buildings

MDPI

Article

HBIM and Digital Twin in Architectural Heritage: A Bibliometric Analysis and Future Research Directions

Yang Wang *, Jorge Luis García Valldecabres and Pablo Ariel Escudero

Centro de Investigación en Arquitectura, Patrimonio y Gestión para el Desarrollo Sostenible (PEGASO), Universitat Politècnica de València, 46022 Valencia, Spain; jgvallde@ega.upv.es (J.L.G.V.); pabes@upv.es (P.A.E.)
* Correspondence: ywang25y@upv.edu.es

Abstract

The rapid development of digital technologies has significantly transformed architectural heritage research through the emergence of Historic Building Information Modeling (HBIM) and Historic Digital Twin (HDT) approaches. This study aims to analyze and compare the scientific evolution, collaboration patterns, and technological trends of these two research domains between 2019 and 2025. A comparative bibliometric analysis was conducted using publications retrieved from the Web of Science Core Collection (WoSCC) and Scopus databases. The results indicate that the HBIM domain represents a more mature and consolidated research field characterized by stable publication growth and strong international collaboration networks, particularly in European countries. The findings also reveal a strong conceptual relationship between both domains, suggesting that HBIM currently functions as a foundational framework for the development of HDT systems.

Keywords: Historic Building Information Modeling (HBIM); Historic Digital Twin (HDT); digital twin; architectural heritage; heritage conservation; bibliometric analysis; artificial intelligence (AI); Internet of Things (IoT); real-time monitoring

1. Introduction

Architectural heritage constitutes a fundamental component of cultural identity and historical continuity, requiring advanced methods for its documentation, conservation, and long-term management. In recent years, digital technologies have played an increasingly important role in this domain, enabling more accurate recording, analysis, and dissemination of heritage assets. Among these technologies, Historic Building Information Modeling (HBIM) has emerged as a key approach for the digital representation of historic buildings, integrating geometric data with semantic and historical information [1–3].

HBIM extends conventional Building Information Modeling (BIM) methodologies to the specific requirements of heritage assets, such as irregular geometries, stratified historical phases, and material degradation [4,5]. As a result, it has been widely adopted for applications including documentation, restoration planning, and heritage management [6]. Bibliometric evidence further highlights the central role of early contributions in shaping the field, particularly the work of Murphy, whose 2013 publication is widely recognized as a foundational milestone and remains one of the most cited studies in HBIM research. This influence is reflected in the high citation concentration around 2013, followed by a significant increase in publication output, with a notable peak in 2019 and the emergence of new research directions in 2023 [7].

Check for updates

Academic Editor: Fabrizio Banfi

Received: 4 June 2026
Revised: 2 July 2026
Accepted: 9 July 2026
Published: 12 July 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

The concept of the Digital Twin (DT) can be traced back to the early 2000s, when Michael Grieves introduced it within the framework of Product Lifecycle Management, with early presentations around 2003 often considered the origin of the DT paradigm [8,9]. During this initial phase, research activity was limited, representing a formative stage in the development of the concept. Between 2003 and 2011, advances in enabling technologies, particularly the Internet of Things (IoT), sensor systems, data analytics, and simulation tools, provided the technological foundation for its evolution [10]. A key milestone occurred in 2011 with the publication of one of the first journal articles demonstrating the application of DT for predicting aircraft structural performance, followed by the formalization of the concept by NASA in 2012, which significantly accelerated its development [11,12]. Subsequently, the paradigm expanded beyond aerospace into manufacturing and other engineering domains, supported by increasing research output and practical implementations. According to Grieves et al. [9], the DT can be understood as comprising three fundamental elements: the physical asset, its digital representation, and the link that connects them. Building on this framework, Tao et al. [10] further expanded the model by introducing additional dimensions, incorporating data and service components, and thereby extending the DT structure into a five-dimensional framework.

Some authors consider BIM and DT independent but complementary concepts, emphasizing their differences in terms of functionality and interaction with physical assets [13–16]. Unlike BIM models, which can be developed before the construction of a building and are mainly oriented towards design and construction management, DT environments require a continuous connection with a physical counterpart [17].

Despite the apparent complementarity between BIM and DT, their relationship remains a topic of ongoing debate within the scientific community. Many scholars recognize BIM as a key enabling technology for DT implementation; as noted by Sacks et al. [16], "many practitioners see BIM as the core technology enabling construction of digital twins." This perspective emphasizes the role of BIM and BIM-based models as structured digital representations that support data integration and system interoperability. Batty in 2018 [18] argues that, although BIM and 3D models provide highly detailed digital representations of physical assets, they remain largely static and therefore lack the real-time interaction, feedback mechanisms, and dynamic capabilities that characterize fully developed DT systems. In recent years, advances in the IoT have significantly improved real-time monitoring and data integration capabilities, enabling more dynamic and responsive digital environments [19–21]. Nevertheless, these developments have not yet fully bridged the gap between static information models and fully operational DT systems, particularly in the context of architectural heritage.

As for the relationship between BIM and DT, Deng et al. [22] proposed a five-level ladder taxonomy illustrating the evolution from BIM to DT, consisting of Level 1 as BIM, Level 2 as BIM-supported simulations, Level 3 as BIM integrated with IoT technologies, Level 4 as BIM combined with artificial intelligence (AI) techniques for predictive purposes, and Level 5 as fully developed or ideal DT systems.

In architectural heritage, DT approaches have been applied to both heritage documentation and preventive conservation, supporting functionalities such as 3D visualization, damage and deterioration mapping, documentation, data management, digital fruition, digital reconstruction, monitoring, environmental and energy simulations, and structural assessment through different digital representations, including point clouds, HBIM models, numerical models, and virtual tours. Jouan et al. [23] defined the DT as the integration of semantically enriched HBIM models and real-time sensor data via IoT, a concept later adopted by Marra et al. [24] in the definition of the Historic Digital Twin (HDT), combining static and dynamic components in 2021.

Recent bibliometric studies have increasingly explored the evolution of HBIM and DT research. Banfi et al. [25] highlighted the global expansion of HBIM research, emphasizing the dominant role of European countries and the growing contribution of China in the field, while Italy emerged as one of the main hubs of research activity and international scientific collaboration within this domain. Similarly, Ding et al. [26] conducted a bibliometric analysis of HBIM research in China, concluding that studies in this area began around 2007 and experienced significant growth after 2013. More recently, Parente et al. [27] in 2025 identified an increasing research interest in the integration of AI within HBIM workflows, particularly through semi-automatic scan-to-BIM approaches aimed at improving modeling efficiency and data processing capabilities. In parallel, Tao et al. [10] performed a bibliometric analysis of DT research in industrial contexts, outlining key enabling technologies such as simulation, data fusion, interaction mechanisms, and collaborative systems that support DT development. Furthermore, Baik [28] analyzed the convergence between BIM, HBIM, DT, and IoT, concluding that Cheng J.C.P. was among the most influential authors in the intersection of HBIM, IoT, and DT research, while Hong Kong Polytechnic University ranked highest in institutional scientific output. Finally, Mazzetto [29] examined the implementation of DT technologies in heritage buildings and concluded that major challenges remain, particularly regarding data collection processes, interoperability, and the integration of heterogeneous data sources.

Despite the increasing number of bibliometric studies on HBIM and DT technologies, existing research has predominantly addressed these domains independently, with limited efforts to establish a systematic comparative analysis between them. In particular, there is still a lack of integrated studies examining the scientific evolution, structural relationships, and technological convergence between HBIM and DT within the context of architectural heritage. This gap limits a comprehensive understanding of how both domains interact and evolve toward more advanced digital heritage frameworks.

Although isolated HDT-related publications were identified before 2019 in both Scopus and WoSCC, these contributions were sporadic and did not establish a continuous research trajectory. Specifically, Scopus recorded single publications in 2008, 2013, 2014, and 2015, while WoSCC identified only one publication in 2008 and another in 2015. Notably, no HDT-related publications were indexed in either database during the period 2016–2018. In contrast, publication activity resumed in 2019 and subsequently exhibited sustained growth, indicating the emergence and consolidation of HDT as a distinct research domain. Furthermore, 2019 coincides with a notable increase in HBIM research integrating sensing technologies and monitoring systems [7]. Therefore, 2019 was selected as the starting year for the comparative analysis between HBIM and HDT.

The aim of this study is to analyze and compare the scientific development of HBIM and HDT research in architectural heritage between 2019 and 2025 through comparative bibliometric analysis. Specifically, the objectives of this article are to identify publication trends, influential authors, institutional and international collaboration networks, and the main thematic areas within both research domains. In addition, the study aims to explore emerging technological trends and identify potential future research directions.

2. Materials and Methods

The bibliometric methodology adopted in this study provides a systematic and quantitative framework for analyzing the evolution and structure of scientific research related to HBIM and HDT in architectural heritage. Bibliometric approaches have been widely used to explore research trends, intellectual structures, and emerging themes across interdisciplinary domains. Recent studies have further strengthened these methodologies by proposing structured frameworks and advanced analytical techniques. For instance, Pas-

sas [30] outlines the fundamental steps of bibliometric analysis, including data collection, refinement, and pattern identification. Similarly, Öztürk et al. [31] propose a comprehensive framework for designing rigorous bibliometric research, while Chen et al. [32] highlight the integration of text mining and science mapping to enhance analytical depth. More recently, Marlés-Sáenz et al. [33] have demonstrated the application of big data–driven bibliometric methodologies, reflecting the increasing sophistication of analytical tools. These contributions confirm the robustness and continuous evolution of bibliometric methods in analyzing complex scientific domains.

2.1. Data Source and Search Strategy

Previous studies have demonstrated that the combined use of WoS and Scopus provides a more comprehensive and reliable dataset by compensating for the limitations of each individual database, as they differ in journal coverage, indexing policies, and disciplinary scope [7].

