviewer, Biblioshiny, and CiteSpace were utilized and are all freely available. VOSviewer was selected for its ease of use and ability to handle large-scale data and produce clear bibliometric visualisation networks [22, 23]. Its co-authorship, co-occurrence, and citation analysis functions are used to map scientific collaboration, map publications' keywords, and identify top sources, respectively. Biblioshiny is a web-interface that uses the functions of the Bibliometrix R-tool introduced by Aria and Cuccurullo [19]. It maps the thematic evolution and trending topics of the HBP research field. CiteSpace was selected for performing references co-citation analysis because it not only provides clustering of publications according to their co-cited references but also gives each cluster a label describing its nature. Hence, references co-citation analysis is its strongest feature [20]. Table 1 demonstrates the inputs, outputs, and tools involved in each type of analysis.

Bibliographic data retrieval

In the present study, the Web of Science Core Collection database (comprehensive search engine with a rich range of metadata about every document) was preferred to Scopus as it enables the user to select the area of research journals "Construction & Building Technology" Additionally, Scopus considers departments as separate organizations & only takes the authors' full last names (first & middle names as initials). Also, the reference items are not standardized in Scopus. The search was conducted in December 2022 with the following criteria:

- Category: "Construction & Building Technology" to exclude any irrelevant databases.
- Keywords: "heritage building*" OR "historic building*" OR "cultural building*" OR "built heritage" OR "heritage site*" (The authors did their best to include all possible variations of heritage buildings).
- Date range: 2002–2022.

This initially retrieved 1521 documents [60% Articles (907) and only 2.4% Review (36)], reflecting the need for more review papers. The search results were refined by document type (peer-reviewed journal articles). This retrieved 863 documents after excluding papers irrelevant to preservation by reviewing titles, abstracts, and keywords. Finally, the extracted bibliographic database was revised to ensure that there is no duplication of publications.

Analysis and results

The results of the conducted analysis can be categorized into performance analysis results and science mapping results. Performance analysis results include annual publication trends, most cited articles, geographic distribution analysis, authors collaboration analysis, and journals citation analysis. Science mapping results are concerned with thematic evolution mapping, conceptual and intellectual knowledge structures, co-occurrence, clusters, trend topic analyses.

Performance analysis results

Annual publication trends

Figure 2 shows the number of yearly publications about heritage building preservation during 2002–2021. The number of publications slowly increased between 2002 and 2013. Then, it witnessed a drastic increase at a much faster pace, from 2013 to 2021. This growth encourages researchers to further explore the preservation of heritage buildings as a promising and prevalent research domain.

Most cited articles

In order to pinpoint the highly studied areas in a certain scientific research field, it is important to determine the

Table 1 Adopted tools and outputs for the bibliometric analysis

Analysis	Input	Tool	Output
Aggregation and ranking	Bibliographic data	Microsoft Excel	Annual publication trends & influential articles
Co-authorship	Countries, authors	VOSviewer	Scientific collaboration networks
Citation	Journals	VOSviewer	Productivity, influence & scientific value
Co-citation	References	CiteSpace	Intellectual knowledge structures
Co-occurrence/thematic evolution/trend topics	Keywords	Biblioshiny	Conceptual knowledge structures

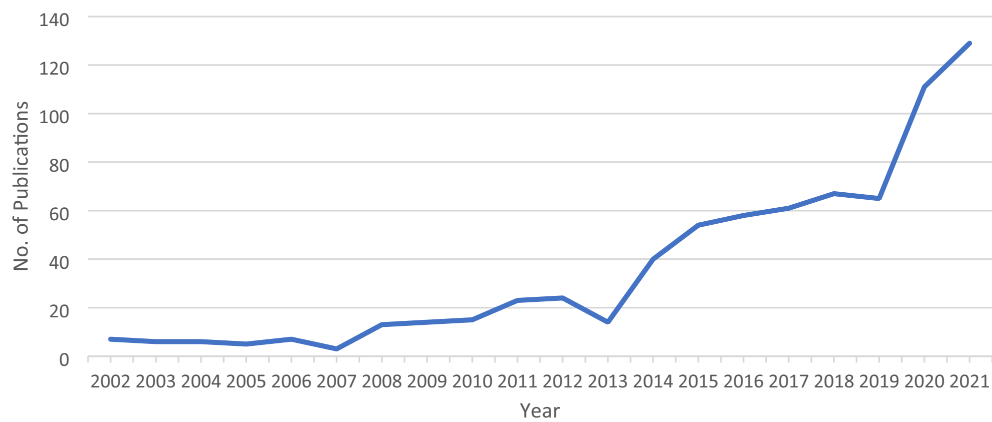

Fig. 2 Number of publications per year

most influential/cited articles [24]. Hence, heritage buildings publications are evaluated for Citation Score (CS), Local Citation Score (LC), and Average Citations per Year (ACY). Citation Score is used to measure the overall influence of the publications, whereas Local Citation Score assesses the influence of the publications within the extracted bibliographic database. The Average Citations per Year is used to determine the effect of the publishing year, as the previous indicators (CS and LC) usually take time to accumulate. Table 2 lists the top 20 publications concerning Citation Score. It is found that these studies were published between 2002 and 2017. Additionally, 7 and 11 out of these publications are among the top locally cited and the publications with the highest average citations per year, respectively. Further, the three most locally cited articles are [25–27] and the three concerning average citations per year are [3, 28, 29]. These articles are mainly concerned with the following topics: energy retrofit [3, 25, 37], construction materials [31, 35, 36, 40], seismic behavior [32, 33, 38], adaptive reuse [34], and climate change [39].

Geographic distribution analysis

Examining the scientific collaboration patterns between countries helps interested researchers understand the geographic distribution of publications in a certain research field, identify the prominent countries, and locate potential research funding opportunities. Countries were identified by having at least five publications and ten citations to be included in the analysis. Out of

Table 2 Most cited articles ranked according to citation score

Article	Title	CS	LC	ACY
Kohler et al. [30]	The building stock as a research object	189	3	9.00
De Rossi et al. [25]	Energy retrofit of historical buildings: theoretical and experimental investigations for the modeling of reliable performance scenarios	138	33	11.50
Mazzarella [3]	Energy retrofit of historic and existing buildings. The legislative and regulatory point of view	129	18	16.13
Cardell et al. [31]	Salt-induced decay in calcareous stone monuments and buildings in a marine environment in SW France	116	5	5.80
Betti and Vignoli [32]	Numerical assessment of the static and seismic behavior of the basilica of Santa Maria all'Impruneta (Italy)	108	9	9.00
Saisi et al. [33]	Post-earthquake continuous dynamic monitoring of the Gabbia Tower in Mantua, Italy	108	9	13.50
Mısırlısoy and Günçe [34]	Adaptive reuse strategies for heritage buildings: a holistic approach	106	16	15.14
Walker and Pavía [35]	Thermal and hygric properties of insulation materials suitable for historic fabrics	105	9	13.13
Cruz et al. [36]	Guidelines for on-site assessment of historic timber structures	105	9	13.13
Ascione et al. [37]	Energy retrofit of an educational building in the ancient center of Benevento	102	20	12.75
Clementi et al. [38]	Assessment of seismic behavior of heritage masonry buildings using numerical modeling	92	6	13.14
Huijbregts et al. [39]	A proposed method to assess the damage risk of future climate change to museum objects in historic buildings	91	13	8.27
Zagorskas et al. [40]	Thermal insulation alternatives of historic brick buildings in the Baltic Sea Region	90	17	10.00

CS citation score, *LC* local citation score, *ACY* average citations per year

76 countries, 43 were selected based on these threshold values.

