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From Heritage BIM to Historic (Digital) Twins: A initial bibliometric analysis of subject coalescence for Architectural Heritage

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Abstract

Digital twins (DT) development and integration into the built environment sector presents an opportunity to explore the potential of fusion of DT Building Information Modelling and Architectural Heritage paradigms to provide a new approach to support the use and management of architectural heritage. This is done by conducting a bibliometric analysis and content analysis by evaluating 10 of the most relevant research articles identified from the Scopus database. This is followed by an analysis through VOSviewer to help visualize the results. The research shows that this area of research is continuously growing, however it revealed that the studies are conducted in isolated clusters with no collaboration between authors.

Keywords

Heritage BIM, Historic Digital Twin, Architectural Heritage, bibliometric analysis, literature review

1. Introduction

Architectural heritage (AH) is increasingly seen as an important part of a country's history and cultural identity (Taher Tolou Del et al., 2020). It is highly valued around the world for its tangible aspects namely; age, authenticity, visual aspect, exclusivity and monumentality (Dewi, 2017). Furthermore, the conservation of heritage buildings is widely acknowledged as critical to the sustainability of the built environment they are considered as limited resources that cannot be replaced if not conserved (Nadkarni & Puthuvayi, 2020). Shan et al. (2022) highlight four methods of conservation of architectural heritage; preservation, reconstruction, rehabilitation and restoration. In the UK, the preservation and restoration of heritage is particularly relevant as there is acute need for housing and limited land available for the creation of new buildings without impinging on protected greenbelt areas. Furthermore, much of the architectural heritage that exists within the UK also classified as existing on 'brownfield land' there is great potential to use these methods of conservation for existing brownfields buildings. There are 21,000 brownfield sites in England alone (Hammond et al., 2021).

In recent years there has been a widespread use of Building Information Modelling (BIM), it has combined both 3D modelling and information management. This has enabled the implementation of Historic/Heritage building information modelling (HBIM) to support historic recording and modelling of historical buildings and built assets (Murphy et al., 2013). As BIM technology and prevailing processes have evolved so methodologies for cultural heritage documentation have begun to adopt BIM (Logothetis, Delinasiou and Stylianidis, 2015). However in previous work, much of the methodologies employed have had a focus on undertaking a survey through the use of laser scanners followed by manual approach (Scan-to-BIM) to construct a 3D model through BIM (Bassier et al., 2016).

The implementation of HBIM has also been deemed to deliver advantages in the operational phase of a historic built asset, as it allows the integration and alignment of data with restoration and conservation guidelines (Oostwegel et al., 2022). Furthermore Oostwegel et al. (2022) highlight the potential to bring the multi-dimensional aspects into BIM into the HBIM paradigm such that the digital data can be used to manage the asset in a more efficient way.

As the efficient and sustainable management of built assets becomes more critical, recent initiatives are beginning to look at how digital technologies and the implementation of digital workflows, including BIM, can unlock the potential of the Digital Twin (DT) for the built environment (Shahzad et al., 2022). This evolution towards the digital twin for built environment presents a great opportunity to better explore and understand the potential of DT in the heritage buildings and provide a wider understanding of how BIM, AH and DT paradigms can coalesce to provide a new approach to support the use and management of architectural heritage.

In order to achieve the above, this paper presents an initial bibliometric review of these three topics including how they intersect at various levels to better understand prevailing research agendas and opportunities for new areas of enquiry.

2. Research Methods

Bibliometric analysis is a method of research that has been used since its first introduction by Pritchard in (1969). It has since replaced the statistical bibliography and has become a scientific technique for conducting scientific research (Khanra et al., 2020). The three steps of the research process conducted for this study are presented in figure 1.