In contrast, this study specifically applies to the Web of Science Core Collection (WoSCC), ensuring greater transparency and methodological rigor by clearly defining the selected sub-indexes.

The sub-datasets and their coverage periods are reported to enhance methodological transparency and reproducibility by clearly defining the scope of the indexed literature included in the bibliometric analysis, as differences in database coverage may influence retrieval results and subsequent analyses. The WoSCC dataset used in this study includes the following indexes and their respective coverage periods: Science Citation Index Expanded (SCI-Expanded, 1900–present), Social Sciences Citation Index (SSCI, 1956–present), Arts & Humanities Citation Index (AHCI, 1975–present), Conference Proceedings Citation Index—Science (CPCI-S, 1990–present), Conference Proceedings Citation Index—Social Science & Humanities (CPCI-SSH, 1990–present), Book Citation Index—Science (BKCI-S, 2005–present), Book Citation Index—Social Sciences & Humanities (BKCI-SSH, 2005–present), and Emerging Sources Citation Index (ESCI, 2005–present) [34]. In this study, we included multiple WoSCC indexes at the initial stage in order to ensure broader data coverage. No filtering was applied at the index level, as a subsequent filtering step was conducted based on document types, subject areas, and relevance criteria. This multi-stage filtering approach allows us to refine the dataset progressively while maintaining consistency in data collection [7].

Furthermore, although WoSCC was considered a more selective and high-quality reference due to its rigorous journal evaluation process, Scopus was also included to complement the dataset and enhance coverage, allowing for a more robust comparative analysis [35,36]. These databases were selected due to their extensive coverage of peer-reviewed literature and their widespread use in bibliometric research. Both databases were last accessed on 28 April 2026. In WoSCC, the search was performed using the "Topic" field (TS), which includes title, abstract, author keywords, and Keywords Plus [34]. In Scopus, the search was performed using the "TITLE-ABS-KEY" field [37]. The overall data collection and screening process adopted in this study is summarized in Figure 1, which presents the PRISMA 2020 flow diagram used to identify, filter, and select the final datasets included in the bibliometric analysis.

The search query was designed to achieve a balance between recall and precision by combining multiple relevant keywords and their variations using Boolean operators (AND/OR). This approach allows for the retrieval of a comprehensive set of publications while maintaining thematic relevance. For the HBIM domain (domain 1), the search query ("hbim" OR "h-bim" OR "historic bim" OR "heritage bim") was applied, yielding an initial

dataset of 1141 records in WoSCC and 1535 records in Scopus. A three-step filtering process was subsequently implemented to refine the dataset.

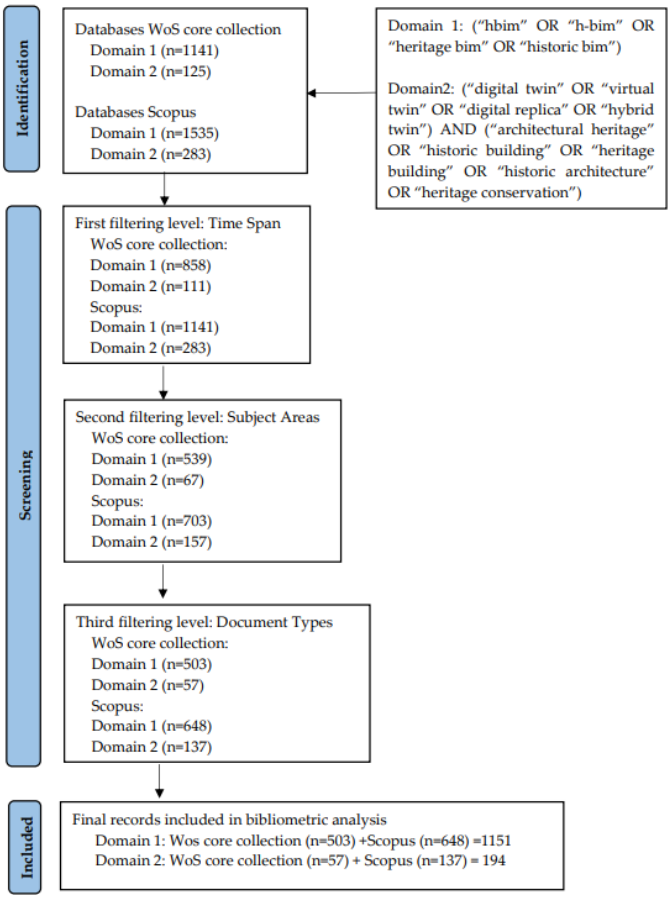


Figure 1. PRISMA 2020 flow diagram illustrating bibliometric search, screening, and three-layer selection strategy across two domains. Own elaboration.

First, the time span was restricted to the period 2019–2025 to focus on recent developments, reducing the dataset to 858 records in WoSCC and 1141 records in Scopus. Second, subject area filtering was applied, taking into account differences between the classification systems of both databases. In WoSCC, the selected categories were Architecture, Construction & Building Technology, Civil Engineering, Multidisciplinary Engineering, and Materials Science, resulting in 539 records. In Scopus, the selected subject areas were Engineering, Arts and Humanities, and Materials Science, resulting in 703 records. Third, document types were limited to articles, proceedings papers, and book chapters in WoSCC (n = 503) and to articles, conference papers, and book chapters in Scopus (n = 648).

A similar procedure was applied to the HDT domain (Domain 2), corresponding to DT research within the context of architectural heritage, using the same databases, access date, and search fields. The search query ("digital twin" OR "virtual twin" OR "digital replica" OR "hybrid twin") AND ("architectural heritage" OR "heritage building" OR "historic building" OR "historic architecture" OR "heritage conservation") yielded 126 records in Web of Science Core Collection and 283 records in Scopus. The same three-step filtering strategy was then applied.

First, limiting the time span to 2019–2025 resulted in 111 records in WoSCC and 237 records in Scopus. Second, applying the same subject area criteria reduced the dataset to 67 records in WoSCC and 157 records in Scopus. Third, restricting document types to articles, proceedings papers, and book chapters in WoSCC maintained 57 records, while in Scopus, limiting to articles, conference papers, and book chapters resulted in 137 records.

2.2. Data Collection and Processing

Following data retrieval, the records obtained from WoSCC and Scopus were processed independently to preserve the integrity of each dataset. This approach was adopted due to differences in indexing structures, metadata organization, and export formats between the two databases.

Specifically, WoSCC records were exported in plain-text format using tagged fields (e.g., AU for authors, TI for title, PY for publication year, and DE for keywords), whereas Scopus records were exported in CSV format with column-based metadata (e.g., Authors, Title, Year, and Author Keywords). These structural differences affect data compatibility and therefore require separate preprocessing procedures before bibliometric analysis.

To improve data reliability and analytical consistency, a comprehensive data refinement process was conducted for each dataset. First, duplicate records were identified and removed. Duplicate entries may occur because of indexing updates, metadata inconsistencies, multiple versions of the same publication, or the coexistence of conference papers and their subsequently published journal versions. Duplicate detection was performed using a combination of publication titles, author names, publication years, and DOI information [38].

Second, records containing missing essential metadata were excluded from the analysis. Particular attention was given to publication year, author names, institutional affiliations, and keywords because these fields directly influence bibliometric indicators and network analyses [39]. Missing publication years can distort temporal trend analyses and publication-growth patterns, while incomplete author or keyword information may affect co-authorship, collaboration, and keyword co-occurrence networks. Similar metadata quality issues have been widely discussed in bibliometric research and represent a recognized limitation of large bibliographic databases.

Third, records were manually screened based on titles and abstracts to ensure relevance to architectural heritage and the research domains under investigation. Publications belonging to unrelated subject areas were excluded to improve dataset accuracy and thematic consistency [40].

Attention was also given to author name disambiguation and metadata normalization. Author name disambiguation is a common challenge in bibliometric analysis due to variations in naming conventions (e.g., initials, abbreviations, or spelling differences). In this study, this issue was addressed through name normalization procedures and manual verification in cases of ambiguity, using affiliation information, co-authorship patterns, and publication records to improve data consistency.

In addition, keyword standardization was applied to reduce fragmentation in the analysis. Synonymous terms, abbreviations, spelling variants, and singular/plural forms were harmonized to ensure consistent representation of research topics and to improve the accuracy of subsequent co-occurrence and network analyses.

2.3. Bibliometric Analysis

The bibliometric analysis was conducted using the open-source software VOSviewer 1.6.20 (Centre for Science and Technology Studies, Leiden University, Leiden, The Netherlands), which enables the construction and visualization of bibliometric networks based on relationships such as co-authorship, keyword co-occurrence, and citation links. The analysis was performed separately for each dataset to ensure consistency and comparability between WoSCC and Scopus.

Several analytical techniques were applied to explore the structure and evolution of the research field. First, a temporal analysis was carried out to examine publication trends over time. Second, co-authorship analysis was performed to identify collaboration

patterns among authors, institutions, and countries. Third, keyword co-occurrence analysis was used to detect research hotspots and thematic clusters, providing insights into the conceptual structure of the field. Finally, citation and co-citation analyses were conducted to identify influential publications and to map the intellectual base of the research domain.

To improve the clarity and interpretability of the visualizations, threshold values were applied to filter low-frequency items. For instance, minimum occurrence thresholds were set for keywords and authors to ensure that only the most relevant elements were included in the network maps. The normalization method adopted in VOSviewer was based on the association strength, which is commonly used to measure the strength of relationships between items in bibliometric networks [41,42].

Network visualizations were generated using distance-based mapping, where the spatial proximity between nodes reflects the strength of their relationships. Clustering algorithms implemented in the software were used to group related items into clusters, allowing the identification of major research themes and subfields [43]. The size of nodes represents the frequency of occurrence or citation impact, while links between nodes indicate the strength of their connections.

3. Results

This section presents the results of the bibliometric analysis of HBIM and HDT research, based on data retrieved from Scopus and WoSCC. The findings are organized to highlight publication trends, influential authors, and thematic structures, allowing a comparative understanding of the development and convergence of both research domains.