Using VOSviewer, the countries' collaboration network was developed and shown in Fig. 3, with 43 nodes and 182 links. Each node represents a country, and the node size reflects the number of published documents (the more documents, the bigger the nodes). In contrast, the coloring scheme demonstrates their average citation per document. On the other hand, the links between them reflect the collaboration relationships between countries, and their thicknesses represent the strength of these countries' collaboration in common publications. It is worth noting that the map is fully interconnected.

The identified 43 countries are ranked based on Productivity (No. of Publications), Centrality (Collaboration Links), Influence (Citation Score), Scientific Value (Average Citation per document), and Activeness (Average Publication per Year), and in Table 3. The strength of collaboration and the strongest collaborations are illustrated in Table 4. These top 5 of the 182 links observed in the authors' collaboration network resulted in more than seven documents.

Authors collaboration analysis

Exploring scientific collaboration networks between researchers is important to identify the field pioneers and their co-operation patterns [41]. This is helpful for new researchers to find opportunities for future

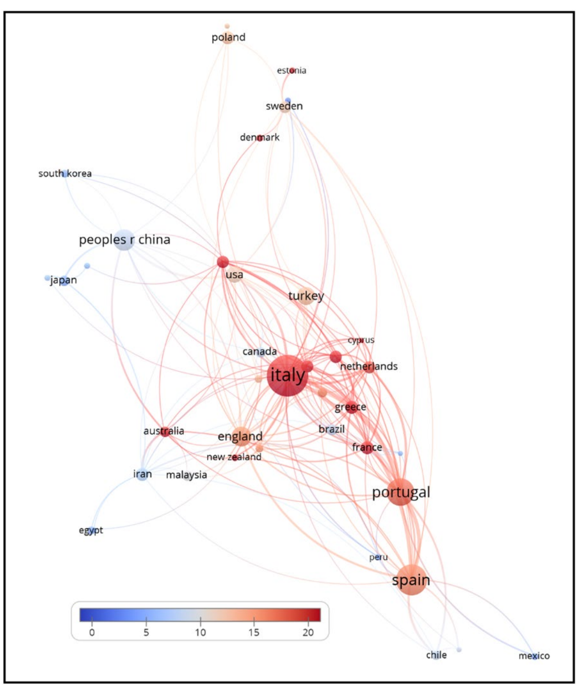

Fig. 3 Countries collaboration network

Table 3 Top contributing countries in heritage buildings preservation

Country	NP	CL	CS	ACD	APY
Italy	311	26	6101	19.62	2016.70
Spain	171	17	2760	16.14	2017.19
Portugal	139	22	2462	17.71	2016.83
Peoples R China	89	13	771	8.66	2019.23
England	70	21	1067	15.24	2016.43
Turkey	62	8	801	12.92	2015.59
USA	52	18	606	11.65	2017.18
Poland	33	5	422	12.79	2018.41
France	32	15	625	19.53	2016.03
Greece	30	15	858	28.60	2012.97
Iran	30	14	219	7.30	2016.85
Netherlands	29	13	541	18.66	2016.66
Germany	26	17	677	26.04	2013.48
Belgium	26	14	644	24.77	2015.38
Czech Republic	26	13	573	22.04	2013.44
Sweden	26	13	306	11.77	2017.12
Brazil	25	10	209	8.36	2018.68
Australia	20	10	401	20.05	2015.58
Canada	20	9	166	8.30	2019.05
Japan	20	4	92	4.60	2016.11
Malaysia	19	4	187	9.84	2017.33
Switzerland	18	9	289	16.06	2017.44
Chile	17	5	148	8.71	2019.19
Scotland	13	9	201	15.46	2014.54
South Korea	12	4	59	4.92	2017.83
Egypt	12	2	51	4.25	2020.09
Norway	11	9	145	13.18	2015.22
New Zealand	10	5	197	19.70	2017.70
Denmark	9	2	234	26.00	2016.67
Mexico	9	2	35	3.89	2017.78
Estonia	8	1	174	21.75	2016.00
Hungary	8	2	54	6.75	2019.25
Taiwan	8	2	47	5.88	2015.13
Peru	7	5	28	4.00	2018.50
Austria	7	3	16	2.29	2016.86
Ireland	6	0	200	33.33	2009.67
Croatia	6	1	74	12.33	2018.67
Colombia	6	3	54	9.00	2018.50
India	6	0	40	6.67	2019.67
Romania	6	4	33	5.50	2018.17
Cyprus	5	10	98	19.60	2015.80
Serbia	5	2	56	11.20	2016.80
Iraq	5	3	25	5.00	2020.00

NP number of publications, *CL* collaboration links, *CS* citation score, *ACD* average citations per document, *APY* average publication per year

Table 4 Highest countries collaborations

Country 1	Country 2	No. of common publications
Italy	Portugal	18
Portugal	Spain	17
Italy	Spain	14
Italy	USA	8
China	USA	8

collaborations with well-established professionals that can provide them with expertise and funds [42]. In the total 863 publications, a total of 3461 authors were identified. Those having at least three publications and ten citations are included in the analysis resulting in 141 Authors. VOSviewer software package was used to analyse authors of the heritage buildings research field using the co-authorship functionality. Figure 4 shows the co-authorship network map of the authors, where each node represents an author. In contrast, the links between them reflect the collaboration relationships between researchers, and their thicknesses represent the strength of these researchers' collaboration in terms of common publications. The node size variation reflects the authors' number of publications, while the coloring scheme demonstrates their average citation per document. Such maps facilitate knowing where collaborations occur without inquiring about authors' background information. Additionally, authors nodes that are placed away from the clusters can be due to conducting unique research different from others or having fewer collaborations with other authors on the map. It can be concluded that the authors' map is not as homogeneous and interconnected as the countries' network in the previous section. Researchers in the heritage buildings research field are ranked based on Productivity (No. of Publications), Scientific Value (Average Citation per document), Activeness (Average Publication per Year), Centrality (Collaboration Links), and Influence (Citation Score) in Table 5.

Based on the network in Fig. 4 and Table 5, it is shown that the most productive authors form small scientific groups, leading to multiple disconnected clusters of researchers. This could be the case of a professor and his/her group of graduate students. Regarding productivity and centrality, Paulo B. Lourenco is the top author with 17 publications and 11 collaboration links. His research interests are related to seismic retrofitting [43], seismic analysis of masonry structures [44], and information management systems [45]. The strength of collaboration and the strongest collaborations are illustrated in Table 6. Approximately 3.3% of the 148 links observed in the

