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Digital twin application in heritage facilities management: systematic literature review and future development directions

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Abstract

Purpose – This paper aims to investigate the theoretical and practical links between digital twin (DT) application in heritage facilities management (HFM) from a life cycle management perspective and to signpost the future development directions of DT in HFM.

Design/methodology/approach – This state-of-the-art review was conducted using a systematic literature review method. Inclusive and exclusive criteria were identified and used to retrieve relevant literature from renowned literature databases. Shortlisted publications were analysed using the VOSviewer software and then critically reviewed to reveal the status quo of research in the subject area.

Findings – The review results show that DT has been mainly adopted to support decision-making on conservation approach and method selection, performance monitoring and prediction, maintenance strategies design and development, and energy evaluation and management. Although many researchers attempted to develop DT models for part of a heritage building at component or system level and test the models using real-life cases, their works were constrained by availability of empirical data. Furthermore, data capture approaches, data acquisition methods and modelling with multi-source data are found to be the existing challenges of DT application in HFM.

Originality/value – In a broader sense, this study contributes to the field of engineering, construction and architectural management by providing an overview of how DT has been applied to support management activities throughout the building life cycle. For the HFM practice, a DT-cum-heritage building information modelling (HBIM) framework was developed to illustrate how DT can be integrated with HBIM to facilitate future DT application in HFM. The overall implication of this study is that it reveals the potential of heritage DT in facilitating HFM in the urban development context.

Keywords Literature review, Digital twin, Built environment, Heritage life cycle, Facilities management

Paper type Literature review

1. Introduction

Heritage conservation management has gradually evolved into heritage facilities management (HFM) during the past decade, with the management focus shifting from

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mainly preservation to holistic asset management from a life cycle perspective (Machete *et al.*, 2021). HFM emphasises the management of the interactions between the heritage building and its surrounding environment, with "people" being a crucial component (Hou and Wu, 2019; Ho and Hou, 2019). In the meantime, new technologies have been increasingly applied to building heritage documentation, analysis and preservation (Janisio-Pawlowska, 2021). The heritage digitisation tools, such as three-dimensional (3D) scanning, global positioning system (GPS), satellite imagery, rectified photography and building information modelling (BIM), have not only enabled the visual presentation of heritage, but also provided technological solutions for efficient conservation management (Piaia *et al.*, 2021). Digital twin (DT) has been proposed to connect the real-time dynamic data that record the changes (e.g. physical dilapidation, people-building interactions, external environment development) with heritage building information modelling (HBIM) model and knowledge systems (e.g. life cycle management mechanism, heritage value ranking mechanism) to achieve systematic management.

According to the United Nations Educational, Scientific and Cultural Organisation (UNESCO), heritage buildings include monuments, groups of buildings and sites that are of outstanding value from the historical, aesthetic, ethnological or anthropological point of view (UNESCO, 2022). In the context of HFM, the changes that occur in their components, structures, surrounding environment are important dynamic elements for HFM strategies formation and decision-making. These changes are mainly generated due to the external environment, such as weather and temperature. As the level of human-heritage building interaction increases, human is also regarded as an important dynamic element in the life cycle of heritage buildings. The dynamic and static elements, and their relationships in HFM can be conceptualised in terms of a "4P" model that includes "Place, Product, Process and People". Each "P" represents a dimension of HFM.

Recognising the nature of HFM and the importance of both the dynamic and static elements of HFM, Jouan and Hallot (2020) proposed the development of DT with HBIM integration, given DT's capability of combining static and dynamic elements with real-time information (Al-Sehrawy and Kumar, 2021). Several extant research on heritage DT concentrate primarily on the technical development of DT and are typically undertaken on case study basis. How DT can support multiple management activities in the process of heritage conservation has not been adequately researched (Jouan and Hallot, 2020; Pan and Zhang, 2021). Also, DT application in the built environment, especially for heritage facilities, is still scarce, as the majority of heritage buildings lack up-to-date digital representations and it is costly to create such digital models from scratch. Therefore, it is essential to identify how current advance in DT can facilitate HFM, and to understand how a DT for HFM can be established with HBIM integration. Future built environment management will rely heavily on digital solutions; hence, a systematic review on existing literature regarding DT in HFM is timely research.

Aiming to address the above knowledge gaps, the present study intends to answer the following research questions:

RQ1. What is the current status of DT application in the built environment discipline?

RQ2. What is the current status of DT application in HFM?

RQ3. How HBIM can benefit and facilitate the development and operation of DT in supporting HFM?

RQ4. What should be the future development of DT in research and in practice of HFM?

In response to these enquiries, a systematic literature review was conducted. It aimed to provide the state-of-the-art in identifying, selecting and critically appraising the relevant research, thus contributing to the understanding of DT application in the built environment discipline including HFM. The systematic literature review identified and extracted the most essential literature (Section 3), revealed the relationships among the extracted literature and categorised the extracted literature from a life cycle management perspective (Section 4). Section 5 provides discussion on the identified literature based on a critical review process. Section 6 interprets the relationships between DT and HBIM, proposes a conceptual illustration of DT-HBIM and recommends four-stage of pathways to the development of HBIM-based DT. Section 7 elaborates the future development of DT application in both research and practice of HFM.

2. Digital twin: definitions and applications

The definition of digital twin (DT) was first provided by The National Aeronautics and Space Administration (NASA) (Shafto *et al.*, 2010) after Grieves first mentioned the concept in 2003 (Pan and Zhang, 2021). Grieves (2015) defined DT as "a virtual representation of what has been produced". Gabor *et al.* (2016) defined DT as "a special simulation, built based on the expert knowledge and real data collected from the existing system, to realize a more accurate simulation in different scales of time and space" (Tao *et al.*, 2018a). DT is widely understood as a virtual representation or digital entity of physical object or system (Böke *et al.*, 2020; Du *et al.*, 2020; Lee *et al.*, 2020; Liu *et al.*, 2020a; Rasheed *et al.*, 2020). Some researchers focus on the simulation of DT while others argue that DT is composed of five dimensions: physical entities (PE), virtual entities (VE), connections (CN), data (DD) and services (Ss) (Tao *et al.*, 2018b).

A DT provides both static and dynamic virtual manifestations of physical entities, systems and processes; the revolutionary merit of DT lies in its capability of embracing changes to the physical counterparts on a real-time basis by utilising enabling technologies, such as Internet of things (IoT), artificial intelligence (AI), machine learning and data analytics to capture real-time data and carry out real-time calculation (Angjeliu *et al.*, 2020; Austin *et al.*, 2020; Lu *et al.*, 2020a; Moretti *et al.*, 2020; Tekinerdogan and Verdouw, 2020; Aheleroff *et al.*, 2021).