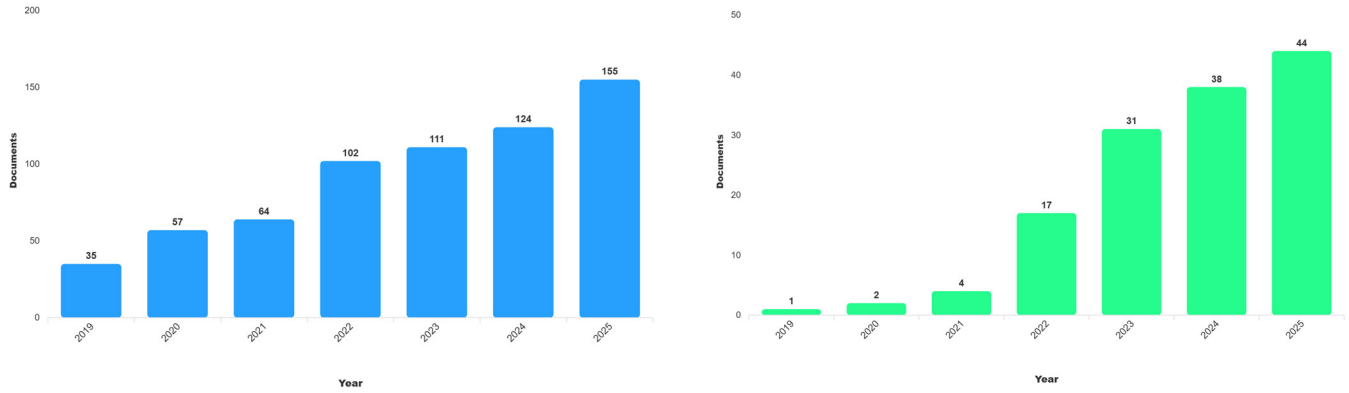
Publication trends and keyword analyses were conducted using both WoSCC and Scopus datasets to enable direct comparison of research evolution and thematic structures across databases. In contrast, author-, country-, and institution-level analyses were primarily based on Scopus data because Scopus contained a substantially larger number of records and provided more comprehensive metadata coverage for these entities. Preliminary comparisons indicated that the overall patterns identified in WoSCC were consistent with those observed in Scopus. It should also be noted that part of the growth observed in both databases may be associated with the continuous expansion of their journal and source coverage over time, in addition to the increasing scholarly interest in the field [37,44]. Therefore, Scopus was selected as the principal source for these analyses to provide more representative and statistically robust results while avoiding redundant visualizations.

3.1. Publication Trends (2019–2025)

The temporal distribution of publications indexed in Scopus reveals distinct growth patterns between Domain 1 and Domain 2.

For Domain 1 (HBIM), the results indicate a steady and continuous increase in publication output over the period analyzed. The number of documents increases from 35 in 2019 to 155 in 2025, reflecting a stable growth trajectory with a particularly notable increase after 2021 (Figure 2a). This trend confirms the consolidation of HBIM as a mature and widely adopted research field within architectural heritage, supported by consistent academic interest and methodological development.

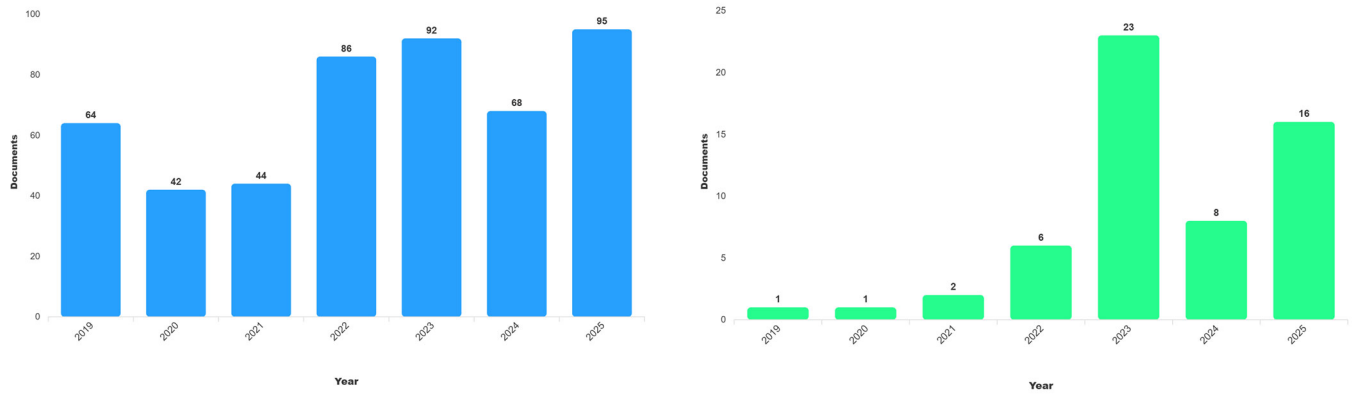
In contrast, Domain 2 (HDT) exhibits a markedly different pattern. The number of publications remains very low in the early years, with only 1 document in 2019 and 2 in 2020, followed by a gradual increase to 4 in 2021. However, from 2022 onwards, a sharp acceleration is observed, with publications rising to 17 in 2022, 31 in 2023, 38 in 2024, and reaching 44 in 2025 (Figure 2b). This exponential growth highlights the emergence of HDT as a rapidly expanding research domain, driven by advances in data integration, sensing technologies, and digital transformation in the built environment.



(**a**) (**b**)

Figure 2. (**a**) Annual publication trends of HBIM research (Domain 1) in Scopus; (**b**) annual publication trends of HDT research (Domain 2) in Scopus. Own elaboration based on data from Scopus.

The publication trends observed in the WoSCC dataset further support the patterns identified in Scopus, while revealing some differences in scale and temporal distribution. For Domain 1 (HBIM), the number of publications shows an overall increasing trend, rising from 64 documents in 2019 to 95 in 2025 (Figure 3a). Although the growth is not strictly linear, with slight fluctuations observed in 2020 and 2024, the general trajectory confirms the sustained research activity and maturity of the HBIM domain within architectural heritage.



(**a**) (**b**)

Figure 3. (**a**) Annual publication trends of HBIM research (Domain 1) in WoSCC; (**b**) annual publication trends of HDT research (Domain 2) in WoSCC. Own elaboration based on data from WoSCC.

In the case of Domain 2 (HDT), the results reveal a delayed but notable expansion. The number of publications remains minimal in the early years, with only 1 document in both 2019 and 2020, followed by a gradual increase to 2 in 2021 and 6 in 2022. A significant rise is observed in 2023, reaching 23 publications, which represents the peak within the analyzed period. Although a slight decrease occurs in 2024 (8 publications), the number increases again to 16 in 2025, indicating continued research interest despite some variability (Figure 3b).

The comparison between the two domains clearly illustrates a temporal shift in research focus. While HBIM demonstrates the characteristics of a consolidated and stable research area, HDT reflects an emerging and rapidly evolving field. The convergence of both trends after 2022 suggests a growing interest in bridging static information modeling approaches with dynamic, real-time digital systems in architectural heritage.

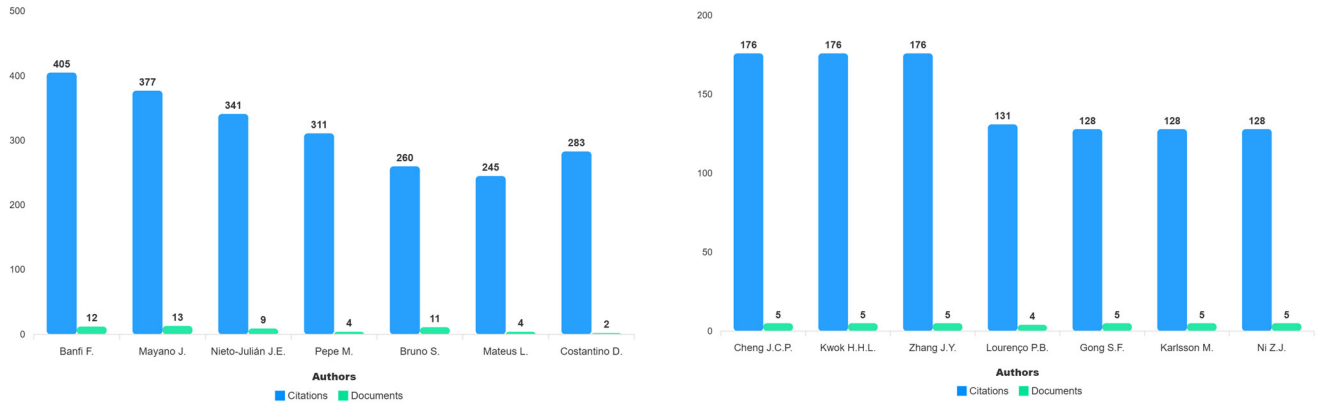
The analysis based on the Scopus dataset indicates that HDT research, although still limited in volume, is gaining significant momentum and may play a key role in

the future evolution of HBIM-based methodologies. Similarly, results from the WoSCC confirm the contrasting development stages of the two domains, with HBIM representing a mature field and HDT exhibiting a more recent and variable growth pattern. Despite these differences, both datasets reveal an overall increase in research activity, reinforcing the ongoing transition toward the integration of information modeling and dynamic digital technologies in architectural heritage.

3.2. Authors with the Highest Citations and Publications

The analysis of the most influential authors in the Scopus dataset reveals significant differences between Domain 1 and Domain 2. The results were evaluated based on the number of citations and publications, allowing the identification of the most impactful and productive researchers within each domain.