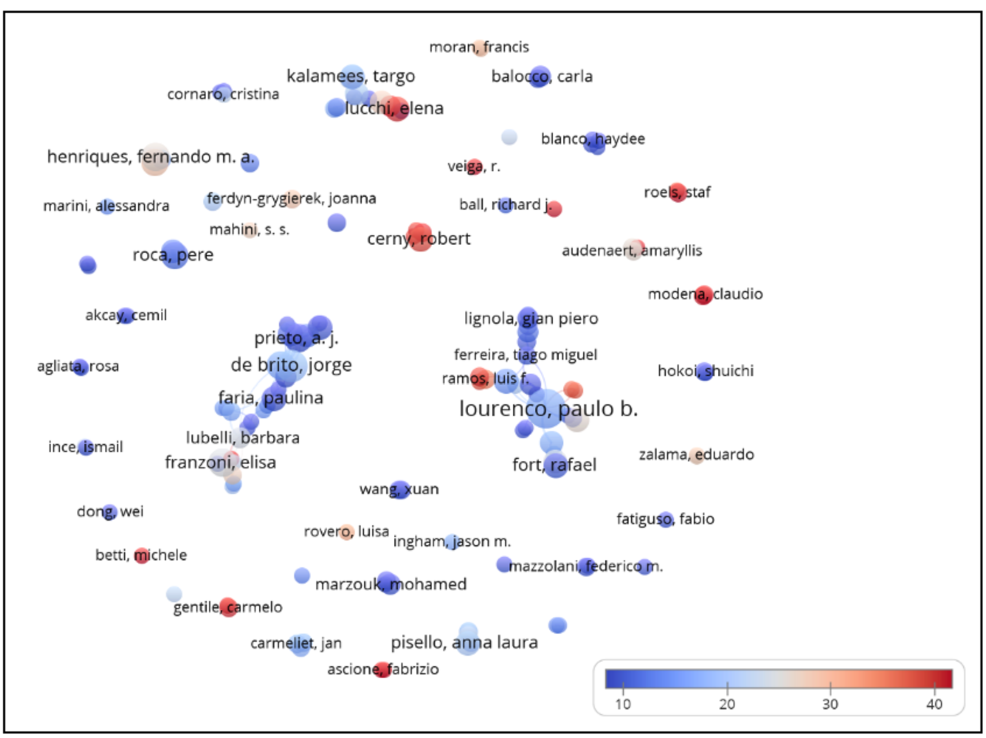

Fig. 4 Co-authorship network map

Table 5 Authors collaboration network indicators

Author	Affiliation	NP	ACD	APY	CL	CS
Most productive authors						
Paulo B. Lourenco	University of Minho, Portugal	18	16.24	2016.64	11	276
Jorge De Brito	Instituto Superior Técnico, Portugal	11	18.91	2015.91	6	208
Fernando M. A. Henriques	Universidade Nova de Lisboa, Portugal	9	25.56	2017.89	2	230
Elisa Franzoni	University of Bologna, Italy	9	24.67	2015.44	5	222
Antonio Santos Silva	National Laboratory for Civil Engineering, Portugal	9	16.33	2018.33	8	147
Authors with the highest scientific value						
Fabrizio Ascione	Università degli Studi di Napoli Federico II, Italy	3	98.33	2013.6	1	295
Giuseppe Peter Vanoli	Università degli Studi del Molise, Italy	3	98.33	2013.66	1	295
R. Veiga	Tecpetrol, Argentina	3	54	2012.33	0	162
Kristian Fabbri	University of Bologna, Italy	3	49.33	2014.33	2	148
Staf Roels	KU Leuven, Belgium	4	49	2013.5	1	196
Most active authors						
Ismail Ince	Konya Teknik University, Turkey	3	4.00	2021.33	1	12
Yan Ma	National Institute of Biological Sciences, China	3	4.00	2021.33	1	12
David Bienvenido-Huertas	Universidad de Sevilla, Spain	3	7.33	2021.00	1	22
Maria Teresa Freire	National Laboratory for Civil Engineering Research and Innovation, Portugal	3	5.33	2021.00	4	16
Germana Barone	Università di Catania, Italy	3	5.33	2021.00	1	16
Authors with the highest centrality						
Paulo B. Lourenco	University of Minho, Portugal	17	16.23	2016.64	11	276
Antonio Santos Silva	National Laboratory for Civil Engineering, Portugal	9	16.33	2018.33	8	147
Barbara Lubelli	Delft University of Technology, Netherlands	5	24.2	2014.8	8	121
A. J. Prieto	Pontificia Universidad Católica de Chile	9	9.77	2019.5	7	88
Daniel V. Oliveira	University of Minho, Portugal	7	14.85	2018.85	7	104
Authors with the highest influence						
Fabrizio Ascione	Università degli Studi di Napoli Federico II, Italy	3	98.33	2013.67	1	295
Giuseppe Peter Vanoli	Università degli Studi del Molise, Italy	3	98.33	2013.67	1	295
Paulo B. Lourenco	University of Minho, Portugal	17	16.24	2016.64	11	276
Elena Lucchi	Politecnico di Milano, Italy	7	38.57	2017.86	3	270
Robert Cerny	Czech Technical University, Prague	7	37.71	2011.29	3	264

NP number of publications, *ACD* average citations per document, *APY* average publication per year, *CL* collaboration links, *CS* citation score

Table 6 Highest authors collaborations

Author 1	Author 2	No. of common documents
Fernando m. a. Henriques	Hugo Entradas Silva	8
F. J. Alejandre	A. J. Prieto	5
Jorge de Brito	Antonio Santos Silva	5
J. M. Macias-Bernal	A. J. Prieto	5
Luca Pela	Pere Roca	5

authors collaboration network resulted in more than four documents.

For scientific value and influence, Fabrizio Ascione, and Giuseppe Peter Vanoli both had the highest average citations per year and total citations of 98.3 and 295, respectively. They co-authored four publications about the cost-effective refurbishment of Italian heritage buildings [37, 46, 47] as well as applying multi-criteria approaches and experimental and numerical studies for energy refurbishment of historic buildings [25].

Journals citation analysis

Distinguishing the pioneer peer-reviewed journals of a research field is beneficial for interested readers to find reliable information sources, as well as academic researchers to facilitate the publication process of their research studies and maximize their benefit from peer review. The total number of journals that published articles about heritage buildings during 2002–2022 is 77 journals. Journals were identified by having at least three publications and ten citations to be included in the analysis. This resulted in 41 journals shown in the network generated by VOSviewer in Fig. 5. Each node represents a journal. The node size reflects the number of publications, and the node size illustrates each journal's average citations per document. Table 7 lists the top journals ranked based on Productivity (No. of Publications), Centrality (Collaboration Links), Global Citation Score to measure the overall influence of the publications, and Local Citation Score to assess the influence of the publications within the extracted bibliographic database. The growth of publications count over the years in the five most productive journals is presented in Fig. 6. The Scientific Value (Average Citation per document) and the top 5 articles are listed in Table 8. It is worth noting that only two of the most productive journals have the highest average citations per document: "Building and Environment" and "Energy and Buildings."