In recent years, scholars comprehend and interpret DT with the knowledge and practice from a specific industry and aim to integrate the characteristics of the industry into a DT-based (or DT-supported) frameworks or mechanisms. Some of these frameworks or mechanisms are to be further modified for use in design (Li *et al.*, 2019; Tao *et al.*, 2019), monitoring (Zipper *et al.*, 2018; Revetria *et al.*, 2019; Lu *et al.*, 2020a), prototyping (Yildiz *et al.*, 2021) and training (Kaarlela *et al.*, 2020) in the respective industries (Hasan *et al.*, 2022). Having gained popularity in a wide range of industries such as astronautical, aerospace, manufacturing, mechanical and infrastructure engineering (Rasheed *et al.*, 2020), DT has been adopted to build the cyber-physical models for supporting digital development in the field of built environment.

The development of DT in the built environment context is desirable as modern management of built environment is a multi-dimensional process, which requires systematic integration of data from dynamic sources. Not only can a DT utilise virtual representation to reflect the physical counterpart, but it can also simulate, monitor, control and predict changes in the physical and societal elements of the built environment. The expression and functions of a DT depend on the types and scope of captured data, computerised control mechanism and object type scales (Sepasgozar, 2020, 2021; Yitmen and Alizadehsalehi, 2021). Capable of integrating the upmost level of digital technologies to capture the dynamic changes of the built environment at the component, building, project and city levels, DT can construct a virtual system based on built facilities and relevant data, and this system allows retroactive adjustment. This implies that it is a matter of time for DT to be applied and become prosperous in the field of HFM. DT has been a long-awaited digital tool for HFM, as the demand for effective HFM has intensified with the rapidly evolving needs of effective management for heritage buildings. This underscores the importance and complexity of the use of DT in HFM processes. In this study, DT is defined as a virtual "ecology system" constructed to provide virtual representation of building ("place"), human ("people) and the components or sub-systems of the building ("product") and conduct real-time data collection and analysis based on their interaction ("process"). In a technical manner, a DT is a computer programme that utilises the real-world data to simulate and predict the real-time future performance of a physical object with the integration of technologies, such as AI and IoT.

3. Method and process of systematic review

A thorough search that examines the pertinent body of literature using specific, understandable search criteria and selection criteria defines a systematic literature review (Ruhlandt, 2018). Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for systematic literature reviews (Moher *et al.*, 2015) with a focus on DT application in HFM, this review adopted keywords that were identified and selected based on relevant studies within the research domain (Lu *et al.*, 2020a, b).

Since this study focused on DTs instead of specific digital technologies used for DTs, terms of those technologies such as laser scanning and photogrammetry were not adopted as keywords for the literature search. In order to seek answers for the first and second research questions, "building", "architecture", "facilities" were included as keywords aside from "heritage" and "historic building". This included literature focusing on DT application in the built environment and thus the relationship between DT application in HFM and that in built environment can be further identified in the qualitative analysis. As BIM/HBIM is widely accepted as a useful tool in heritage management, "BIM" and "HBIM" were included as keywords. The keywords and their combinations used in the literature search process were ("digital twin") AND ("building" OR "architecture" OR "facilities" OR "heritage" OR "historic building" OR "BIM" OR "HBIM"), as depicted in Figure 1.

Based on two well-known literature databases: Scopus and Web of Science Core Collection, the search was first conducted in December 2020 and later updated in May 2021. The procedures for retrieving, screening and selecting publications for review were proceeded in stages, as shown in Figure 2.

Stage 1 identified a total of 1,105 publications from Scopus and 648 publications from Web of Science Core Collection, including journal papers, conference proceedings and books

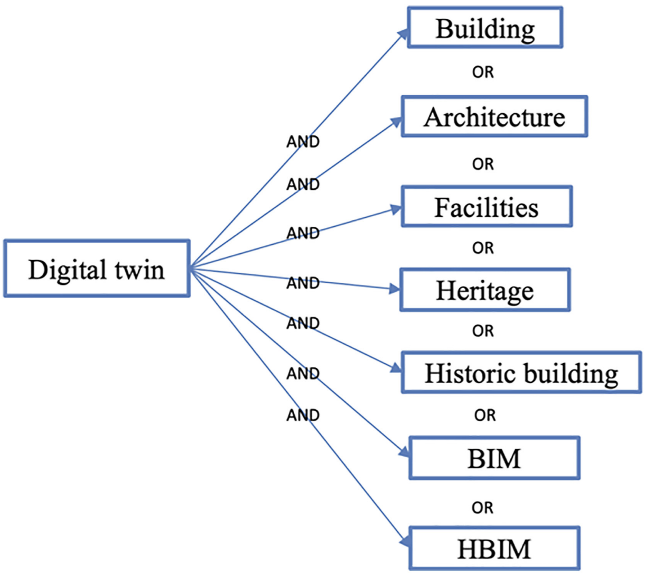

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Figure 1.
Literature search terms and combinations