For Domain 1 (HBIM), the results indicate a strong concentration of citations among a relatively consolidated group of authors. Banfi F. emerges as the most cited author, with 405 citations and 12 publications, followed by Moyano J. with 377 citations and 13 publications, and Nieto-Julián J.E. with 341 citations and 9 publications. Other influential authors include Pepe M. (311 citations), Costantino D. (283 citations), Bruno S. (260 citations), and Mateus L. (245 citations), as shown in Figure 4a. These findings confirm the existence of a mature research community with established scientific contributions and continuous publication activity in HBIM-related studies.



(**a**) (**b**)

Figure 4. (**a**) Most cited and productive authors in HBIM research (Domain 1) in Scopus; (**b**) most cited and productive authors in HDT research (Domain 2) in Scopus. Own elaboration based on data from Scopus.

In contrast, Domain 2 (HDT) presents a more balanced citation distribution among authors, reflecting the emerging nature of the field. Cheng J.C.P., Kwok H.H.L., and Zhang J.Y. each recorded 176 citations and 5 publications, positioning them among the leading contributors in this research area. Lourenço P.B. follows with 131 citations and 4 publications, while Gong S.F., Karlsson M., and Ni Z.J. each accumulated 128 citations with 5 publications (Figure 4b). Compared with HBIM, the lower citation counts and smaller publication volumes suggest that HDT research contexts are still in an early developmental stage, although rapidly gaining academic visibility.

To further explore the thematic relationship between influential authors and dominant research concepts, a Sankey diagram analysis was conducted using the Domain 2 (HDT) dataset retrieved from Scopus (Figure 5). The analysis was performed by applying a minimum citation threshold of 50 citations and a minimum keyword occurrence threshold of 3. Under these parameters, two dominant thematic nodes emerged: “HBIM” and

"Digital Twin". The Sankey visualization reveals how highly cited authors are connected to these two research directions, illustrating the coexistence and partial convergence of both concepts within architectural heritage studies.

The Sankey analysis also highlights the contribution of several influential authors within the two dominant research directions. Authors such as Banfi F., Brumana R., and Previtali M. are predominantly associated with HBIM research, reflecting their strong contributions to heritage documentation, scan-to-HBIM workflows, and information modeling methodologies [44–49]. Some authors, particularly Zhang J., Cheng J.C.P., Tong J.C.K., and Kwok H.H.L., appear linked to both HBIM and DT themes, suggesting a growing interdisciplinary convergence between static information modeling and dynamic digital environments [50–53]. This overlap indicates that HBIM-based methodologies are increasingly being adopted as foundational frameworks for the development of DT applications in architectural heritage.

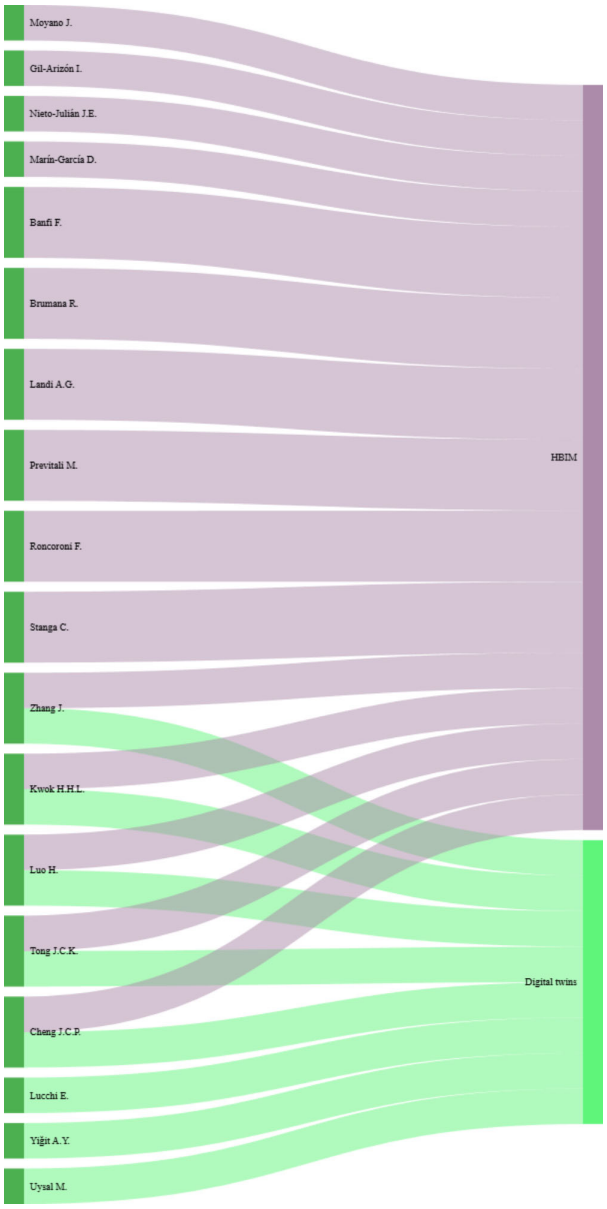
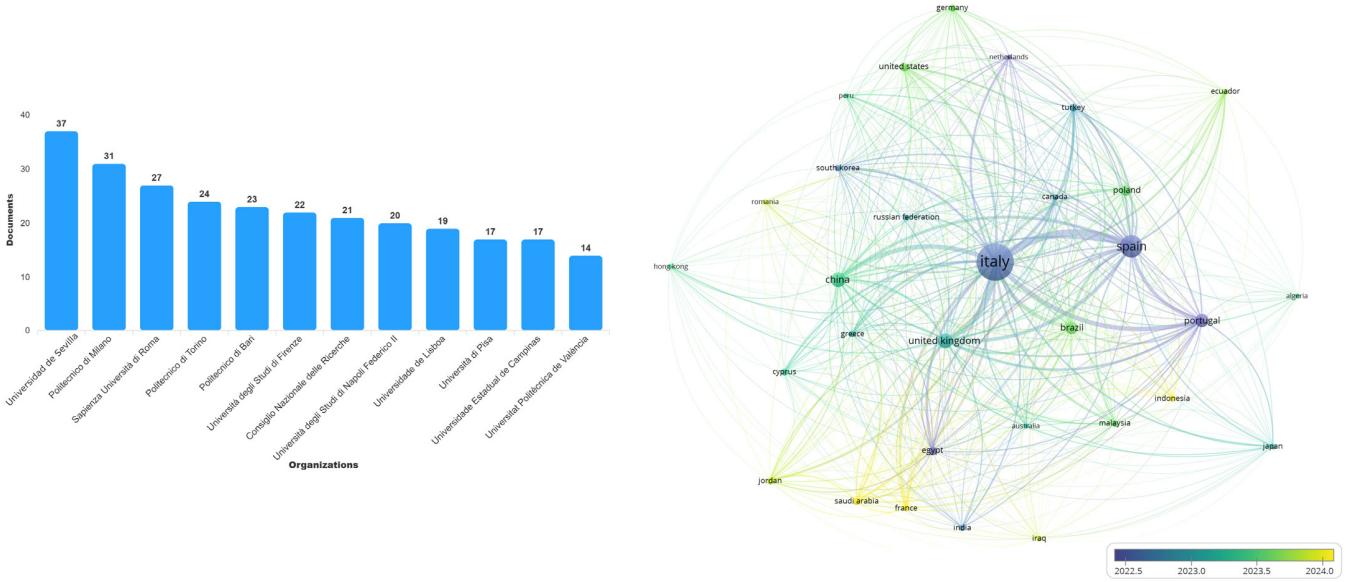


Figure 5. Sankey diagram of influential authors and thematic relationships between HBIM and DT research in architectural heritage (Scopus Domain 2 dataset). Own elaboration using the EasySankey website [54].

3.3. Country and Institutional Contribution Analysis

This section examines the geographical and institutional distribution of research related to HBIM and HDT studies. By analyzing the most productive organizations and the international collaboration networks identified in the Scopus dataset, this analysis provides insights into the leading research centers, dominant countries, and global collaboration patterns shaping the development of both domains.

The analysis of institutional and country contributions in Domain 1 reveals a strong concentration of HBIM research within European academic networks. As shown in Figure 6a, Universidad de Sevilla is the most productive institution with 37 publications, followed by Politecnico di Milano with 31 publications and Sapienza Università di Roma with 27 publications. Other major contributors include Politecnico di Torino, Politecnico di Bari, and Università degli Studi di Firenze. This institutional dominance is also reflected in the country collaboration network generated in VOSviewer through bibliographic coupling analysis. Using "country" as the unit of analysis and applying a minimum threshold of five documents per country, 31 countries met the threshold out of 65 identified countries. Figure 6b shows that Italy occupies the central position within the collaboration network, maintaining strong bibliographic connections with Spain, the United Kingdom, Portugal, and China. Spain also appears as an important collaborative hub with extensive international links.