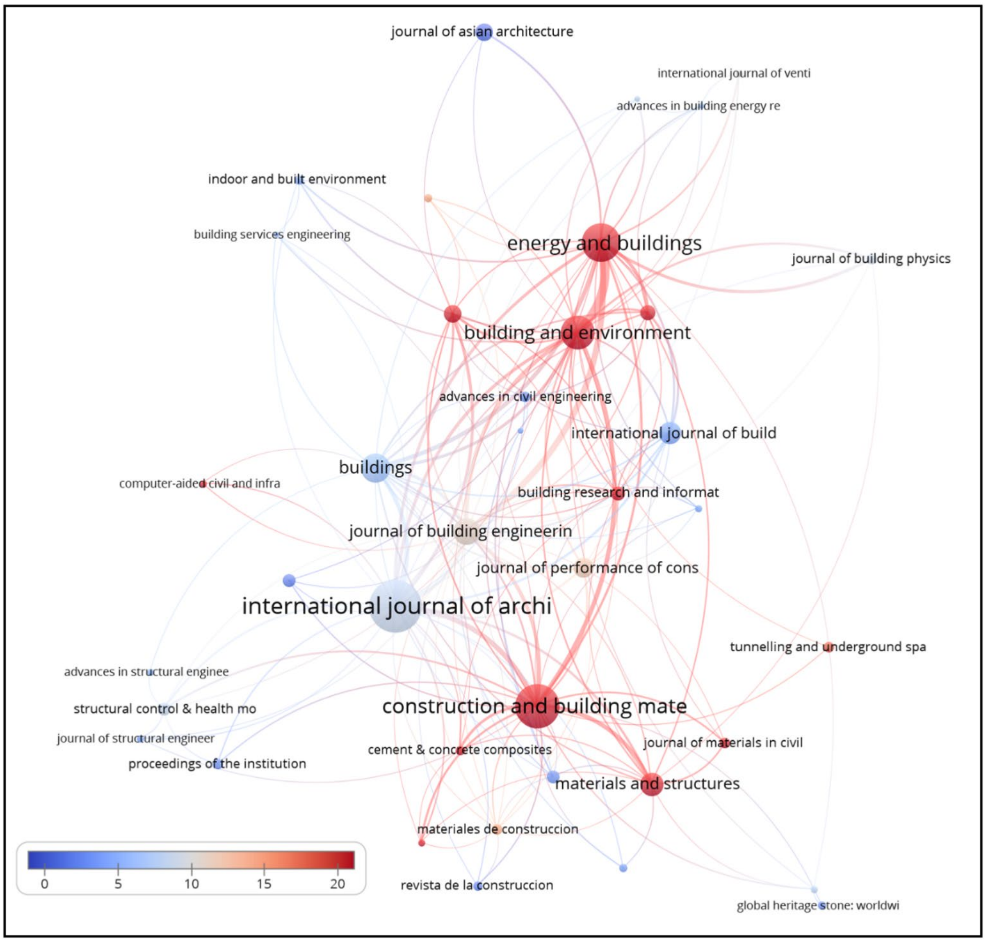

Fig. 5 Journals citation visualisation network

Table 7 Top contributing journals in HBP

Journal	NP	% of publications	CL	CS	LC
International Journal of Architectural Heritage	187	15.66	27	1941	658
Construction and Building Materials	162	13.57	26	3718	1756
Energy and Buildings	117	9.80	23	3179	1654
Building and Environment	95	7.96	25	2764	1280
Buildings	71	5.95	20	456	42
Journal of Building Engineering	61	5.11	27	651	211
Materials and Structures	45	3.77	15	901	434

NP number of publications, *CL* collaboration links, *CS* global citation score, *LC* local citation score

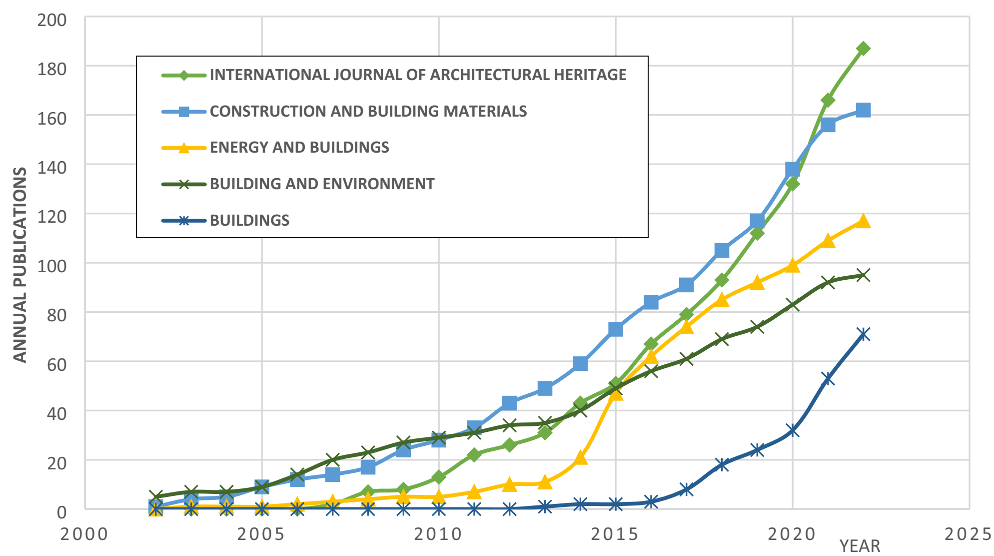

Fig. 6 Annual publications of the most productive journals

Table 8 Journals with the highest scientific value

Journal	Average citation per document
Cement and Concrete Research	87.00
Cement and Concrete Composites	33.25
Building and Environment	29.09
Energy and Buildings	27.17
Building Research and Information	24.25

Table 9 Top keywords in heritage buildings preservation

Keyword	No. of occurrences	Collaboration links
Heritage buildings	443	128
Construction materials	244	91
Heritage preservation	166	89
Masonry	84	47
Seismic analysis	76	39
Indoor thermal comfort	57	39
Energy efficiency	50	37
Energy retrofit	40	35
Moisture	31	22
Structural health monitoring	28	23
HBIM (heritage/historic BIM)	23	22
Damage	22	20
Deterioration	21	19
Adaptive reuse	19	18
Finite element analysis	19	16
Sustainability	19	21
Experimental tests	19	15
Monitoring	19	26
Thermal properties	18	22
Climate	18	17

Science mapping results

Conceptual knowledge structure analysis

Analyzing author-chosen keywords in scientific publications enables interested researchers to establish the key topics in a research domain [41]. In the present study, author keywords were analysed based on their co-occurrence, identified clusters, trending patterns, and thematic evolution over the 20-year study period.

Co-occurrence analysis

The total number of author keywords in published articles about heritage buildings from 2002 to 2022 is 3637. Keywords were identified by occurring at least three times to be included in the analysis. Then, a thesaurus file was created to merge similar terms and avoid duplication of keywords (for example, merge "Heritage BIM", "Historic BIM" and "HBIM", merge "historic buildings and heritage building" with "heritage buildings", and merge "conservation" with "preservation"). This process reduced the number of keywords to 153 keywords. Table 9 lists the most occurring keywords and their associated centrality measures (Collaboration Links CL) in the extracted bibliographic data regarding the research domain of Heritage Buildings Preservation during 2002–2022.

Cluster analysis

Using VOSviewer co-occurrence analysis, the author keywords are arranged in 8 clusters in the network visualization map in Fig. 7. This conducted cluster analysis of keywords in research articles can help categorize research trends, study their evolution over time, and uncover the interconnection between them. Each node represents a keyword, and the node size is determined by the number of occurrences of its associated keyword. In addition, each node is assigned a color that corresponds to its cluster. Clusters are formed of keywords that appear together in similar research or sometimes in the same discipline in the case of multidisciplinary research. Such a map facilitates understanding the research landscape and identifying terms used in the research of heritage buildings. In this case, there are eight different clusters listed in Table 10. It is worth noting that there is a lot of overlap between the clusters, as the network visualisation map shows. Hence, the total percentage of publications doesn't necessarily add up to 100% since some publications may be related to Clusters 1, 6, and 8 simultaneously, for example.

Table 10 Identified keywords clusters

Cluster ID	Cluster label	% of publications
1	Seismic analysis	27.3
2	Indoor thermal comfort	18.26
3	Sustainability & energy consumption	10.00
4	Moisture & insulation	12.48
5	Vernacular architecture	7.87
6	Construction materials	27.55
7	HBIM & photogrammetry	7.37
8	Structural health monitoring	5.28

Trend topic analysis

Burst words imply that an item has drawn a lot of attention in the corresponding year since they show a considerable increase in the frequency of the keyword over a short period [48]. Figure 8 represents a visual display of the burst keywords of the total author keywords. The start and the end of the line marks the start and end of the topic publication in the extracted database, whereas the circle stands for the year at which the topics peaked in the database.