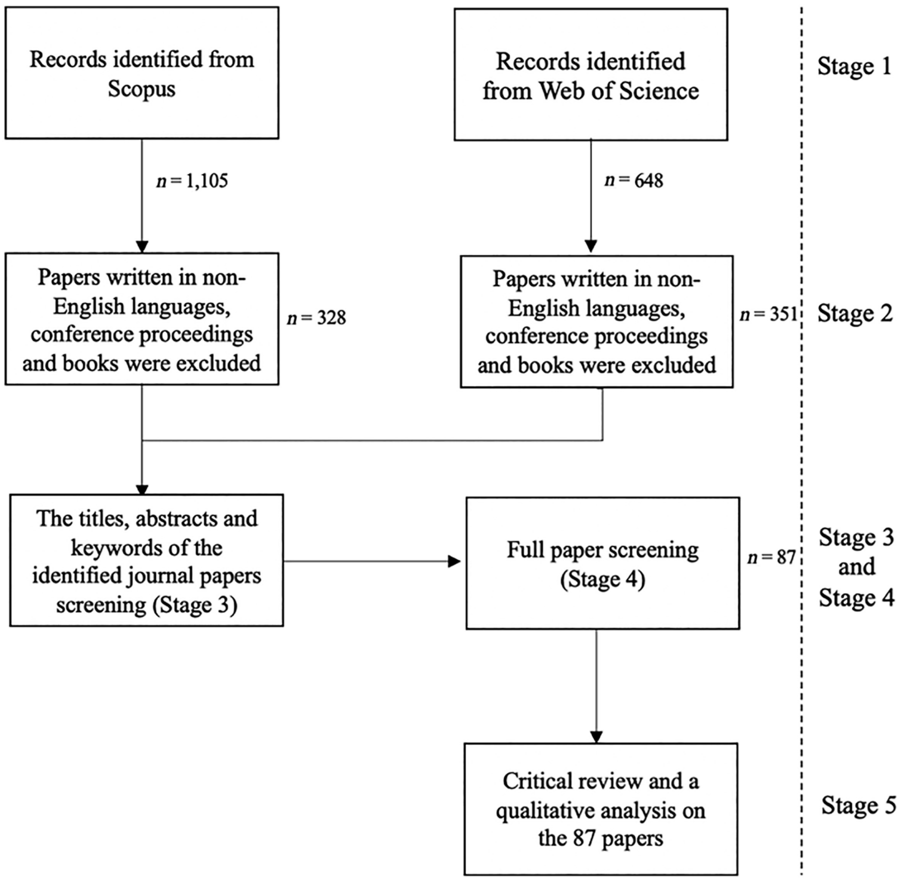

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Figure 2.
The systematic literature review process

published between 2000 and 2021 (before May 31st 2021) were retrieved using the search rules mentioned above (Figure 3). Stage 2: To extract essence from prominent studies or well acknowledged cases, the review focused on research published in international scholarly journals. The number of conference paper is 1.7 times of the papers published in journals. As a lack of international acknowledged mechanism for recognising the ranking or quality of conference paper, papers published in conference proceedings will be excluded. Journal papers written in non-English languages, conference proceedings and books were excluded. In stage 3, the titles, abstracts and keywords of the identified journal papers were screened for relevance. Papers not focussing on built environment topics were excluded. In stage 4, after screening full texts papers identified in Stage 3, 87 papers on DT application in building life cycle (e.g. design, construction, operation) were selected for critical review. Stage 5 involved a qualitative analysis of the 87 key papers to reveal how DT was applied to past built environment studies and directions for future research on DT in the built environment. The first, second and third authors were involved in the five stages of the reviewing process. The first author directed and guided the review process. To ensure the validity and reliability of the results of the literature review, the participation of multiple reviewers allowed to jointly decide whether a paper should be included or excluded.

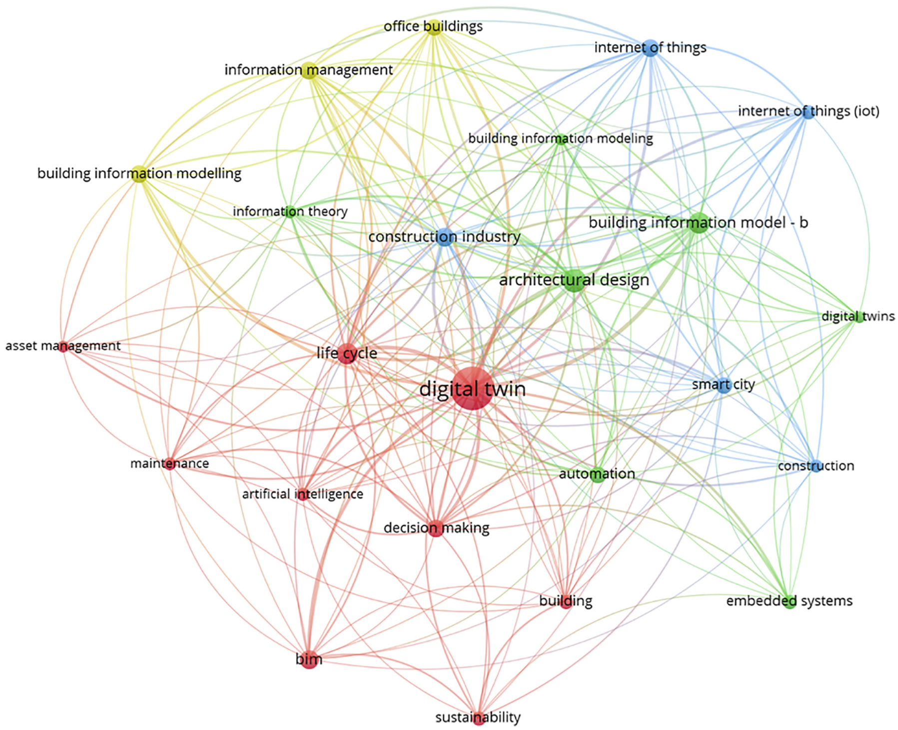


Figure 3.
Co-occurrence of keywords of the identified publications

Source(s): Authors

4. Literature selection and results

4.1 Identified literature and visualisation

In order to present a visualised format of the current development status of DT application in the built environment studies and its relationship with HFM development, the present study used VOSViewer – a computer programme developed for creating, visualising and exploring bibliometric maps of science (Van Eck and Waltman, 2010, 2014), to generate a bibliometric map based on the publications selected in Stage 4.

The map generated by VOSViewer, as shown in Figure 3, depicts the co-occurrence (frequencies being 5 or above) of keywords of the 87 selected publications. There was a total of 24 such keywords identified. The size of a circle in this keywords co-occurrence map indicates the number of times a keyword appears alongside with other keywords. Aside from the circle for "digital twin", the remaining 23 circles are of comparable size, implying that their co-occurrences are comparable. A shorter distance between two keywords indicates a larger number of their co-occurrences.

Table 1 contains a list of the 24 keywords. The term "occurrence" refers to the number of documents (among the 87 publications identified) in which the corresponding keyword occurred. The number of co-occurrences in a document is shown by the "link strength" between two keywords. "Total link strength" denotes the total strength of a keyword's co-occurrence links with other keywords. Despite the variations of some keywords (for example, "Building information model -BIM", "Building information modelling", "Building information modelling", "BIM") used in different papers, Table 1 shows that on the whole, "digital twin", "architectural design", "life cycle", "building information model -BIM", "information management",

Keywords	Occurrence	Total link strength
Digital twin	61	160
Architectural design	18	90
Life cycle	15	80
Building information model -BIM	14	72
Information management	10	58
Construction industry	11	55
Internet of things	10	53
Decision making	10	51
Office buildings	9	43
Internet of things (IOT)	7	38
Building information modelling	10	37
Information theory	6	37
Building information modeling	5	36
Smart city	9	36
Automation	9	32
BIM	11	30
Artificial intelligence	6	26
Construction	6	26
Maintenance	6	25
Digital twins	5	23
Building	7	22
Embedded systems	7	21
Sustainability	7	20
Asset management	5	17

Source(s): Authors

Table 1. Keywords analysis of the identified publications

"construction industry", "Internet of things" and "decision making" have the highest total strengths of co-occurrence links. In other words, these eight keywords appear together with the other keywords the most frequently in the documents examined.