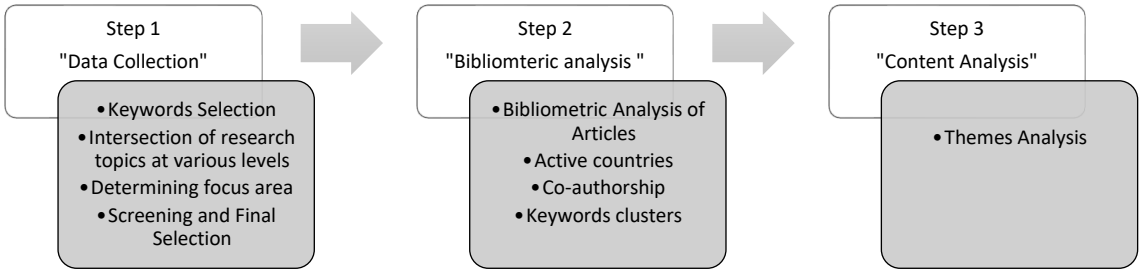

Figure 1- Steps of research process

Step 1: This step aims to collect data related to the intersection of DT, BIM and AH. The initial search was conducted in February 2023 in Scopus as it is among the largest databases of peer reviewed journals. The keywords used for data collection included definitions and keywords related to the study scope. The resulting query is: (TITLE-ABS-KEY (digital AND twin*) AND TITLE-ABS-KEY (bim OR building AND information AND model*) AND TITLE-ABS-KEY (architectur* AND heritage OR built AND heritage)).

Step 2: This step starts with the application of bibliometric techniques to conduct quantitative analysis of the number of papers extracted in step 1. Several data mining software tools are available to conduct scientometric analysis. However for this research VOSviewer was chosen as it is widely available and is suitable for visualising extensive networks of data (van Eck & Waltman, 2013). VOSviewer makes use of the bibliometric data extracted from Scopus search engine to present new perceptions for the research area (Yunwei et al., 2009). The analysis in this section includes the following categories: Countries, authors analysis, authors' keywords, clusters of keywords.

Step 3: This step presents the qualitative analysis identifying knowledge areas and revealing the evolving trends in research related to the intersection of DT, BIM and AH.

3. Results

3. 1 Number of papers and trend of research

This research aims to shed light on an evolving research area that is emerging from the fusion of DT, BIM, and AH. Therefore, a thorough investigation was conducted initially to reveal the number of research papers that focused on each of the specified fields. The search method mentioned in step 1 of the research process was used to find the total number of articles in each area and their intersection at various levels (Figure 2). The results are as follows:

- DT research field: 14,361

- BIM research field: 76,695

- AH research field: 9,162
- DT and BIM fields intersection: 637
- DT and AH fields intersection: 34
- BIM and AH fields intersection: 781
- DT and BIM and AH intersection: 17

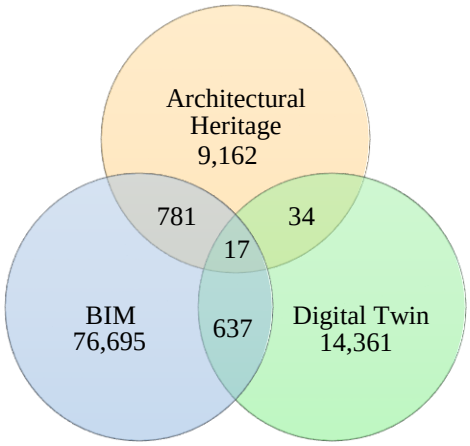

Figure 2- Overall research in each related field

The results enable a clear comparison to identify how the fusion of the three focus areas are investigated in the literature. It is evident that it is discussed in a small number of articles namely 17 in comparison to the individual fields. Due to the limited number of articles the filtering criteria applied was selecting both journal articles and conference papers excluding other types of documents. As a result, only 10 research articles were selected to be exported for further analysis.

The first analysis conducted is publication metric analysis. This is performed to identify the trend in publication rates. The year range for the papers is between 2019-2022 as can be seen in figure 3. Although the overall number of publications is not large, it is evident from the figure that there is a rising trend since the start in 2019, with the highest numbers of publications being in 2022. Nevertheless, the significantly smaller number of publications compared to other areas shown in figure 2 proves the lack of attention paid to this research field.