Several observations can be deduced from Fig. 8. Topics related to Masonry and Monitoring (Cluster 1), Deterioration and Moisture (Cluster 4), and Porosity (Cluster 6) tend to be well-studied and outdated concerning current publications. Additionally, publications related to Sustainability (Cluster 3) and Structural Health Monitoring (Cluster 8) received strong attention around 2018

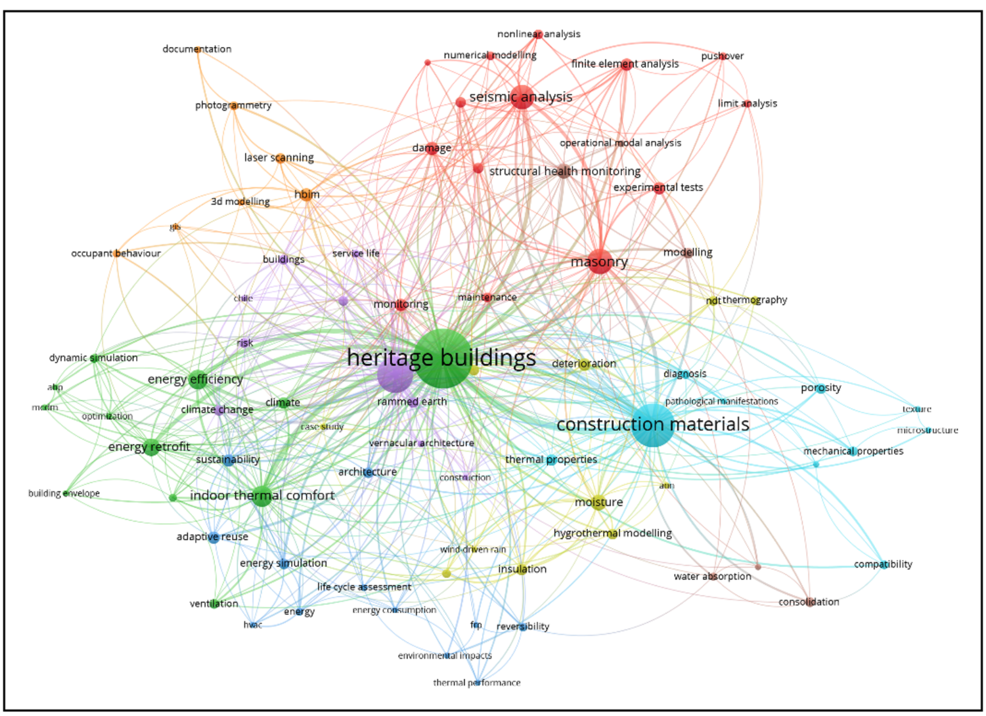

Fig. 7 Co-occurrence visualisation network

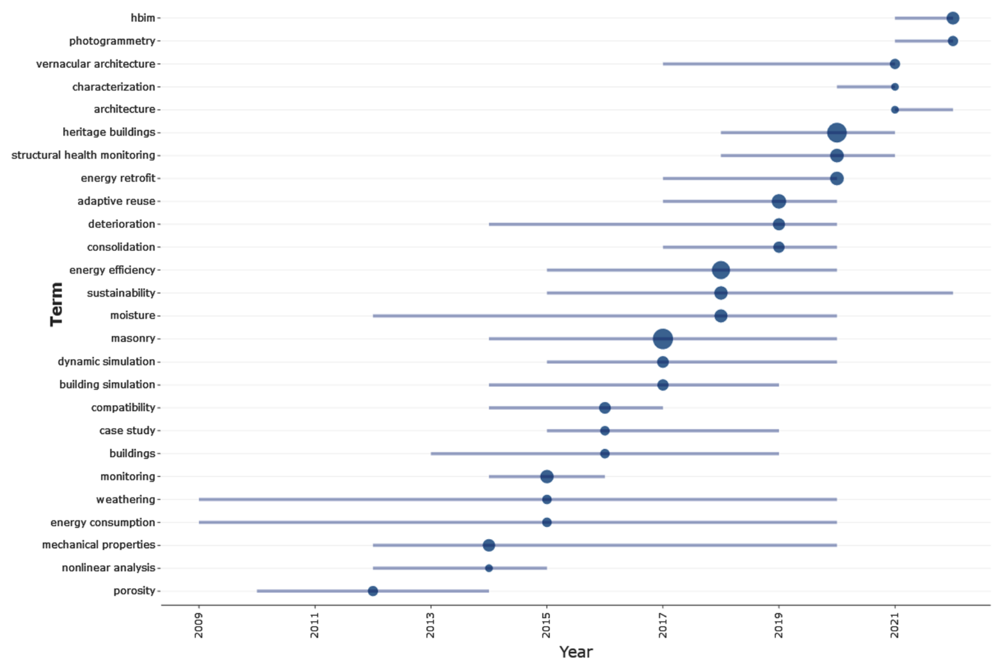

Fig. 8 Burst keywords

and 2020, respectively. They are also still addressed in publications up until 2022. Finally, Vernacular architecture (Cluster 5), HBIM, Photogrammetry (Cluster 7), and Energy Retrofit (Cluster 2) are considered the most popular recent topics, which are still peaking in 2021 and 2022. Thus, they are considered among the most promising topics in heritage buildings preservation due to their tendencies to use local materials and optimize designs for energy savings.

Thematic evolution map

As per the annual publication trends of the extracted bibliographic data, it was observed that nearly half of the publications were produced in the last 4 years (2019–2022). Thus, to examine the temporal evolution of research studies concerned with preserving heritage buildings, it was decided to divide the data into two-time slices (2002–2018) and (2019–2022) using Biblioshiny. The keywords of publications in each time slice are categorized into themes/thematic areas and given labels based on the most frequent keyword in each area, whereas the size of the label refers to the total frequencies of all keywords. These labels are 2D represented using two axes denoting "centrality" and "density" in the so-called "strategic diagrams." Centrality refers to the relevant value of a theme in a given research domain, while density refers to how developed and categorized a theme [16]:

- Motor Themes in the upper right quadrant: These are well-developed research areas.
- Basic and Transversal Themes in the lower right quadrant: These are considered relevant to a research field, despite not being fully developed.
- Niche Themes in the upper left quadrant are highly developed and isolated themes of marginal importance.
- Emerging or Declining Themes in the lower left quadrant: These themes are either starting to develop or are declining and becoming irrelevant to a research field.

Figures 9 and 10 show the two strategic diagrams developed for 2002–2018 and 2019–2022, respectively. It can be concluded that motor themes have evolved from "thermal performance" and "energy consumption" during 2002–2018 to more developed topics, including "energy efficiency," "construction materials," "HBIM," "energy consumption," "reversibility," and "adaptive reuse" during 2019–2022.

Motor themes during 2019–2022 can be considered the most promising research domains worthy of further exploration. These include:

- Energy Consumption refers to climate change, life cycle assessment, vulnerability assessment, digital management, fuzzy logic, and Analytical Hierarchy Process (AHP) [39, 100].