The connections between DT and other seven keywords reflect the academic interest as well as current development trend of DT application in the field of built environment management. "Architectural design" is a specific stage in the life cycle of a building. It has a high level of occurrence with DT as keywords used in the identified literature, along with "Life cycle" and "Construction industry", indicating that DT has been relatively frequently applied in supporting building construction activities. "Building information model – BIM", "Information management" and "Internet of things" are digital tools. They are also frequently associated with DT, implying that these digital technologies are more frequently integrated with/into DT in the field of built environment management. According to Table 1, "decision-making" is also at a higher rank in the list. This means that many studies have been conducted to investigate how DT can aid in decision-making, which is an important management activity.

4.2 Overview of the selected papers

An overview of the 87 papers is shown in Table 2. The first and second columns show the journals in which the papers were published as well as the number of papers identified from each of those journals. The third column shows the author(s) and year of those publications.

4.3 Identification and categorisation of core literature

Based on an analysis of the keywords, the research areas can be divided by keywords that: (1) describe certain types of digital technologies such as BIM, Internet of things, artificial

Source	No. of publications	Authors (year)
Automation in Construction	9	Kunic *et al.* (2021), Rausch and Haas (2021), Pan and Zhang (2021), Lee *et al.* (2021), Lu *et al.* (2020a), Lu *et al.* (2020b), Wei and Akinci (2019), Love and Matthews (2019), Lu and Brilakis (2019)
Sustainability	8	Tagliabue *et al.* (2021), Kaewunruen *et al.* (2021), Desogus *et al.* (2021), Zaballos *et al.* (2020), Kaewunruen *et al.* (2020), Kaewunruen *et al.* (2019), Park *et al.* (2019) Kaewunruen *et al.* (2018)
Journal of Management in Engineering	7	Du *et al.* (2020), Gurevich and Sacks (2020), Austin *et al.* (2020), Lin and Cheung (2020), Lu *et al.* (2020c), Ham and Kim (2020), Francisco *et al.* (2020)
Advances in Civil Engineering	5	Zhang *et al.* (2021), Zhao *et al.* (2021), Peng *et al.* (2020), Yu *et al.* (2020), Zhang *et al.* (2020)
IEEE Access	4	Broo and Schooling (2021), Godager *et al.* (2021), Camposano *et al.* (2021), Khajavi *et al.* (2019)
Sensors	4	Liu *et al.* (2020b), Marra *et al.* (2021), Lee *et al.* (2020), Gutiérrez González *et al.* (2020)
Advanced Engineering Informatics	3	Taraben and Morgenthal (2021), Aheleroff *et al.* (2021), Schneider *et al.* (2019)
Journal of Cleaner Production	3	He *et al.* (2021), Wang *et al.* (2020), Kaewunruen and Lian (2019)
Applied Sciences	4	Bastos Porsani *et al.* (2021), Seghezzi *et al.* (2021) Moretti *et al.* (2020), Park *et al.* (2018)
ISPRS International Journal of Geo-Information	2	Beil *et al.* (2020), Jouan and Hallot (2020)
Engineering, Construction and Architectural Management	1	Xie *et al.* (2020)
Computers, Environment and Urban Systems	1	Diakite and Zlatanova (2020)
Journal of Asian Architecture and Building Engineering	1	Hasan *et al.* (2022)
Journal of Environmental Engineering (Japan)	1	Matsuda and Ooka (2020)
International Journal of Construction Management	1	Rausch *et al.* (2023)
Journal of Information Technology in Construction	1	Deng *et al.* (2021)
PFG - Journal of Photogrammetry, Remote Sensing and Geoinformation Science	1	Schrotter and Hürzeler (2020)
International Journal of Safety and Security Engineering	1	Antonino *et al.* (2019)
International Information and Library Review	1	Mujoo-Munshi (2003)
Production Engineering	1	Burggräf *et al.* (2021)
Applied Geomatics	1	Khalil *et al.* (2021)
Computers in Industry	1	Greif *et al.* (2020)
Building Research and Information	1	Turk and Klinc (2020)
ASHRAE Journal	1	Quirk *et al.* (2020)

Table 2.
An overview of the selected papers

(*continued*)

Source	No. of publications	Authors (year)
At-Automatisierungstechnik	1	Brosinsky *et al.* (2020)
Journal of Airport Management	1	Oliveira (2020)
Curator	1	Sabiescu (2020)
Computers and Structures	1	Angjeliu *et al.* (2020)
Journal of Building Engineering	1	Böke *et al.* (2020)
Designs	1	Gichane *et al.* (2020)
Software and Systems Modeling	1	Visconti *et al.* (2021)
IET Renewable Power Generation	1	Song *et al.* (2020)
Journal of Advanced Transportation	1	Meža *et al.* (2021)
Construction Innovation	1	Bosch-Sijtsema *et al.* (2021)
IEEE Transactions on Industrial Informatics	1	Turner *et al.* (2020)
Cities	1	White *et al.* (2021)
Agricultural Systems	1	Verdouw *et al.* (2021)
Fusion Engineering and Design	1	Jimenez *et al.* (2021)
Open Engineering	1	Huynh and Nguyen-Ky (2020)
Smart and Sustainable Built Environment	1	Götz *et al.* (2020)
Journal of Cultural Heritage	1	Scalas *et al.* (2020)
Energy and Buildings	1	Lydon *et al.* (2019)
Buildings	1	Tahmasebinia *et al.* (2019)
Frontiers in Built Environment	1	Kaewunruen and Xu (2018)
Journal of Digital Landscape Architecture	1	Shilton (2018)
Building and Environment	1	Nghana and Tariku (2016)
Renewable Energy	1	Berry *et al.* (2014)
Informatica	1	Styliadis (2007)

Source(s): Authors

Table 2.

intelligence and digital twin; (2) describe the scale/level of built environment, including smart city and buildings; and (3) describe activities in built environment, including construction, asset management, facilities management, architectural design and decision-making. This finding indicates that among the selected research, DT has been utilised more frequently to explore built environment management activities, such as construction management, asset management, facilities management and decision-making. Furthermore, the scale/level of the built environment ranges from city level to building level and management activities undertaken in the office buildings have been frequently researched from the perspective of DT application.

During the critical review process, a number of thematic categories or codes were generated for identifying the emerging themes. Various categories and sub-categories were identified and refined as a result of the many reviewing processes. Based on the iterative coding method offered by Wolfswinkel *et al.* (2013), the coding process was adjusted to suit the requirements of the author's review. The critical review technique used an inductive analytic methodology. During the critical review process, coding and categorisation was conducted in three steps.