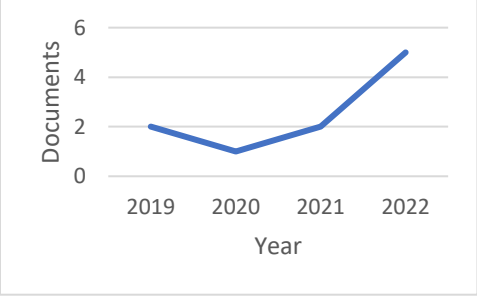

Figure 3- Number of documents per year

3.2 Bibliometrics analysis results

Based on co-authorship analysis, the geographical distribution of the research shows 7 countries are involved in the research field as identified in Table 1. The highest number of published articles came from Italy. This aligns with findings from (Zhang & Zou, 2022) indicating that Italy has the highest number of publications related to heritage BIM research as well. Spain was second with 2 research articles and the remaining regions have 1 research article related to this field. However, Belgium has the largest number of citations (28) which is 42% of the total citations.

The countries that first published around the research topic were United Kingdom and Belgium. Italy has a co-authorship network with Spain and Taiwan and is the latest country to start taking interest in this field of study.

Table 1. The most active countries in the research field

Country	Documents	Citations
Italy	6	15
Spain	2	10
Taiwan	1	0
Belgium	1	28
Brazil	1	6
China	1	3
United Kingdom	1	4

A co-authorship network analysis was conducted in VOSviewer to examine the collaboration of authors, and understand the contribution of each author, this allows a comparison between the number of papers, citations and year of publication. However, figure 4 extracted from VOSviewer shows the network to be fragmented and scattered, revealing a need for more collaboration between authors in the field. This can be due to the novelty of the research topic and lack of research in the field in general. The total number of authors is 37. Jouan & Hallot, (2019) are the earliest researchers who investigated the research topic. They called for a need to strengthen the relationships between the digitalized models of heritage structures and the real-world, to better support preventive conservation of historic buildings. This article suggested the use of DT principles to fulfill that. Bruno et al., (2022) discussed the need to solve criticalities of exchanging data during a restoration project, from the early preliminary stages until the execution and monitoring process. Those authors also indicated that the digital twin capabilities are investigated to overcome this fragmentation in the restoration process (Bruno et al., 2022).

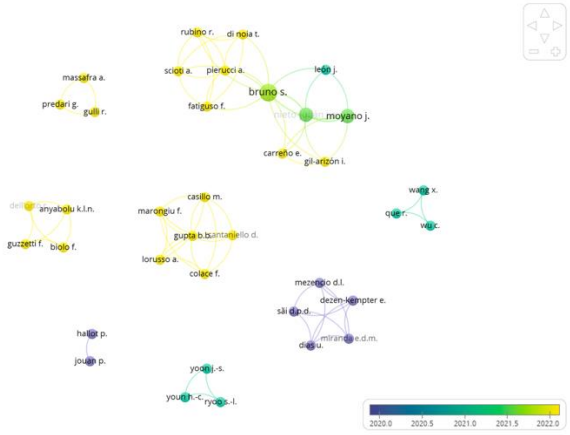

Figure 4- Co-authorship network of the most active authors

The co-occurrence of author keywords analysis was carried out to simplify the visualisation of the most pressing issues in this research area. This aids in identifying the emergent research trends. The analysis is a method to understand the knowledge components and knowledge structure. All keywords were divided according to relative groups of clusters generated by VOSviewer software. The main keywords and their related words from each cluster are shown in table 2. Figure 5 is a visual representation of the themes that have been the focus of investigation in papers related to the fusion of DT, BIM and AH.

Table 2- Keywords clusters as presented in VOSviewer

1- Digital Twin	
Keyword	**Occurrence**

Digital twin	7
Heritage documentation	1
Parametric objects	1
Preventive conservation	1
Restoration project	1
Revit	1

2- Architectural Heritage	
Keyword	**Occurrence**
HBIM	6
Architectural heritage	1
Algorithm rebuild	1
Augmented Reality (AR)	1
Automatic segmentation	1
Conservation and documentation	1
Grasshopper	1
Heritage interpretation	1
Laser scanning and photogrammetry	1
Modern architecture	1
Segmentation algorithm	1

3- BIM	
Keyword	**Occurrence**
BIM	3
Castello sforzesco	1
Deep learning	1
Digitization	1
Historic preservation	1
Information heritage	1
Internet of things	1
Methodological approach	1

4- Building Energy Model	
Keyword	**Occurrence**
Cultural Heritage	2
Building Energy Model	1
Building performance	1
Energy improvement	1
International Foundation Class	1
Material characterization	1
Multi-criteria analysis	1
Non-destructive evaluation	1
Virtual Reality (VR)	1