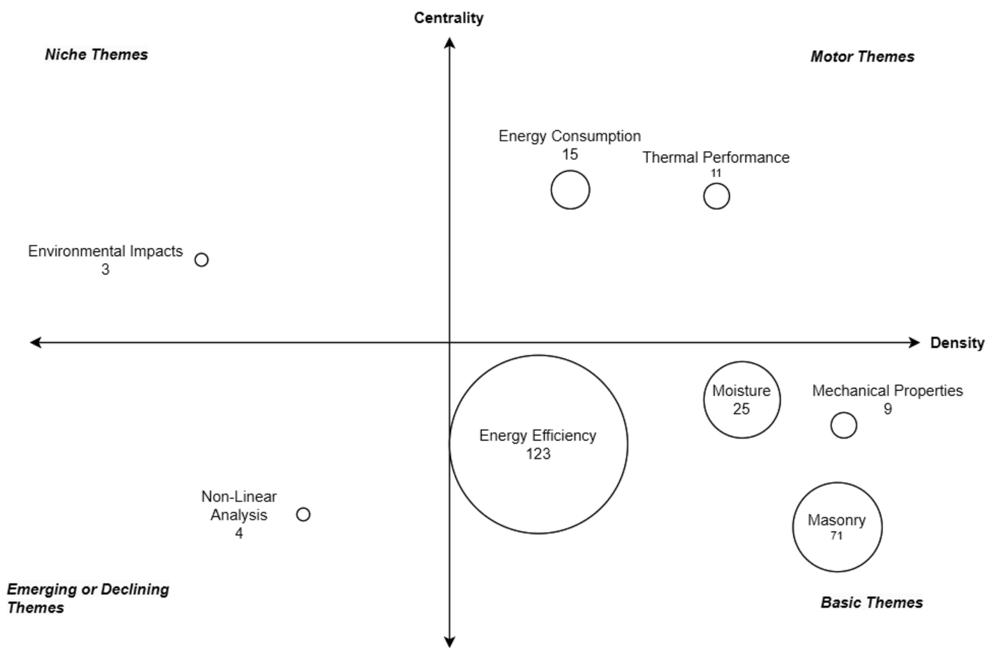

Fig. 9 Strategic diagram from 2002 to 2018

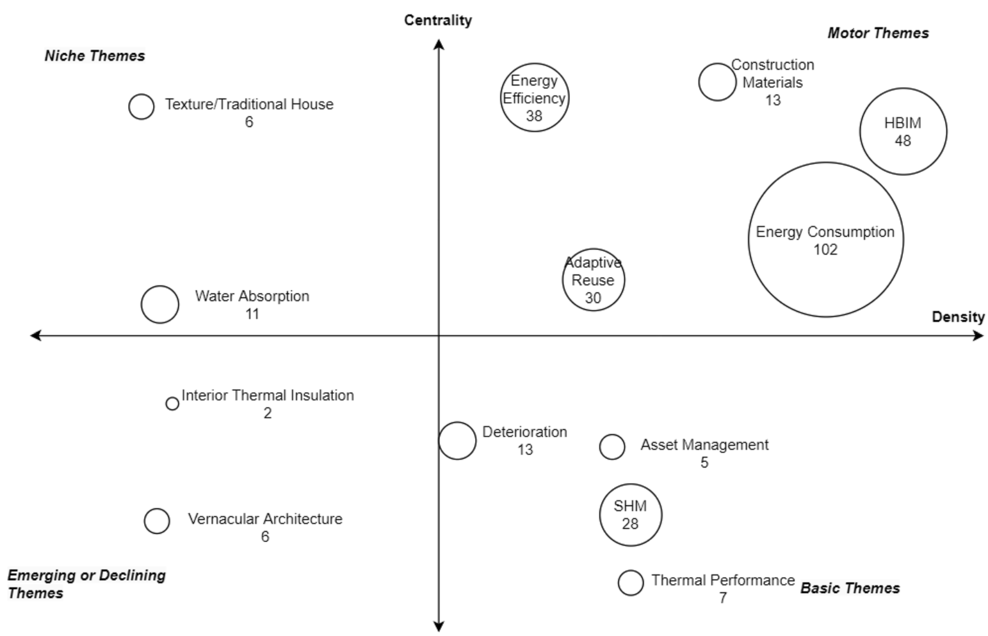

Fig. 10 Strategic diagram from 2019 to 2022

- HBIM refers to laser scanning, point cloud, 3D modeling, photogrammetry, infrared thermography, and machine learning [8–10].
- Energy Efficiency refers to energy retrofit, occupant behavior, and residential heritage [11, 14, 25].
- Adaptive Reuse refers to authenticity, cultural significance, heritage values, and heritage preservation [34].

- Construction Materials, which refers to Ground Penetration Radar (GPR), materials, and tomography [35, 36, 72].

These deductions coincide with the findings of the clusters and trend topics analyses.

Intellectual analysis

Studying and clustering the co-cited references of the bibliographic data of any research domain enables the formation of its intellectual structure and highlighting its key topics and methods [21]. Table 11 shows the identified: clusters' labels (research directions identified by text mining the titles of the citing documents as per [20], sizes (number of cited references in each cluster), silhouette values (a measure of the clustering quality between −1 and 1; the higher the value, the better the clustering quality as per Adabre et al. [49], an average year, year range for the cited references in each cluster, and top cited references. It is worth noting that the research directions conform with the results of keyword co-occurrence and thematic evolution analyses. Figure 11 shows the references co-citation network generated by CiteSpace containing 525 nodes and 5,708 links. The nodes represent the cited references, the lines (links) between nodes represent the co-citation relations, and the nodes' colors refer to the 12 identified cluster labels. Figure 12 shows the temporal evolution of the identified clusters. The nodes colors are yellow, light green, dark green, blue and purple which represent the publication years 2022, 2021, 2020, 2019, 2018, respectively. The nodes depths demonstrate the frequency of co-citations of articles in the different clusters. This evolution shows that Clusters 0–5 are more active than the remaining clusters, with many more co-citation links among the references. Clusters 6–11 are emerging trends that require further exploration.

Another important reference analysis method is the citation burst analysis, which highlights an active research area [20]. A citation burst detected by Kleinberg's algorithm [84], can last for only 1 year or multiple years. This burst means that a publication has received exceptional attention from the research community, embodied in a surge of citations [20]. In addition, many nodes with high citation bursts indicate that this cluster/research area/topic/issue is an active or emerging research trend [20]. Table 12 shows the Top 14 References with the Strongest Citation Bursts, the beginning and end of the citation burst period, the citation burst duration, and the clusters associated with each reference. It is worth noting that Cluster 0 (Thermal Comfort), Cluster 4 (Internal Insulation), and Cluster 5 (Seismic Retrofit) have 43%, 29%, and 21.5% of the strongest references, which means that these research areas are active with intense development.

Research findings and contributions

Findings

Instead of using subjective qualitative methods, the current study was able to quantitatively study the "Heritage Buildings Preservation" research domain, and the key

Table 11 References clusters

Cluster ID	Cluster label	Size	Silhouette	Average year	Year range	Top cited references
0	Thermal comfort	73	0.882	2015	2010–2020	Varas-Muriel et al. [50]; Silva and Henriques [51]; Muñoz-González et al. [52]
1	BIM	71	0.926	2003	2013–2022	Khodeir et al. [53]; Bruno et al. [54]; De Berardinis et al. [55]
2	Energy efficiency	63	0.826	2015	2010–2019	Ascione et al. [37]; Şahin et al. [56]; Tadeu et al. [57]
3	Operational modal analysis (structural health monitoring)	41	0.95	2015	2011–2019	Asteris et al. [58]; Masciotta et al. [59]; Clementi et al. [38]
4	Internal insulation	37	0.871	2015	2011–2021	Finken et al. [60]; Vereecken and Roels [61]; Harrestrup and Svendsen [62]
5	Seismic retrofit	36	0.938	2014	2010–2019	Lagomarsino and Cattari [63]; Brandonisio et al. [64]; Moreira et al. [65]
6	Vulnerability	31	0.934	2018	2014–2021	Ortiz and Ortiz [66]; Reimann et al. [67]; Prieto et al. [68]
7	Microstructure	23	0.988	2014	2012–2017	Gulotta et al. [69]; Pacheco-Torgal et al. [70]; Dewanckele et al. [71]
8	Chile (fuzzy logic, digital management, functional service life)	21	0.978	2017	2011–2021	Prieto et al. [72]; Sánchez-Aparicio et al. [73]; Prieto et al. [74]
9	Adaptive reuse	18	0.978	2016	2012–2021	Mısırlısoy and Günçe [34]; Vardopoulos [75]; Conejos [76]; Langston et al. [77]
10	Historic heritage	14	0.989	2019	2017–2022	Hadzima-Nyarko et al. [78]; Işık et al. [79]; Illampas et al. [80]
11	Daylight performance	11	0.994	2016	2012–2019	Salata et al. [81]; De Luca et al. [82]; Kaya et al. [83]