First, based on the inquiry context of DT application, 52 essential papers were selected and were then divided into four groups: (1) construction management, (2) building operation and management, (3) heritage conservation and (4) smart city development (Table 3).

Second, a more thorough categorisation of the relevant publication was carried out in order to respond to research question 1: what is the current status of DT application in the built environment discipline. Following a more thorough examination of the selected papers, two themes – "the scale of DT application" and "certain digital technologies used for

Paper selected		DT application in specific areas			
Author(s)	Year	Construction management	Building operation and management	Heritage conservation	Smart city development
Kunic *et al*	2021	+			
Pan and Zhang	2021	+			
Rausch *et al*	2023	+			
Hasan *et al*	2021	+			
Bastos Porsani *et al*	2021		+		
Camposano *et al*	2021		+		
Desogus *et al*	2021		+		
Deng *et al*	2021		+		
Jimenez *et al*	2021		+		
Kaewunruen *et al*	2021		+		
Khalil *et al*	2021			+	
Seghezzi *et al*	2021		+		
Tagliabue *et al*	2021		+		
White *et al*	2021				+
Zhao *et al*	2021		+		
Angjeliu *et al*	2020			+	
Austin *et al*	2020				+
Beil *et al*	2020				+
Du *et al*	2020				+
Gong *et al*	2020			+	
Greif *et al*	2020	+			
Götz *et al*	2020		+		
Francisco *et al*	2020				+
Ham and Kim	2020				+
Huynh and Nguyen-Ky	2020		+		
Jouan and Hallot	2020			+	
Kaewunruen *et al*	2020		+		
Lin and Cheung	2020		+		
Liu *et al*	2020b		+		
Lu *et al*	2020a		+		
Lu *et al*	2020b		+		
Moretti *et al*	2020		+		
Oliveira	2020		+		
Sabiescu	2020			+	
Schrotter and Hürzeler	2020				+
Turk and Klinc	2020	+			
Xie *et al*	2020		+		
Zaballos *et al*	2020		+		
Antonino *et al*	2019		+		
Kaewunruen *et al*	2019		+		
Kaewunruen and Lian	2019		+		
Khajavi *et al*	2019		+		
Love and Matthews	2019		+		
Lu and Brilakis	2019		+		
Park *et al*	2019				+
Tahmasebinia *et al*	2019		+		
Tahmasebinia *et al*	2019			+	
Jouan and Hallot	2019			+	
Kaewunruen *et al*	2018		+		
Kaewunruen and Xu	2018		+		
Park *et al*	2018				+
Styliadis	2007			+	

Source(s): Authors

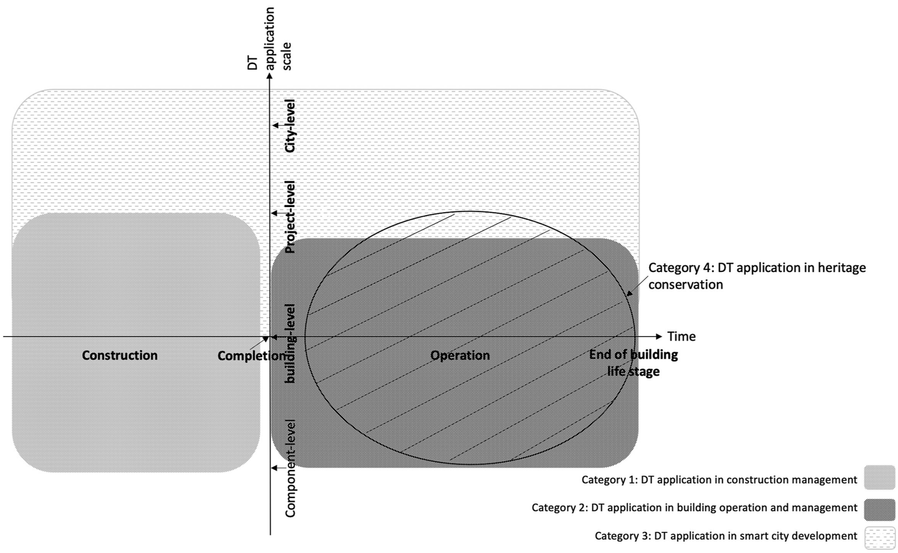
Table 3.
Categorisation of the key papers

construction a DT" – were discovered. The two themes were utilised to group the papers that were selected. However, only a small number of studies (of the 52 papers) described the precise digital technologies utilised to create a DT. As a result, it was challenging to group the papers according to the many digital technologies that were utilised to create a DT. On the other hand, it was discovered that among the papers, the scale of DT application had significant characteristics. The papers were then divided into four groups according to the scale of the DT application: "component level", "building level", "project level" and "city level". Developed based on the findings in Table 3, Figure 4 was created to illustrate the extents and relationships of the four groups of literature.

Third, a thorough analysis of the literature categorised as "heritage conservation" (Table 3) led to the division of the DT application into three sub-categorises depending on the roles of DT application plays in assisting heritage conservation. They are: "DT used for inspection and defect detection", "DT as integrative decision-making tool" and "DT and HBIM integration". The discussion on the three sub-categories of literature is elaborated under Section 5.2.

In Figure 4, the x-axis and y-axis respectively denote "Time" and "DT application scale". "Time" refers to the stages of a building's life cycle. "DT application scale" refers to the scale of DT proposed to be constructed or constructed, as described in the respective paper(s). The intersection point where the two axes intersect represents building completion time (x-axis) and DT application at building level (y-axis). The three shaded blocks represent the literature of DT application in three focus areas: construction management; building operation and management; and smart city development. Their shading densities indicate the number of papers in their respective category - the darker the shading, the greater the number of papers. The ellipse represents the group of DT application in heritage conservation.

Category 1 papers focus on utilising DT technologies to enhance construction management; among them, DT technologies are applied to develop virtual system replica at component, building and project levels. Category 2 papers describe DT application in building operation and management. Category 3 papers discuss utilisation of DT



Source(s): Authors

Figure 4. An illustration of the literature on DT application for built environment management

technologies to facilitate smart city development. While this category does not include papers on application of DT to build digital systems at component level, a major group of category 2 papers discuss DT application at component and/or building level. Among the papers, those on DT application in the building operation and management stage tend to focus on regular maintenance, predictive maintenance and long-term asset management. DT application at project level was not elaborated. Category 4 (ellipse shape) papers highlight DT application in heritage conservation its characteristics different from the preceding three categories is scarce and limited. The next section discusses the challenges of DT application in heritage conservation including future development of DT application in HFM, along with discussions of the other three categories (Figure 4).