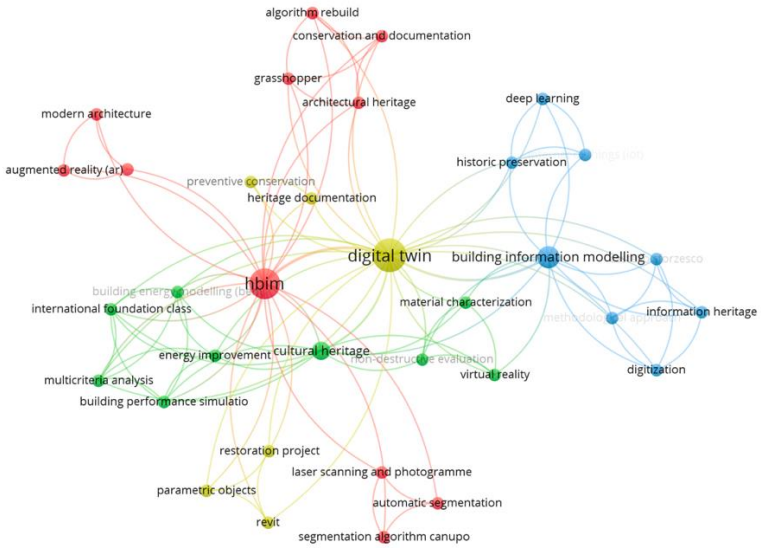

Figure 5- Scientific analysis map of author keywords

3.3 Content analysis

The content analysis results are based on the co-occurrence of author keywords analysis which is part of the scientometric analysis conducted in VOSviewer. Both table 2 and figure 5 serve as a visual aid for the qualitative analysis. As can be seen from table 2, in the group of Architectural Heritage (AH) the most occurring word is "HBIM", the remaining keywords such as "Automatic segmentation", "Grasshopper" , "Laser scanning and photogrammetry" are all related to HBIM. The strong links of HBIM to Architectural Heritage that are evident in this cluster are proof that HBIM is becoming an integral part of Architectural Heritage.

Whilst HBIM is still a valid field of research, many in the sector are seeing the Digital Twin as being a natural evolution of the implementation of more general 'BIM' and this is postulated by the research behind the Digital Twin group and the BIM group in the keywords analysis clusters. Moyano et al. (2022) indicated that the process of restoration of a historic building through HBIM should start with obtaining measured tangible data through remote sensing techniques, creating a point cloud to go through the scan-to-BIM process, processing the content of data applying ontologies to HBIM, classifying data and lastly evolving towards a Digital Twin. Massafra et al. (2022) discussed the steps towards developing a digital twin driven heritage assets management in heritage buildings.

Managing energy usage in heritage facilities is another aspect related to HBIM as evident from group 4 in the cluster analysis. Authors from this area namely Massafra et al. (2022) suggest using digital twins to achieve performance based heritage management. The digital twins can detect the conditions after a refurbishment in the building and will allow the sensor data collected around the conditions in the building to dictate the performance expectations and make recommendations for O&M through analytics (Massafra et al., 2022).

The importance of "heritage documentation" and "conservation and documentation" has been highlighted by several authors. Some authors pointed out that although each step of the conservation process requires participation from a diverse group of experts, there is no scientific record documenting a systematic approach for the complete process (Moyano et al., 2022). Moreover, pointing out that adopting a systematic approach to generate HBIM in restoration projects will support developing a DT of architectural elements for life-cycle management (Moyano et al., 2022). Similarly Guzzetti et al. (2022) called for a need to digitize the information asset of architectural heritage. The authors looked into associating the 3D model of a heritage building to different levels of data sets that include the history of the building, documentation, facility management, tourism fruition (Guzzetti et al., 2022).

4. Discussion

The above review and initial bibliometric analysis highlight significant correlation and focus of efforts in the field of BIM and a substantial body of work on HBIM. As would be anticipated, there is more limited research effort on the

emerging application of digital twin to the field of architectural heritage and very limited focus of efforts in bringing together the knowledge of HBIM, Heritage and digital twins. This is an area that could yield significant benefits in the future as society looks to better reuse, adapt, and manage historic buildings for future and more sustainable use.