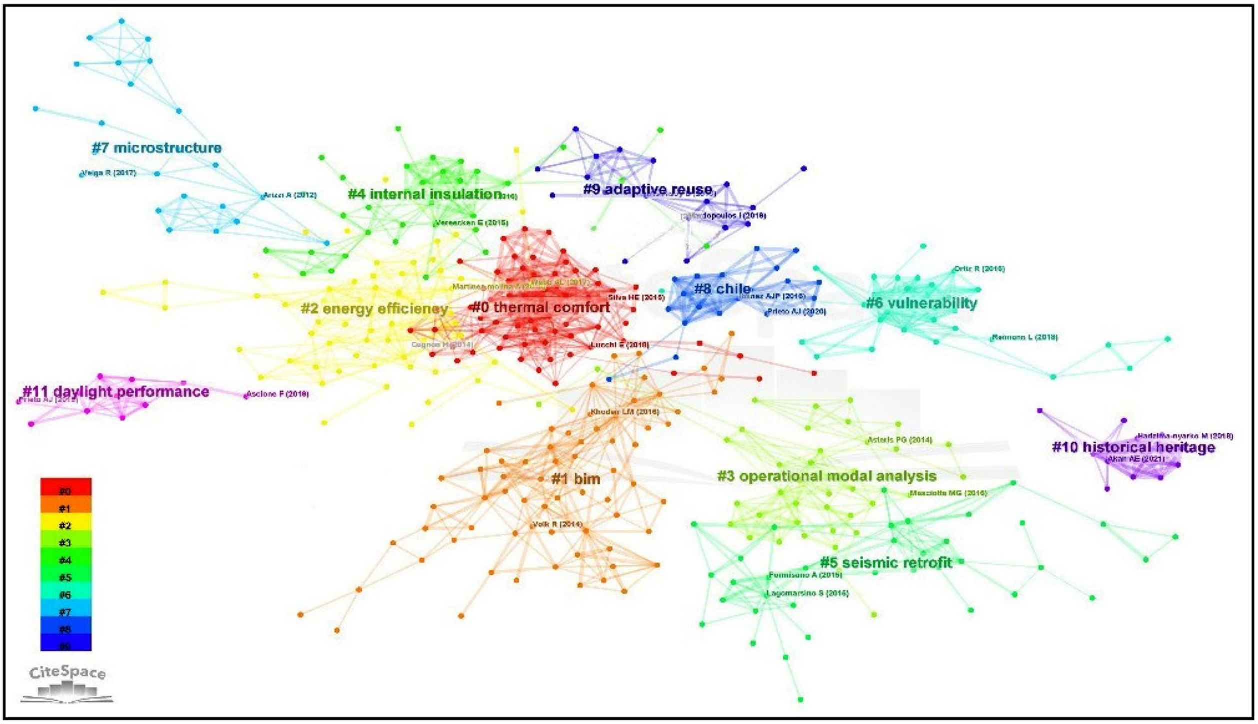

Fig. 11 References co-citation network

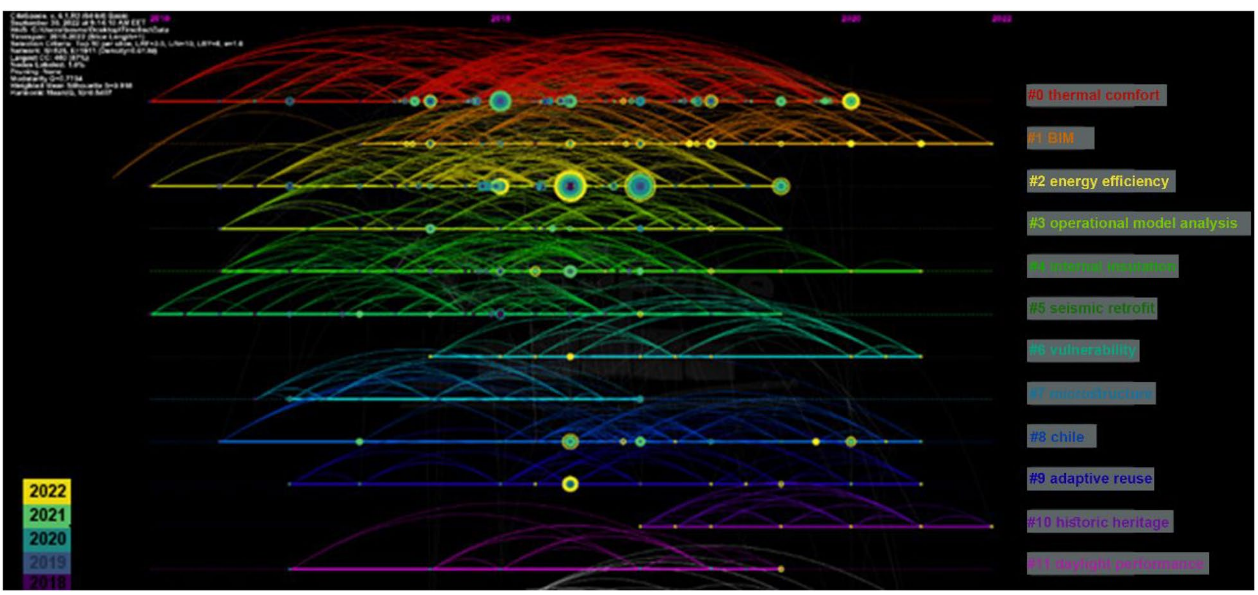

Fig. 12 Temporal evolution of clusters

findings can be summarized as follows regarding performance analysis and science mapping analysis:

First, the annual publication trends and citations uncovered some interesting observations. Annual publications drastically increased from 29 in 2013 to 178 by the end of 2021. This may be attributed to the rapid advancement and wide-spread use of different techniques, including machine learning, non-destructive testing, simulation, photogrammetry, thermography, etc. Regarding the document type distribution, only

Table 12 Top 14 references with the strongest citation bursts

References	Beginning	End	Burst duration (years)	Cluster label	%
Litti et al. [85]	2018	2019	2	Thermal comfort	43
D'agostino et al. [86]	2018	2019	2	Thermal comfort	
Sciurpi et al. [87]	2018	2019	2	Thermal comfort	
Kramer et al. [88]	2019	2020	2	Thermal comfort	
Muñoz-González et al. [89]	2020	2022	3	Thermal comfort	
Coelho et al. [90]	2020	2022	3	Thermal comfort	
Bullen and Love [91]	2018	2019	2	Energy efficiency	7
Klõšeiko et al. [92]	2018	2019	2	Internal insulation	29
Ibrahim et al. [93]	2018	2019	2	Internal insulation	
Vereecken et al. [94]	2018	2019	2	Internal insulation	
Zhao et al. [95]	2018	2019	2	Internal insulation	
Formisano et al. [96]	2018	2019	2	Seismic retrofit	22
Lagomarsino et al. [97]	2018	2019	2	Seismic retrofit	
Maio et al. [98]	2018	2019	2	Seismic retrofit	

2.4% of the scientific production were review papers, and 60% were peer-reviewed journal papers. Further, the articles with the highest average citation per year were concerned with damage detection using mobile deep learning [28], energy retrofit [3], and seismic risk analysis of unreinforced masonry buildings [29].