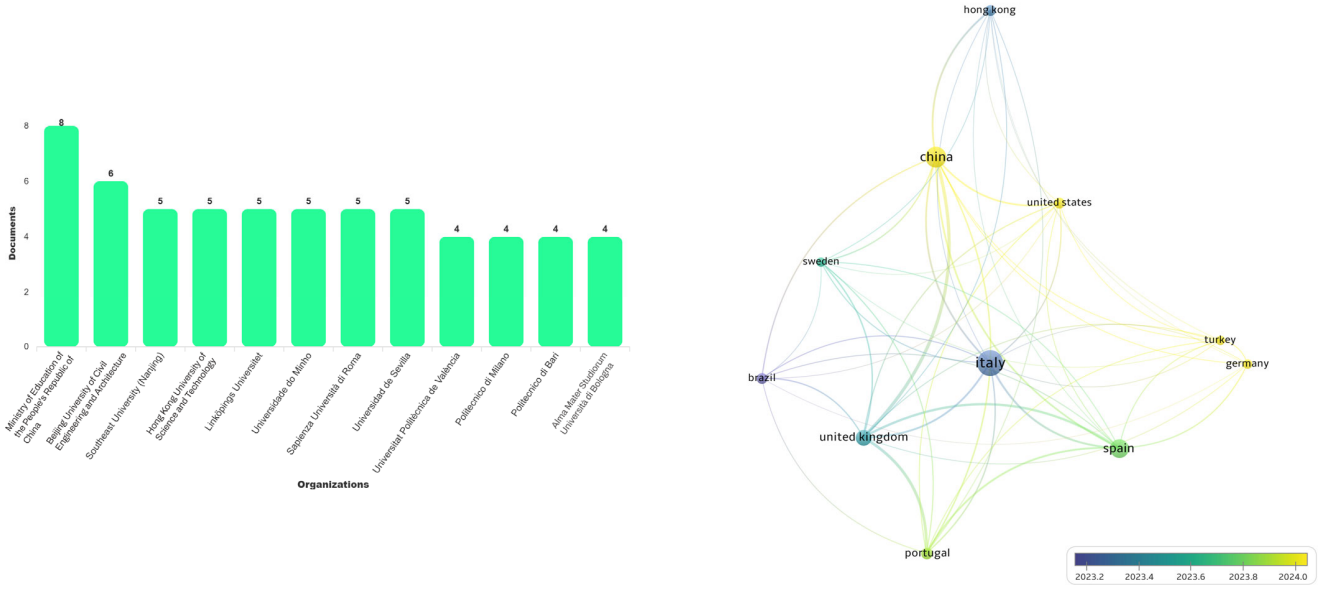
(**a**) (**b**)

Figure 6. (**a**) Top contributing organizations in HBIM research (Domain 1) based on the Scopus dataset; (**b**) international country collaboration network in HBIM research (Domain 1) generated using VOSviewer bibliographic coupling analysis. Own elaboration based on data from Scopus.

The network visualization demonstrates that HBIM research is characterized by a highly interconnected international collaboration structure, dominated primarily by European countries. Nevertheless, the increasing participation of countries such as China, the United States, Brazil, and Saudi Arabia indicates a progressive global expansion of HBIM-related research. These results confirm the consolidation of HBIM as a mature research domain supported by stable institutional networks and extensive international scientific collaboration.

Compared with Domain 1 (HBIM), the institutional and geographical distribution of HDT research presents a more emerging and technologically oriented landscape. The institutional productivity in the HDT domain also appears more distributed and less con-

centrated, reflecting the relatively recent and interdisciplinary nature of HDT research. As shown in Figure 7a, the most productive organization is the Ministry of Education of the People's Republic of China, with 8 publications, followed by Beijing University of Civil Engineering and Architecture, with 6 publications. Several institutions contribute with similar publication outputs, including Southeast University, Hong Kong University of Science and Technology, Linköping University, Universidade do Minho, Sapienza Università di Roma, and Universidad de Sevilla. This result can be explained by the structure of affiliation data in bibliometric databases, where Chinese publications are sometimes indexed under broader governmental bodies rather than individual universities. For instance, the Ministry of Education of China appears as a highly productive organization in the dataset because publications from multiple affiliated universities may be aggregated under this umbrella institution. In contrast, universities in many other countries are typically indexed individually. Consequently, publication output may be concentrated at the national organizational level, leading to higher publication counts for governmental or umbrella institutions.



(**a**) (**b**)

Figure 7. (**a**) Top contributing organizations in HDT research (Domain 2) based on the Scopus dataset; (**b**) international country collaboration network in HDT research (Domain 2) generated using VOSviewer bibliographic coupling analysis. Own elaboration based on data from Scopus.

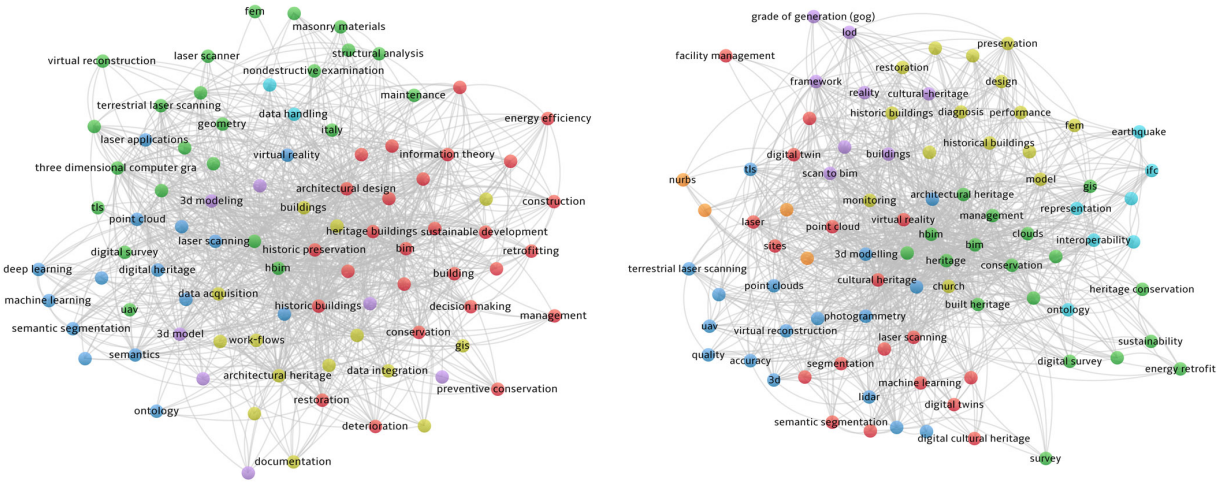
Using bibliographic coupling analysis with a minimum threshold of five documents per country, only 11 countries met the threshold out of 45 identified countries, considerably fewer than the 31 countries identified in Domain 1 (HBIM). As illustrated in Figure 7b, Italy again occupies a central position within the collaboration network, maintaining strong links with Spain, the United Kingdom, Portugal, and China. However, unlike HBIM research, China emerges as one of the dominant nodes in the HDT network, demonstrating its growing influence in data-driven and smart heritage technologies. The collaboration structure in Domain 2 is also more compact and less dense than that observed in Domain 1, indicating that international research networks related to DT applications in heritage are still under development.

3.4. Keyword Co-Occurrence and Association Strength Analysis

The keyword co-occurrence analysis reveals the conceptual structure and thematic evolution of research trends within Domain 1 and Domain 2. The visual networks generated

using VOSviewer demonstrate significant differences in thematic focus, technological integration, and research maturity between the two domains.

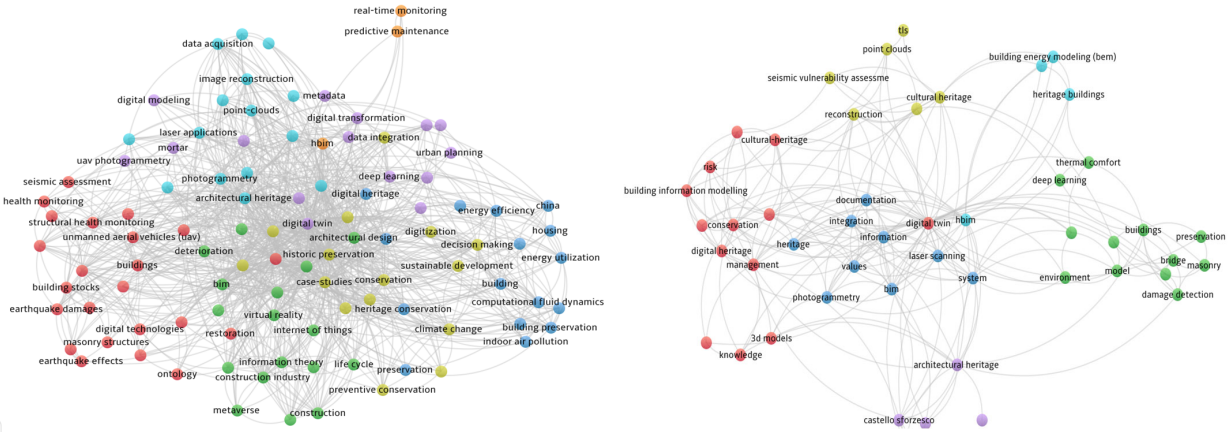
In Domain 1, the keyword network is strongly centered around terms related to HBIM, architectural documentation, and geometric data acquisition. The dominant clusters are associated with keywords such as "architectural design", "historic preservation", "building information modelling", "point-clouds", "laser scanning", "3D modeling", and "architectural heritage" (Figure 8). These results indicate that Domain 1 mainly focuses on digital documentation, geometric reconstruction, semantic modeling, and conservation-oriented representation of heritage buildings. Although the term DT appears within the network, its node size and connectivity remain relatively limited.



(**a**) (**b**)

Figure 8. (**a**) Keyword co-occurrence network visualization for HBIM research (Domain 1) based on Scopus data using VOSviewer; (**b**) keyword co-occurrence network visualization for HBIM research (Domain 1) based on WoSCC data using VOSviewer.

The keyword structure of Domain 2 demonstrates a more technologically integrated and dynamic research landscape. The central position of "DT" is strongly connected with keywords such as "historic preservation", "virtual reality", "internet of things", "decision making", "energy efficiency", and "real-time monitoring" (Figure 9).



(**a**) (**b**)

Figure 9. (**a**) Keyword co-occurrence network visualization for HDT research (Domain 2) based on Scopus data using VOSviewer; (**b**) keyword co-occurrence network visualization for HDT research (Domain 2) based on WoSCC data using VOSviewer.

3.5. Analysis of the Most Influential HDT Publications

Table 1 presents an analysis of the ten most cited publications related to the HDT domain in the WoSCC. The results reveal that a significant proportion of highly cited studies consider HBIM as a fundamental framework for HDT implementation in architectural heritage. Several studies strongly rely on HBIM methodologies for semantic information management, scan-to-BIM workflows, and the integration of monitoring and sensing technologies into digital environments. In particular, works focused on preventive conservation, environmental monitoring, and intelligent building management frequently use HBIM as the core infrastructure supporting DT functionalities [52,53,55–62]. Overall, the findings suggest that HBIM currently represents one of the principal technological and semantic foundations for the development of HDT systems in architectural heritage contexts.