Tables 1 and 3 and Figure 4 have provided an overview of the current status of DT application in the discipline of built environment. The majority of the identified literature focuses on DT application in building operation and management. While it has been acknowledged that the application of DT during the design and engineering phase of a construction project is predominately based on BIM (Opoku *et al.*, 2021), the characteristics of DT application in the building operation and management phase, particularly in the field of heritage conservation, are not clearly reflected in the identified literature. In addition, less than 10% of the identified literature discusses DT application in heritage conservation. Due to the paucity of literature on the application of DT in heritage conservation, it can be inferred that studies on DT application in heritage facilities management are even scarcer.

To understand the current status of DT application in the operational phase of built environment management (research question 1), it is necessary to summarise the DT application throughout the lifecycle of built environment management activities based on the four categories of the identified literature and to identify how DT has been applied in facilitating specific types of HFM activities (research question 2).

Section 5 is divided into two sub-sections: Section 5.1 answers the first research question and Section 5.2 provides structured explanations for answering the second research question. Section 6 proposes a conceptual illustration of DT-HBIM and elaborates the answers to the third research question, and Section 7 answers the fourth research question.

5. Discussions

5.1 DT application in the built environment context

A number of identified literature focuses on how to monitor/evaluate buildings using DT/BIM. According to these literature studies, the application of DT to construction management, building operation and management and smart city development will contribute to future application of DT in HFM.

5.1.1 DT application in construction management. The application of DT to HFM is linked to construction management and DT models at the component, building and project levels. As the most crucial stage of building formation, the construction phase has yet to fully embrace digital technology for automation in construction (Greif *et al.*, 2020; Kunic *et al.*, 2021). Multi-streamline activities implemented by multi-group participants require multi-dimensional management strategies for optimising construction process. To this end, DT will be highly relevant.

5.1.2 DT application in building operation and management. DT application to building operation management is approached from five dimensions of physical entities, visual model, DT data, services in DT and connections (Xie *et al.*, 2020; Qi *et al.*, 2021). The development of a framework or a roadmap is the first step to map physical entities' functional characteristics and operation process (Gong *et al.*, 2020; Huynh and Nguyen-Ky, 2020; Liu *et al.*, 2020b; Desogus *et al.*, 2021; Jimenez *et al.*, 2021). Some studies concentrated on developing DT models and applying them to energy management (Desogus *et al.*, 2021), maintenance (Jimenez *et al.*, 2021), health and safety (Antonino *et al.*, 2019), building audit and surveying (Park *et al.*, 2019; Francisco *et al.*, 2020), process management (Greif *et al.*, 2020; Kunic *et al.*, 2021; Hasan *et al.*, 2022) and user comfort evaluation (Zaballos *et al.*, 2020). Developed application include: evaluation of existing net zero energy building (Kaewunruen *et al.*, 2018), DT-aid indoor safety management framework (Liu *et al.*, 2020b), open-BIM supported asset management decision tool (Moretti *et al.*, 2020), image-based localisation and semantic mapping system (Wei and Akinci, 2019), smart campus development with BIM integration and IoT-enabled wireless sensors networks for environmental monitoring and emotion detection for user comforts (Zaballos *et al.*, 2020), DT energy audit with BIM and IoT technologies (Desogus *et al.*, 2021) and automated maintenance with simulation of modular robot cell for fusion power plants (Jimenez *et al.*, 2021). The application of DT to a city or area reflects or solves urban design, urban policy problems, fostering interaction between built environment and people (Austin *et al.*, 2020; Schrotter and Hürzeler, 2020; White *et al.*, 2021).

5.1.3 DT application in smart city development. The scope of city-level DT development is wider than that of building-level DT, and its input data layers are dynamic and multiple (Beil *et al.*, 2020; White *et al.*, 2021). According to Austin *et al.* (2020), Beil *et al.* (2020), Du *et al.* (2020), Schrotter and Hürzeler (2020) and White *et al.* (2021), city-level DTs concern buildings interaction with infrastructure and transportation, help identify patterns for deeper learning and prediction of people's role and their behaviour (Du *et al.*, 2020; Ham and Kim, 2020).

5.2 DT application in heritage conservation

The comprehensive literature review uncovered just seven works on the DT application in heritage conservation. However, these studies are of significant importance as they provide real-life cases to demonstrate the opportunity of applying DT to conserve built heritage. Five of these papers were published in or after 2020; they focused on the use of DT technologies to optimise maintenance performance of heritage building, and their scopes ranged from component (Angjeliu *et al.*, 2020) through building (Tahmasebinia *et al.*, 2019; Khalil *et al.*, 2021) to project levels (Rasheed *et al.*, 2020; Jouan and Hallot, 2019, 2020). "DT application in heritage conservation" falls under the category of "building operation and management" in building life cycle (Figure 4). DT has been used to monitor the performance of heritage building and as a tool to support heritage management.

5.2.1 DT used for inspection and defect detection. Three studies - Tahmasebinia *et al.* (2019), Angjeliu *et al.* (2020) and Khalil *et al.* (2021) - proposed using DT in heritage conservation activities such as maintenance prediction and heritage documentation management. Tahmasebinia *et al.* (2019) conducted a case study of the Sydney Opera House and found that the conservation of this iconic built heritage shall focus on shifting from large structural concerns to inspection and maintenance of minor issues of surface cracking and water ingress. They argue the importance of "digital twin" to develop integrated building information models for significant historic buildings.

According to Angjeliu *et al.* (2020), who approached the role of DT for built heritage conservation from the building structural safety perspective, DT can help to predict structural condition of historic buildings on a real-time basis using an accurate simulation model and monitoring system. Their study describes the development procedure of a DT application for a historic masonry building. The development process includes building the geometry to structural components material properties, construction technique, their construction in time, introducing the organisation of a DT model (in a hierarchical manner with separate parts and assembled together to create the final model in a later period). The study suggests that a part of the structural geometry can be imported from BIM or CAD models. Khalil *et al.* (2021) emphasised the importance of documentation of historic buildings and considered development of digital documentation of historic buildings would lead to development of DT for digitalisation of historic buildings.

These studies reflect that DTs are employed to inspect heritage building for defect detection, with an emphasis on obtaining data from physical parts to inform the virtual parts. The condition of heritage buildings needs to be monitored as continuous process for corrective maintenance. Obtaining and integrating geometric data in a DT is the essential task to carry out inspection and defect detection. Point clouds, digital images and thermal images collected from laser scanners, cameras, thermal imaging devices are used to demonstrate virtual representation of heritage buildings. Štroner *et al.* (2022) proposed an algorithm used for point cloud dilution. A DT can detect the as-built deviation based on data collected at different points of time. Sensors are frequently used to support DT to monitor performance of the built environment, buildings, facilities and equipment.