Second, the geographic distribution of the extracted bibliographic data showed that European countries (Italy, Spain, Portugal, and England) are superior to the remaining countries, with 691 publications (almost 58% of the gathered database). They also outperform other countries in collaboration links (86 of 182 links = 47%) and citation score. This comes as no surprise since the European cultural heritage accounts for 30% of the total world stock [2]. China is the fourth largest country concerning publications (89 documents, 7.5% of the database). This can be attributed to the presence of many historic sites and buildings worthy of preservation in these countries. Moreover, Ireland, Greece, and Germany have the highest average citations per document of 33.33, 28.6, and 26.04, respectively, indicating the strong impact of their publications on the scientific community. The average publication year for Egypt, India, and China is 2020, 2019.67, and 2019.23 because of their rich history and presence of many cultural heritage landmarks, as well as the increased interest in preserving this heritage using the newly introduced technologies, especially in Egypt and India. The results show that North and South African regions (apart from Egypt) have no representation in this domain. Therefore, there is an opportunity to conduct contextual HBP research in those and other underrepresented regions.

Third, the co-authorship analysis of authors demonstrated that only 4% (141/3,461) of total authors had at least three publications and ten citations. Paulo B. Lourenço is the top author with 17 publications and 11 collaboration links, whereas Fabrizio Ascione, and Giuseppe Peter Vanoli both had the highest average citations per document (98.33) and total citations (295).

Fourth, the citation analysis of journals showed that the most prominent journal in this research domain is "International Journal of Architectural Heritage," followed by "Construction and Building Materials." They also published 75 and 45 articles in the last 3 years (2020–2022). Follow-up research can be conducted by gathering research articles about heritage buildings from these top journals. Additionally, "Construction and Building Materials" and "Energy and Buildings" together have more than 6850 global citations and 3400 local citations, highlighting their publications' influence, especially in the heritage buildings preservation research domain.

Fifth, science mapping analysis was conducted using the authors keywords extracted from the gathered bibliographic data to analyze the literature output. The co-occurrence analysis using VOSviewer showed that the top-occurring keywords apart from the search keywords were construction materials, masonry, seismic analysis, indoor thermal comfort, energy efficiency, energy retrofit, moisture, structural health monitoring, HBIM, and damage. Additionally, the cluster analysis showed that the identified clusters could be categorized as those pertaining to the physical structure of buildings (Clusters 1, 5, 6 & 8), which also represent the majority of publications (almost 60%) as well as those related to BIM, thermal comfort, energy, and sustainability (Clusters # 2, 3, 4 & 7), which tend to be understudied and represent promising research areas for further exploration. Moreover, the trend topic analysis and thematic evolution illustrated that topics related to vernacular architecture, HBIM, photogrammetry, energy retrofit, energy consumption, and construction materials are considered the most popular recent topics, which are still peaking in 2021 and 2022. Thus, they are considered among the most promising topics in HBP. Further, the topics of the most cited articles coincide with the well-developed motor themes concluded from the thematic evolution map analysis in the extracted database (energy retrofit, construction materials, and adaptive reuse). This could be attributed to the emergence of new techniques which facilitate the preservation of heritage buildings such as Ground Penetrating Radar, Machine Learning, etc.

Sixth, the co-citation analysis indicated that thermal Comfort, internal insulation, and seismic retrofit research topics have 43%, 29%, and 21.5% of the strongest references, which means that these research areas are active with intense development. The top references with the strongest citation bursts for thermal comfort included Muñoz-González et al. [89] and Coelho et al. [90], and the citation burst lasted for 3 years (2020–2022). Further, the references with the strongest citation bursts for internal insulation and seismic retrofit included Klõšeiko et al. [92] and Formisano et al. [96], respectively.

Based on the findings above from the implemented bibliometric analysis, it can be inferred that the most persistent high-demand issues in the research domain of HBP are those related to "Energy Retrofit," "Energy Efficiency," "Indoor Thermal Comfort," "HBIM," and "Seismic Analysis." Therefore, there ought to be different partnerships between academia and policymakers to benefit from available techniques and technologies such as laser scanning, thermal imaging, photogrammetry, nondestructive testing, etc., to address the issues of energy and structural integrity of the valuable cultural heritage buildings all over the world.

It is worth noting that protecting cultural heritage with respect to energy and structural integrity poses some challenges. On the one hand, heritage buildings constitute almost 10–40% of the world's building stock. They will continue to exist because of their significant value, making them suited for achieving large energy reductions [99]. This is especially helpful since the rate of developing new buildings to substitute existing buildings is only 1–3% worldwide, and devoting resources to constructing new zero-energy buildings is not the solution to the current climate change crisis [100]. On the other hand, conducting energy retrofits in heritage buildings should consider their non-homogeneous construction materials, unique construction, lack of as-built documentation, and their older inefficient HVAC systems [11]. In addition, maintaining the structural integrity of heritage buildings also faces some difficulties. For instance, establishing a comprehensive database for predicting the compressive strength of masonry requires cumbersome data-gathering efforts to apply to buildings located in different parts of the world [10]. Moreover, using outdated construction techniques can complicate numerical modeling [10]. Finally, any conducted changes to upgrade heritage buildings shouldn't impact the conservation of their cultural values.

Contributions

The conducted bibliometric analysis in the present study represents an exploratory endeavor to conceptualise and quantitatively analyse the various aspects of the "Heritage Buildings Preservation" research domain. To the best of the authors' knowledge, such comprehensive quantitative analysis has not been conducted in this research area. Its unique contribution to the body of knowledge also stems from including more research papers than previous review papers in the literature providing a rather wider view of the subject from a holistic viewpoint. Further, the gathered findings offer different members of the scientific research community and concerned policy makers a valuable opportunity to understand this research field comprehensively and quantitatively. The study establishes an understanding of the HBP foundation, how it has evolved throughout 2002–2022 for publications volume and research topics, and the promising areas that are likely to be at the front of future research areas. Hence, new researchers can greatly benefit from such analysis to identify hot topics, authors to form collaborations with, countries that provide adequate funding, and best-fit journals for their work. Moreover, university research groups can determine and focus on emerging research topics to support their research policies. In addition, policymakers can utilize the results from this research to find expert authors and academic support to facilitate forming partnerships to plan and fund relevant research and address the practical implications of preserving valuable heritage buildings.

Conclusions

The current study has quantitatively examined the research conducted about heritage buildings preservation (HBP) over the period 2002–2022. The research methodology comprised five steps: (1) defining the research objective and question, (2) research design, (3) bibliographic data retrieval that resulted in 863 peer-reviewed journal articles from the Web of Science Core Collection database, (4) bibliometric analysis, and

(5) interpretation of findings. It was found that almost half of the articles were published between 2019 and 2022, which confirms that HBP is a promising and prevalent research domain. The bibliometric analysis consisted of co-authorship, citation, co-occurrence, and co-citation analyses. The findings included identifying annual publication trends, influential articles, the geographic distribution of the literature, important authors and journals, research hot spots, and the thematic evolution of the research domain. Such analysis is a comprehensive substitute for subjective literature review for academic researchers, as it enables making literature-related discoveries that wouldn't be possible using other methods. Further, it provides policy makers the opportunity to advance the HBP research field and its practical applications, especially with respect to sustainability and structural integrity and their associated challenges in preserving heritage buildings. The bibliometric analysis results indicate that the most pressing topics to tackle regarding the preservation of heritage buildings are those related to structural integrity and energy and their associated challenges in the cultural heritage preservation context.

The present research study has some limitations. The results are limited to using a single database (Web of Science Core Collection), and the bibliometric analysis in the present study was based on the publications' abstracts, keywords, and titles instead of detailed content analysis. Therefore, the scope of this paper can be expanded by performing a core content analysis of bibliographic data from more than one database. Also, the subjectively determined search criteria (search keywords, date range, document type, and language) may have impacted the analysis results. Different criteria may bring about a different perspective of the research domain.

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Author contributions
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Declarations

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Consent for publication
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