Table 1. Analysis of the top 10 most cited HDT publications in the WoS Core Collection.

Reference	Year	Main Topic	HBIM as Basis for HDT
Jouan et al. [55]	2019	HBIM and DT methodology for heritage preservation	Strongly yes
Vuoto et al. [56]	2024	Literature review of DT in built cultural heritage	Partial
Zhang et al. [52]	2022	DT for humidity control in underground heritage sites	Strongly yes
Jiménez et al. [57]	2023	DT for anomaly detection in historical bridge	No
Banfi et al. [58]	2022	DT for documenting and reconstructing earthquake damaged heritage	Yes
Hou et al. [59]	2024	Systematic review of DT applications in heritage facilities management	Yes
Qian et al. [60]	2023	Digital twin–based monitoring and adaptive thermal comfort analysis of a traditional courtyard	Yes
Pan et al. [61]	2024	Methods for converting point clouds into semantic HBIM models for HDT	Strongly yes
Dang et al. [62]	2023	Overview of Digital Twin applications in China's cultural World Heritage sites	Yes
Zhang et al. [53]	2023	Adaptive HVAC control for energy efficient indoor air quality management in heritage buildings	Strongly yes

4. Discussion

The results obtained from the bibliometric analysis provide important insights into the current evolution of research related to BIM and DT in architectural heritage. Although the analysis based on the WoSCC produced a smaller number of publications compared with Scopus, the database offers a more selective and academically rigorous dataset, allowing for a more accurate representation of highly influential scientific contributions.

4.1. Evolution of HBIM and HDT Research

Complementary approaches such as management systems and historical analysis became increasingly integrated into HBIM research around 2019 and gained greater relevance by 2022 [27,63]. During the same period, additional technologies, including structural analysis, archaeological architecture, ancient masonry analysis, and building sustainability, were progressively incorporated into HBIM workflows [64–67]. More recently, since 2021 and especially after 2023, the research focus has shifted toward the integration of multi-criteria decision-making methodologies, demonstrating the transition of HBIM from static documentation systems toward more intelligent and data-driven environments. [7,27,68,69]. The results obtained in the present study further confirm that the HBIM domain has continued to grow after 2019, particularly in the Scopus dataset, where publication trends show a relatively continuous increase. Although the WoSCC dataset presents some fluctuations and less stable annual growth, the overall trend still indicates the sustained expansion and consolidation of HBIM research within architectural heritage studies.

The present study also demonstrates that the HDT domain began experiencing significant growth after 2022, with a more evident increase after 2023 (Figures 2 and 3). This trend appears closely connected to the recent technological evolution observed in the HBIM domain, particularly through the integration of AI, IoT, sensing technologies, and real-time data management systems [15,70,71].

4.2. HBIM as a Foundation for HDT Development

In the field of architectural heritage, the implementation of HDT is frequently grounded in HBIM workflows, where reality capture data are transformed into semantically enriched digital models. Table 1 further supports this relationship, showing that a significant proportion of the most influential HDT publications consider HBIM as a fundamental framework for HDT implementation. This tendency is reflected in recent case studies such as Xuanluo Hall and the Church of San Juan del Hospital, where HBIM-based environments are progressively extended toward HDT systems through data integration and real-time information management strategies [72,73]. These examples indicate that HBIM often acts as the core semantic and technological foundation for HDT development in heritage contexts, although most current implementations remain at an early developmental stage.

4.3. Technological Maturity and Current Challenges of HDT

HDT applications in architectural heritage remain in an early developmental stage, mainly due to the complexity of heritage assets and the difficulties associated with integrating heterogeneous data sources, sensing technologies, and semantic information models. Current challenges also include interoperability limitations, high computational and economic requirements, and the absence of standardized workflows for real-time synchronization between physical heritage assets and digital environments.

4.4. Future Perspectives Toward Intelligent Historic Digital Twins

Compared with the architectural heritage field, the development of DT technologies in industrial contexts is more advanced and has reached a higher level of technological maturity. In this context, recent industrial contributions further illustrate the application of DT technologies [74]. Ferrari et al. [75] developed simulation-based approaches for DT modeling, while Wei et al. [76] focused on the construction and optimization of DT mechanisms for mechatronic systems. Zhang et al. [77] explored predictive applications through thermomechanical process analysis, and Xue et al. [78] addressed fault diagnosis using DT for Computer Numerical Control (CNC) machine tools. At a system level, Zhang et al. [79] proposed data-driven management frameworks for smart manufacturing envi-

ronments, whereas Yang et al. [80] extended DT applications to large-scale infrastructures. From this perspective, these developments suggest that similar approaches can be adapted and extended to architectural heritage, particularly for predictive analysis and intelligent conservation strategies.

One possible hypothesis emerging from the present study is that the future evolution of the HDT domain will progressively move from IoT-connected heritage information systems toward AI-driven intelligent DT environments. As the integration of real-time monitoring, sensing technologies, and semantic HBIM infrastructures continues to advance, future HDT may evolve beyond static data visualization and predictive simulations toward autonomous decision-support systems capable of adaptive conservation management, anomaly detection, and predictive maintenance [81]. In this context, the incorporation of AI could represent a critical transition stage in the development of a fully operational Intelligent Historic Digital Twin (IHDT).

5. Conclusions

The comparative bibliometric analysis developed in this study demonstrates the rapid digital transformation currently occurring in architectural heritage research. The scientific landscape analyzed between 2019 and 2025 reflects the coexistence of two complementary research directions: the consolidation of HBIM methodologies and the emergence of DT technologies applied to heritage environments.

The results indicate that the evolution of digital heritage research is no longer limited to geometric documentation and information storage. Instead, recent studies increasingly emphasize intelligent interaction between physical heritage assets and dynamic digital environments. The analysis also highlights a progressive diversification of research actors and technological approaches across different regions and institutions. The increasing participation of technologically oriented institutions suggests that architectural heritage research is becoming more interdisciplinary and innovation-driven, combining conservation principles with advanced computational technologies [70,82,83].

Despite the contributions of this study, several limitations should be acknowledged. The analysis is restricted to the WoSCC and Scopus databases, which, although widely recognized, may not include all relevant publications in the field. In particular, the exclusion of regional databases such as the China National Knowledge Infrastructure (CNKI) may lead to an underrepresentation of Chinese research output, which is especially relevant given the growing influence of China in DT applications within architectural heritage [84]. Furthermore, other regional databases such as SciELO could be considered in future research to improve the comprehensiveness and inclusiveness of the dataset [85].

Furthermore, it is important to acknowledge potential regional and language biases associated with WoSCC and Scopus, as these databases tend to prioritize English-language publications and journals indexed in Western countries [34,37]. This may lead to the underrepresentation of research produced in other regions or published in local languages, affecting the global representativeness of the dataset. These limitations may affect the overall representation of the research landscape; however, they do not compromise the main findings of the study. In this context, the results still provide a comprehensive and comparative overview of HBIM and HDT research, offering meaningful insights into their evolution, current trends, and progressive convergence within the field of architectural heritage.

Author Contributions: Conceptualization, W.Y.; methodology, W.Y.; software, W.Y.; validation, J.L.G.V., P.A.E. and W.Y.; formal analysis, W.Y.; investigation, W.Y.; resources, J.L.G.V. and P.A.E.; data curation, W.Y.; writing—original draft preparation, W.Y.; writing—review and editing, J.L.G.V. and P.A.E.; visualization, W.Y.; supervision, J.L.G.V. and P.A.E.; project administration, J.L.G.V.; funding acquisition, J.L.G.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the project "Protocol for risk management through HBIM in heritage sites" (Ref. PAID-01-25), funded by the Universitat Politècnica de València. Funding for open access charge: Universitat Politècnica de València (PAID-12-26).

Data Availability Statement: The datasets used and analyzed during the current study are available from the first author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

HBIM	Historic Building Information Modeling
BIM	Building Information Modeling
HDT	Historic Digital Twin
IoT	Internet of Things
WoSCC	Web of Science Core Collection
IHDT	Intelligent Historic Digital Twin
CNC	Computer Numerical Control
AI	Artificial Intelligence
CNKI	China National Knowledge Infrastructure