5.2.2 DT as integrative decision-making tool. Rasheed *et al.* (2020), for the first time, saw heritage conservation as part of HFM process. They argued DT not only provides real-time information for managing decision-making, it also makes prediction on how the built structure performs better. The eight value additions of DT highlighted for facility management are: (1) real-time remote monitoring and control, (2) higher efficiency and safety, (3) predictive maintenance and scheduling, (4) scenario and risk assessment, (5) better intra- and inter-team synergy and collaboration, (6) more efficient and informed decision support system, (7) personalisation of products and services and (8) better documentation and communication. These values indicate that DT application can provide HFM solutions, including selection of conservation approach and method, performance monitoring and prediction, development of maintenance strategy and energy evaluation.

Rasheed *et al.* (2020) has comprehensively elaborated the potential of DT application in HFM process by stressing how DT can be used to meet the functional needs of heritage facilities. Interpreting Rasheed *et al.* (2020)'s view from a technical perspective, DT can be used not only to inspect and monitor the condition of heritage facilities and detect their existing defects, but also support analysis and diagnosis functions based on various datasets against different parameters, support automatic control of internal service systems, and most importantly as an integrative decision-making tool for dynamic planning for future scenarios. For example, BIM and GIS data can be utilised for integrating in maintenance system to support decision-making. Virtual environment data can be used to conduct crowd management and path planning. Both geometric and non-geometric data are collected through technologies for supporting analysis, diagnosis and decision-making.

Ni *et al.* (2022) have developed a cloud-based DT for a city theatre in Norrköping to carry out predictive conservation activities. A comprehensive explanation on the model development was provided in this study, including system design (physical entities, virtual models, data warehouse, functional services and interaction and synchronisation), architecture development (the local part, the cloud part, insights and application). This study further discussed the impact of occupants on the indoor environment of a heritage building and how the developed DT can coordinate the human-heritage built environment interactions.

5.2.3 DT and HBIM integration. Jouan and Hallot (2020) analysed challenges of heritage conservation throughout a building life cycle and developed a data model that allows integration of semantically enriched HBIM models in the DT environment to support preventive conservation strategies. The potential application of DT in built heritage conservation by delineating heritage conservation process from socio-technical perspectives was discussed. It was suggested that DT can be used to integrate HBIM model and process data to implement monitoring and forecasting for built heritage management. This work contributed to bridging the gap between operation activities (dynamic data) and heritage characteristics (HBIM or static data) by explaining the types of data needed and in what conservation stages to provide them to facilitate decision-making. However, this conceptual model remains general given that databases (data input) vary significantly among individual heritage buildings. It is necessary to validate models by implementing DT in a specific case.

In recent years, BIM has been widely regarded as a powerful digital tool in facilitating built environment management activities (Tan *et al.*, 2022). It has continued to grow with its increasing application in new building design, thus significantly leveraging the efficiency in planning and construction stages of building projects. With the advent of compatible digital technologies, the capacities of BIM in improving existing building conditions have expanded, leading to the increasing utilization of BIM in various aspects of facilities management (Volk *et al.*, 2014; Wong *et al.*, 2018). Not only has this paved the way for the development of HBIM, as Jordan-Palomar *et al.* (2018) identified, the potential of BIM in specific heritage context such as the capability of representing in integrated historic phases, allowing real time information synchronization, creating libraries of historic constructed items designed from historic manuscripts and architectural pattern books, has thrived. In the last few years, HBIM technologies have been increasingly used in supporting heritage conservation activities, yet their main contributions lie in producing digital as-built models and generating BIM geometry from point clouds for supporting maintenance strategy decision-making (Dore and Murphy, 2017).

In the near future, DT can be integrated with HBIM to realise numerous heritage conservation activities, such as defect detection, material monitoring and management, analysis and diagnosis and decision-making. As the social requirements on heritage buildings increase, DT's potential of meeting the social and technical needs of heritage facilities become more explicit. In the past decade, as an increasing number of heritage buildings have been adaptively reused to support social development, the use of HFM have extended from architectural and structural conservation to service system updates and management, such as lighting system improvement, surveillance system enhancement and installation of climate monitoring system (Zhang *et al.*, 2022). While these systems are used to support different functions of HFM, they can be integrated to operate on the physical parts of the heritage facilities, such as automation control, retrofitting and comprehensive asset management.

6. Recommendations for developing HBIM-based DTs for HFM

6.1 A conceptual illustration of DT-HBIM integration

Figure 5 is a DT-HBIM conceptual illustration, elaborating four domains of relationships between the real world and a DT for HFM:

(1) Relationships between the real-world entity and the digital twin,

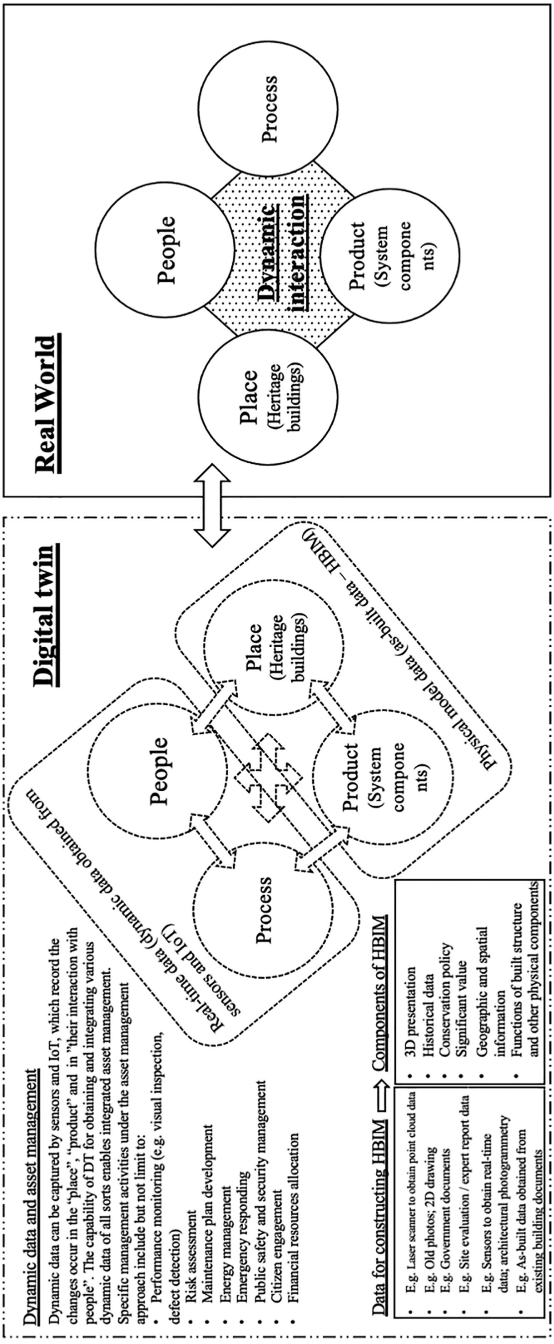
(2) Relationships among the 4Ps,

(3) Relationships between the dynamic data and static data and

(4) Relationships between HBIM and DT

In the context of HFM, a DT is established at the building level. A DT is a virtual representation of a heritage building, which represents all details among the dynamic interactions of the 4Ps – place, product, people and process. For a heritage building conserved in a modern society, it carries certain level of social meaning and allows continuous interaction with the society, especially the public citizen in the society. The conservation approach should take into account the interactions of the 4Ps. A DT is considered to be a suitable tool to realise the dynamic conservation.