Specifically, there exists the potential to focus research in several areas:

- Retro installation of technologies to monitor performance
- Enhanced planned, preventative maintenance based on historic data
- Historic (retrospective) Twinning of heritage assets
- Improved generation of geometric twin data (or digital shadow) based on extensible intangible data sources

Retro installation of technologies to monitor performance
BIM has been integrated into the cultural heritage domain, the HBIM model has potential to evolve into a new method for managing heritage buildings and sharing data with building lifecycle operators (Massafra et al., 2022). The direction where the restoration of architectural heritage is heading, displays a need to develop a comprehensive digital environment for digital twining of the heritage-built assets that will help in overcoming any potential risks to the assets (Bruno et al., 2022). Future research should also look into constructing an efficient framework that shows the evolution of complex heritage structures in a virtual environment (Guzzetti et al., 2022).

Enhanced planned, preventative maintenance based on historic data
Managing heritage assets is a complex process as the projects often deal with scientific, structural and textual data (Moyano et al., 2022). Whilst HBIM is still a valid field of research, many in the sector are seeing the Digital Twin as being a natural evolution of the implementation of more general 'BIM'. HBIM process of restoration of a historic building should lastly evolve towards a Digital Twin (Moyano et al., 2022). Some researchers stress on the need to start a HBIM process with a more accurate architectural survey with a laser scanner and modelling each element of the building as it can be the basis of digital twin to support preventative maintenance in heritage buildings (Casillo et al., 2022).

Historic (retrospective) Twinning of heritage assets
Thus there is a need to digitize the information asset of architectural heritage (Guzzetti et al., 2022). Data collection phase aims to acquire preliminary information regarding the building typology, methods of construction, materials used, previous alterations as well as room layout and use. This data is obtained through archival and bibliographical data, existing drawings, historical memories and photographs (Bruno et al., 2022). Moyano et al2022) called for a systematic approach in every step when working with heritage buildings.

This indicates that the more accurate the data sets gathered at the initial stage through archival research, the more it can help identify properties and characteristics of the building that would otherwise be challenging to find. A survey identifies the current geometrical features of the heritage building (Massafra et al., 2022). Understanding the alterations of cultural heritage through time is a complex procedure, however it is essential in understanding and operating attentively on the heritage assets. (Guzzetti et al., 2022)

Improved generation of geometric twin data (or digital shadow) based on extensible intangible data sources
An operating model is needed to show the history of the architecture and manage its heritage data. The basic idea of a BIM model is to associate information to the model of the asset, similarly cultural heritage data must remain the pivot of a similar system (Guzzetti et al., 2022). Predominantly the creation of a HBIM is undertaken through the process of Scan-to-BIM with measured data obtained of tangible cultural heritage and then transposed through a manual process to a geometric model via the use of BIM authoring tools (Moyano et al., 2022) (Casillo et al., 2022). The conservation of both tangible and intangible data is essential for heritage buildings, as it helps to keep both the physical integrity of the heritage building and its value for the future generations (Casillo et al., 2022).

Where physical measured data is not available, for example where the building fabric is partially non-existent, other data sets (such as photographs or historic drawings) can be used to support the geometric modelling process (Bruno et al., 2022) (Casillo et al., 2022)(Guzzetti et al., 2022).

5. Conclusions

This research is the first to use bibliometric analysis to investigate the state of published articles linking DT to BIM and AH. The analysis revealed that there is not enough research conducted in this area to solve the issues surrounding architectural heritage restoration and conservation. The small amount of research indicates the need for further examinations and studies in the area. Based on the quantitative part of the analysis, it can be concluded that the number of scientific research papers grew since 2019 and reached 10 papers around the topic in 2023. The study contributes to the field and reveals a need to develop a comprehensive digital environment and an efficient framework that shows the process of evolution of complex heritage structures in a virtual environment. Based on the results of the co-authorship network analysis there are 7 countries currently involved in such research with Italy being the country with the most research in that field. The analysis also revealed that fragmentation and isolation between authors calling for more collaborative work and exchanging ideas. Keywords' analysis revealed that HBIM is becoming an integral part of the architectural heritage, however many in the sector identify digital twin as being a natural evolution of the implementation of BIM, discussing a need to develop a digital twin driven heritage assets management.

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