References

1. Murphy, M.; McGovern, E.; Pavia, S. Historic Building Information Modelling—Adding intelligence to laser and image based surveys of European classical architecture. *ISPRS J. Photogramm. Remote Sens.* **2013**, *76*, 89–102. [CrossRef]
2. Dore, C.; Murphy, M. Current state of the art historic building information modelling. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2017**, *XLII-2/W5*, 185–192. [CrossRef]
3. Brumana, R.; Oreni, D.; Raimondi, A.; Georgopoulos, A.; Bregianni, A. From survey to HBIM for documentation, dissemination and management of built heritage. The case study of St. Maria in Scaria d'Intelvi. In Proceedings of the 2013 Digital Heritage International Congress (DigitalHeritage), Marseille, France, 28 October–1 November 2013.
4. Bruno, S.; De Fino, M.; Fatiguso, F. Historic Building Information Modelling: Performance assessment for diagnosis-aided information modelling and management. *Autom. Constr.* **2018**, *86*, 256–276. [CrossRef]
5. Volk, R.; Stengel, J.; Schultmann, F. Building Information Modeling (BIM) for existing buildings—Literature review and future needs. *Autom. Constr.* **2014**, *38*, 109–127. [CrossRef]
6. Brumana, R.; Della Torre, S.; Oreni, D.; Previtali, M.; Cantini, L.; Barazzetti, L.; Franchi, A.; Banfi, F. HBIM challenge among the paradigm of complexity, tools and preservation: The Basilica di Collemaggio eight years after the earthquake (L'Aquila). *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2017**, *XLII-2/W5*, 97–104. [CrossRef]
7. Rolim, R.; López-González, C.; Viñals, M.J. Analysis of the Current Status of Sensors and HBIM Integration: A Review Based on Bibliometric Analysis. *Heritage* **2024**, *7*, 2071–2087. [CrossRef]
8. Grieves, M. *Product Lifecycle Management: Driving the Next Generation of Lean Thinking*; McGraw Hill: New York, NY, USA, 2005.
9. Grieves, M.; Vickers, J. Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In *Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches*; Springer: Cham, Switzerland, 2016; pp. 85–113. [CrossRef]
10. Tao, F.; Zhang, H.; Liu, A.; Nee, A.Y.C. Digital Twin in Industry: State-of-the-Art. *IEEE Trans. Ind. Inform.* **2019**, *15*, 2405–2415. [CrossRef]
11. Shafto, M.; Rich, M.C.; Glaessgen, D.E.; Kemp, C.; Lemoigne, J.; Wang, L. *DRAFT MoDeling, SiMulATion, inFoRMATion Technology & PRoceSSing RoADMAP Technology Area 11*; National Aeronautics and Space Administration: Washinton, DC, USA, 2010.
12. Glaessgen, E.; Stargel, D. The digital twin paradigm for future NASA and U.S. air force vehicles. In Proceedings of the 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, Hawaii, 23–26 April 2012. [CrossRef]
13. Bado, M.F.; Tonelli, D.; Poli, F.; Zonta, D.; Casas, J.R. Digital Twin for Civil Engineering Systems: An Exploratory Review for Distributed Sensing Updating. *Sensors* **2022**, *22*, 3168. [CrossRef] [PubMed]
14. Khajavi, S.H.; Motlagh, N.H.; Jaribion, A.; Werner, L.C.; Holmstrom, J. Digital Twin: Vision, benefits, boundaries, and creation for buildings. *IEEE Access* **2019**, *7*, 147406–147419. [CrossRef]

15. Jiang, F.; Ma, L.; Broyd, T.; Chen, K. Digital twin and its implementations in the civil engineering sector. *Autom. Constr.* **2021**, *130*, 103838. [CrossRef]
16. Sacks, R.; Brilakis, I.; Pikas, E.; Xie, H.S.; Girolami, M. Construction with digital twin information systems. *Data-Cent. Eng.* **2020**, *1*, e14. [CrossRef]
17. Vuoto, A.; Funari, M.F.; Lourenço, P.B. On the Use of the Digital Twin Concept for the Structural Integrity Protection of Architectural Heritage. *Infrastructures* **2023**, *8*, 86. [CrossRef]
18. Batty, M. Digital twins. *Environ. Plan. B* **2018**, *45*, 817–820. [CrossRef]
19. Hu, X.; Assaad, R.H. A BIM-enabled digital twin framework for real-time indoor environment monitoring and visualization by integrating autonomous robotics, LiDAR-based 3D mobile mapping, IoT sensing, and indoor positioning technologies. *J. Build. Eng.* **2024**, *86*, 108901. [CrossRef]
20. Liu, W.; Lv, Y.; Wang, Q.; Sun, B.; Han, D. A Systematic Review of the Digital Twin Technology in Buildings, Landscape and Urban Environment from 2018 to 2024. *Buildings* **2024**, *14*, 3475. [CrossRef]
21. Piras, G.; Agostinelli, S.; Muzi, F. Digital Twin Framework for Built Environment: A Review of Key Enablers. *Energies* **2024**, *17*, 436. [CrossRef]
22. Deng, M.; Menassa, C.C.; Kamat, V.R. From BIM to digital twins: A systematic review of the evolution of intelligent building representations in the AEC-FM industry. *J. Inf. Technol. Constr.* **2021**, *26*, 58–83. [CrossRef]
23. Jouan, P.; Hallot, P. Digital twin: Research framework to support preventive conservation policies. *ISPRS Int. J. Geo-Inf.* **2020**, *9*, 228. [CrossRef]
24. Marra, A.; Trizio, I.; Fabbrocino, G.; Savini, F. Digital models for e-conservation: The HBrIM of a bridge along the Aterno river. *SCIRES-IT* **2021**, *11*, 83–96. [CrossRef]
25. Banfi, F.; Liu, W. The State of HBIM in Digital Heritage: A Critical and Bibliometric Assessment of Six Emerging Frontiers (2015–2025). *Appl. Sci.* **2026**, *16*, 906. [CrossRef]
26. Ding, J.; Liang, M.; Chen, W. Integration of BIM and Chinese Architectural Heritage: A Bibliometric Analysis Research. *Buildings* **2023**, *13*, 593. [CrossRef]
27. Parente, M.; Bruno, N.; Ottoni, F. HBIM and Information Management for Knowledge and Conservation of Architectural Heritage: A Review. *Heritage* **2025**, *8*, 306. [CrossRef]
28. Baik, A. Three Decades of Innovation: A Critical Bibliometric Analysis of BIM, HBIM, Digital Twins, and IoT in the AEC Industry (1993–2024). *Buildings* **2025**, *15*, 1587. [CrossRef]
29. Mazzetto, S. Integrating Emerging Technologies with Digital Twins for Heritage Building Conservation: An Interdisciplinary Approach with Expert Insights and Bibliometric Analysis. *Heritage* **2024**, *7*, 6432–6479. [CrossRef]
30. Passas, I. Bibliometric Analysis: The Main Steps. *Encyclopedia* **2024**, *4*, 1014–1025. [CrossRef]
31. Öztürk, O.; Kocaman, R.; Kanbach, D.K. How to design bibliometric research: An overview and a framework proposal. *Rev. Manag. Sci.* **2024**, *18*, 3333–3361. [CrossRef]
32. Chen, H.; Tsang, Y.P.; Wu, C.H. When text mining meets science mapping in the bibliometric analysis: A review and future opportunities. *Int. J. Eng. Bus. Manag.* **2023**, *15*, 1–15. [CrossRef]
33. Marlés-Sáenz, E.; Gómez-Luna, E.; Guerrero, J.M.; Vasquez, J.C. Innovative Bibliometric Methodology: A New Big Data-Based Framework for Scientific Research. *Energies* **2025**, *18*, 2437. [CrossRef]
34. Clarivate. Web of Science Core Collection. Available online: https://www.webofscience.com/wos/woscc/basic-search (accessed on 16 June 2026).
35. Mongeon, P.; Paul-Hus, A. The journal coverage of Web of Science and Scopus: A comparative analysis. *Scientometrics* **2016**, *106*, 213–228.
36. Martín-Martín, A.; Orduna-Malea, E.; Thelwall, M.; Delgado López-Cózar, E. Google Scholar, Web of Science, and Scopus: A systematic comparison of citations in 252 subject categories. *J. Informetr.* **2018**, *12*, 1160–1177. [CrossRef]
37. Elsevier. Scopus: Abstract and Citation Database. Available online: https://www.scopus.com/pages/home#basic (accessed on 16 June 2026).
38. Valderrama-Zurián, J.C.; Aguilar-Moya, R.; Melero-Fuentes, D.; Aleixandre-Benavent, R. A systematic analysis of duplicate records in Scopus. *J. Informetr.* **2015**, *9*, 570–576. [CrossRef]
39. Visser, M.; van Eck, N.J.; Waltman, L. Large-scale comparison of bibliographic data sources: Scopus, Web of Science, Dimensions, Crossref, and Microsoft Academic. *Quant. Sci. Stud.* **2021**, *2*, 20–41. [CrossRef]
40. Zupic, I.; Čater, T. Bibliometric methods in management and organization. *Organ. Res. Methods* **2015**, *18*, 429–472. [CrossRef]
41. Waltman, L.; van Eck, N.J.; Noyons, E.C.M. A unified approach to mapping and clustering of bibliometric networks. *J. Informetr.* **2010**, *4*, 629–635. [CrossRef]
42. Van Eck, N.J.; Waltman, L. Visualizing Bibliometric Networks. In *Measuring Scholarly Impact: Methods and Practice*; Springer International Publishing: Cham, Switzerland, 2014; pp. 285–320. [CrossRef]

43. Van Eck, N.J.; Waltman, L. Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* **2010**, *84*, 523–538. [CrossRef] [PubMed]
44. Banfi, F.; Previtali, M.; Stanga, C.; Brumana, R. A layered-web interface based on HBIM and 360° panoramas for historical, material and geometric analysis. In *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Copernicus GmbH: Enschede, The Netherlands, 2019; Volume XLII-2/W9, pp. 73–80. [CrossRef]
45. Banfi, F. Building information modelling—A novel parametric modeling approach based on 3D surveys of historic architecture. In *Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection (EuroMed 2016); Lecture Notes in Computer Science*; Springer: Cham, Switzerland, 2016; pp. 116–127. [CrossRef]
46. Brumana, R.; Della Torre, S.; Previtali, M.; Barazzetti, L.; Cantini, L.; Oreni, D.; Banfi, F. Generative HBIM modelling to embody complexity (LOD, LOG, LOA, LOI): Surveying, preservation, site intervention—The Basilica di Collemaggio (L'Aquila). *Appl. Geomat.* **2018**, *10*, 545–567. [CrossRef]
47. Oreni, D.; Brumana, R.; Della Torre, S.; Banfi, F.; Barazzetti, L.; Previtali, M. Survey turned into HBIM: The restoration and the work involved concerning the Basilica di Collemaggio after the earthquake (L'Aquila). In *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Copernicus GmbH: Antalya, Turkey, 2014; pp. 267–273. [CrossRef]
48. Banfi, F.; Brumana, R.; Stanga, C. Extended reality and informative models for the architectural heritage: From scan-to-bim process to virtual and augmented reality. *Virtual Archaeol. Rev.* **2019**, *10*, 14–30. [CrossRef]
49. Barazzetti, L.; Banfi, F.; Brumana, R.; Gusmeroli, G.; Previtali, M.; Schiantarelli, G. Cloud-to-BIM-to-FEM: Structural simulation with accurate historic BIM from laser scans. *Simul. Model. Pract. Theory* **2015**, *57*, 71–87. [CrossRef]
50. Cheng, J.C.P.; Zhang, J.; Kwok, H.H.L.; Tong, J.C.K. Thermal performance improvement for residential heritage building preservation based on digital twins. *J. Build. Eng.* **2024**, *82*, 108283. [CrossRef]
51. Liang, Z.; Chan, J.C.F.; Zhang, J.; Liang, Z.; Wang, B.; Wang, M.; Cheng, J.C. Multimodal LLM-driven language-embedded 3D gaussian splatting for semantic and realistic digitization of historical buildings. *Autom. Constr.* **2026**, *181*, 106628. [CrossRef]
52. Zhang, J.; Chan, C.C.C.; Kwok, H.H.L.; Cheng, J.C.P. Multi-indicator adaptive HVAC control system for low-energy indoor air quality management of heritage building preservation. *Build. Environ.* **2023**, *246*, 110910. [CrossRef]
53. Zhang, J.; Kwok, H.H.L.; Luo, H.; Tong, J.C.K.; Cheng, J.C.P. Automatic relative humidity optimization in underground heritage sites through ventilation system based on digital twins. *Build. Environ.* **2022**, *216*, 108999. [CrossRef]
54. Orozco-Carpio, P.R. EasySankey. Available online: https://prorocar.webs.upv.es/ (accessed on 5 May 2026).
55. Jouan, P.; Hallot, P. Digital twin: A HBIM-based methodology to support preventive conservation of historic assets through heritage significance awareness. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; International Society for Photogrammetry and Remote Sensing: Enschede, The Netherlands, 2019; Volume XLII-2/W15, pp. 609–615. [CrossRef]
56. Vuoto, A.; Funari, M.F.; Lourenço, P.B. Shaping Digital Twin Concept for Built Cultural Heritage Conservation: A Systematic Literature Review. *Int. J. Archit. Herit.* **2024**, *18*, 1762–1795. [CrossRef]
57. Jiménez Rios, A.; Plevris, V.; Nogal, M. Bridge management through digital twin-based anomaly detection systems: A systematic review. *Front. Built Environ.* **2023**, *9*, 1176621. [CrossRef]
58. Banfi, F.; Brumana, R.; Landi, A.G.; Previtali, M.; Roncoroni, F.; Stanga, C. Building archaeology informative modelling turned into 3D volume stratigraphy and extended reality time-lapse communication. *Virtual Archaeol. Rev.* **2022**, *13*, 1–21. [CrossRef]
59. Hou, H.; Lai, J.H.K.; Wu, H.; Wang, T. Digital twin application in heritage facilities management: Systematic literature review and future development directions. *Eng. Constr. Archit. Manag.* **2024**, *31*, 3193–3221. [CrossRef]
60. Qian, Y.; Leng, J.; Chun, Q.; Wang, H.; Zhou, K. A year-long field investigation on the spatio-temporal variations of occupant's thermal comfort in Chinese traditional courtyard dwellings. *Build. Environ.* **2023**, *228*, 109836. [CrossRef]
61. Pan, X.; Lin, Q.; Ye, S.; Li, L.; Guo, L.; Harmon, B. Deep learning based approaches from semantic point clouds to semantic BIM models for heritage digital twin. *Herit. Sci.* **2024**, *12*, 65. [CrossRef]
62. Dang, X.; Liu, W.; Hong, Q.; Wang, Y.; Chen, X. Digital twin applications on cultural world heritage sites in China: A state-of-the-art overview. *J. Cult. Herit.* **2023**, *64*, 228–243. [CrossRef]
63. Yang, X.; Grussenmeyer, P.; Koehl, M.; Macher, H.; Murtiyoso, A.; Landes, T. Review of built heritage modelling: Integration of HBIM and other information techniques. *J. Cult. Herit.* **2020**, *46*, 350–360. [CrossRef]
64. Salvador-García, E.; Viñals, M.J.; García-Valldecabres, J.L. Potential of hbim to improve the efficiency of visitor flow management in heritage sites. Towards smart heritage management. In *ISPRS Archives*; International Society for Photogrammetry and Remote Sensing: Enschede, The Netherlands, 2020; pp. 451–456. [CrossRef]
65. Liu, J.; Willkens, D.; López, C.; Cortés-Meseguer, L.; García-Valldecabres, J.L.; Escudero, P.A.; Alathamneh, S. Comparative analysis of point clouds acquired from a TLS survey and a 3D virtual tour for HBIM development. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; International Society for Photogrammetry and Remote Sensing: Enschede, The Netherlands, 2023; Volume XLVIII-M-2-2023, pp. 959–968. [CrossRef]

66. García, E.S.; García-Valldecabres, J.; Blasco, M.J.V. The use of hbim models as a tool for dissemination and public use management of historical architecture: A review. *Int. J. Sustain. Dev. Plan.* **2018**, *13*, 96–107. [CrossRef]
67. Jordan-Palomar, I.; Tzortzopoulos, P.; García-Valldecabres, J.; Pellicer, E. Protocol to Manage Heritage-Building Interventions Using Heritage Building Information Modelling (HBIM). *Sustainability* **2018**, *10*, 908. [CrossRef]
68. Li, B.; Lim, Y.L.; Li, W. Systematic review: A bibliometric analysis of building technology and its potential applications to artificial intelligence in the field of cultural heritage conservation from 2013 to 2023. *J. Asian Archit. Build. Eng.* **2025**, *25*, 1021–1043. [CrossRef]
69. Puerto, A.; Castañeda, K.; Sánchez, O.; Peña, C.A.; Gutiérrez, L.; Sáenz, P. Building information modeling and complementary technologies in heritage buildings: A bibliometric analysis. *Results Eng.* **2024**, *22*, 102192. [CrossRef]
70. Angjeliu, G.; Coronelli, D.; Cardani, G. Development of the simulation model for Digital Twin applications in historical masonry buildings: The integration between numerical and experimental reality. *Comput. Struct.* **2020**, *238*, 106282. [CrossRef]
71. Hamledari, H.; Fischer, M. Construction payment automation using blockchain-enabled smart contracts and robotic reality capture technologies. *Autom. Constr.* **2021**, *132*, 103926. [CrossRef]
72. Meseguer, L.C.; Valldecabres, J.G. Digital Twins. HBIM information repositories to centralize knowledge and interdisciplinary management of architectural heritage. *Vitruvio* **2023**, *8*, 64–75. [CrossRef]
73. Tan, J.; Leng, J.; Zeng, X.; Feng, D.; Yu, P. Digital Twin for Xiegong's Architectural Archaeological Research: A Case Study of Xuanluo Hall, Sichuan, China. *Buildings* **2022**, *12*, 1053. [CrossRef]
74. Tao, F.; Liu, A.; Anwer, N.; Zhang, M.; Wang, L.; Nee, A.Y.C. Editorial for the special issue on Digital twin in industry. *Int. J. Adv. Manuf. Technol.* **2024**, *131*, 5365–5367. [CrossRef]
75. Ferrari, A.; Carlin, A.; Rafele, C.; Zenezini, G. A method for developing and validating simulation models for automated storage and retrieval system digital twins. *Int. J. Adv. Manuf. Technol.* **2024**, *131*, 5369–5382. [CrossRef]
76. Wei, Y.; Hu, T.; Yue, P.; Wang, X.; Ma, S. Reconfigured lightweight model design method for DT-based mechatronics equipment. *Int. J. Adv. Manuf. Technol.* **2024**, *131*, 5437–5455. [CrossRef]
77. Zhang, L.; Liu, J.; Wu, X.; Zhuang, C. Digital twin-based dynamic prediction of thermomechanical coupling for skiving process. *Int. J. Adv. Manuf. Technol.* **2024**, *131*, 5471–5488. [CrossRef]
78. Xue, R.; Zhang, P.; Huang, Z.; Wang, J. Digital twin-driven fault diagnosis for CNC machine tool. *Int. J. Adv. Manuf. Technol.* **2024**, *131*, 5457–5470. [CrossRef]
79. Zhang, J.; Liu, J.; Zhuang, C.; Guo, H.; Ma, H. A data-driven smart management and control framework for a digital twin shop floor with multi-variety multi-batch production. *Int. J. Adv. Manuf. Technol.* **2024**, *131*, 5553–5569. [CrossRef]
80. Yang, W.; Bao, X.; Zheng, Y.; Zhang, L.; Zhang, Z.; Zhang, Z.; Li, L. A digital twin framework for large comprehensive ports and a case study of Qingdao Port. *Int. J. Adv. Manuf. Technol.* **2024**, *131*, 5571–5588. [CrossRef]
81. Lu, Q.; Xie, X.; Heaton, J.; Parlikad, A.K.; Schooling, J. From BIM Towards Digital Twin: Strategy and Future Development for Smart Asset Management. In *Service Oriented, Holonic and Multi-Agent Manufacturing Systems for Industry of the Future*; Springer International Publishing: Cham, Switzerland, 2020; pp. 392–404.
82. Nieto, J.E.; Moyano, J.J.; Rico Delgado, F.; Antón García, D. Management of built heritage via HBIM Project: A case of study of flooring and tiling. *Virtual Archaeol. Rev.* **2016**, *7*, 1. [CrossRef]
83. Han, H.; Li, Y.; Jiang, F.; Broyd, T.; Ma, L.; Dong, Z. Automatic optimization of BIM masonry layout combining simulated annealing and tabu search. *Autom. Constr.* **2025**, *179*, 106446. [CrossRef]
84. China National Knowledge Infrastructure (CNKI). Available online: https://www.cnki.net (accessed on 25 June 2026).
85. Scientific Electronic Library Online (SciELO). Available online: https://www.scielo.org (accessed on 25 June 2026).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.