Both DT and HBIM can be regarded as integrative digital tools to support the HFM. Their development relies on a number of enabling technologies. The fundamental technologies used by DT to enable real-time sensing, simulating, measuring, modelling and processing based on real-tie data collection are modelling, simulation, visualisation and sensing technologies. A DT is able to mirror, monitor, control and provide strategic solution for a specific heritage building



Source(s): Authors

Figure 5.
A conceptual illustration of DT-HBIM integration

because it is based on a real-time data enabled fused system. In other words, a DT can capture and process real-time data based on programmed algorithms from a big data analytic approach, simulate changes to the heritage building and its interactions with the dynamic surrounding environment, synchronise and store the data in the cloud and provide 3D representation to visualise the heritage building in detail based on its as-built models generated through multiple digital technologies, such as laser scanning, photogrammetry, VR technologies.

As their operations are based on digital models that simulated from the physical elements in the real world, DT and HBIM share some common functions. Despite the fact that algorithm technology, Internet technology, storage technology and process technology are all used in their creation and operation, DT is a more sophisticated built-up because it simulates not only the static built environment but also the dynamic movement of people and their interactive process with the built environment. The components that consist an HBIM include, but are not limited to, 3D presentation (e.g. point cloud data), historical data (e.g. old photos, 2D drawing), conservation policy documents (e.g. government documents), significant value evaluation documents (e.g. site evaluation data, expert report data), geographical and spatial information (e.g. sensor-based real-time data, architectural photogrammetry) and as-built data obtained from existing building documents. While HBIM provides data that mostly obtained based on a constant manual update of the model by the users, DT can directly connect the real-world object and capture instantly updated operation data without users' intervention (Jouan and Hallot, 2019). HBIM is a digital model integrated with a package of information that (1) heavily rely on heritage experts'/ conservationists' input; (2) professional conservation knowledge; (3) standards for unique built structure; and 4) expectation and implication from the society. The components of HBIM and data for constructing HBIM are illustrated in Figure 5.

A DT can effectively connect the "current" with the "past" with the support of HBIM, and the "past" is crucial for the development of HFM key performance indicators (KPIs) for decision-making among various asset management activities. One of the challenges that HFM practices envisage is that different sociocultural backgrounds would have different decision-making KPIs. In other words, they are determined based on the dynamic interaction of the 4Ps. HBIM is insufficient for processing KPIs identification while DT, with the support of real-time data, is capable of achieve the identification.

6.2 Pathways to the development of HBIM-based DT

Building-level DT development faces a number of challenges, including integrating data from various sources (e.g. real-time sensors, building management systems, cloud services, asset management system) (Niccolucci *et al.*, 2022); recognizing and identifying data records of heterogeneous attributes from different systems and incurring high synchronizing costs and data quality loss (Lu *et al.*, 2020c). These challenges are also anticipated in the development of HBIM-based DT. Comparing to modern buildings, the data for constructing DTs for heritage structures are far more complex. In order to establish a DT with integration of BIM, HBIM, GIS and IoT technologies, a DT must adopt an HBIM-centered strategy (Ramírez Eudave and Ferreira, 2021). The following development stages are recommended for building an HBIM-based DT:

The first stage is to determine the most essential information needed to describe the physical entities, the historical value of the heritage buildings and conservation policies. This type of information can be retrieved from historical documentation, photos or drawing stored in relevant government sector or historical centre. At this point, a collection of semantic descriptors (e.g. socio-economic, functional, spatial and material descriptions) can be developed. However, universal guidelines for obtaining the relevant essential information are lacking. The existing practice is involving conservation experts in the heritage conservation projects to facilitate heritage DT development (Ramírez Eudave and Ferreira, 2021).

The next stage is to acquire the information that was identified to be essential in the previous stage. Technologies such as GIS, 3D laser scanning and point clouds are used to obtain up-to-date geographic and spatial data to construct the virtual representation of the heritage buildings. The technical capabilities for acquiring survey data for constructing virtual representation is relatively matured. In this stage, digital models such as GIS and HBIM should also be constructed.

The third stage is to arrange and organise the acquired information in a logical and systematic manner to ensure data integration and data sharing between multiple models/platforms. For example, the HBIM model can be integrated with distributed IoT data based on openGIS. The HBIM-GIS integrated model can support both microscopic analyses and macroscopic management activities. IoT sensors can be installed in the heritage buildings to gather data and store them into a GIS database. IoT data can be utilised to leverage real-time updated models for monitoring the physical changes of the heritage buildings and gather information about the user's movement in the environment through GPS signal analysis and analyse environmental information.

The last stage is to simulate the potential risk phenomena in order to conduct vulnerability analysis. A number of qualitative and quantitative analytical tools, such as Risk Matrix, Failure mode and Effect Analysis (FMEA), Failure Tree Analysis (FTA) (Ramírez Eudave and Ferreira, 2021), can be used to predict the vulnerability scenarios to assess the vulnerability of the heritage buildings. Seismic vulnerability is commonly assessed (Mondello *et al.*, 2019; Shabani *et al.*, 2021; Aguilar *et al.*, 2023). Other vulnerability analyses include fire occurrence (Agapiou *et al.*, 2016), air pollution (Hadjimitsis *et al.*, 2013), precipitation data and flood events (Skilodimou *et al.*, 2019), sea erosion, salinity and coast exposure (Hadjimitsis *et al.*, 2013; Agapiou *et al.*, 2016). This stage is very crucial in the context of multi-hazard risk assessment.

7. Future development of DT application in HFM

The existing literature of DT application in built environment studies, as reviewed above, centres on developing or proposing to develop virtual replica of certain component/systems (products) to monitor changes of both physical objects (products) and dynamic interaction (processes) of involved parties (people) for achieving the aim of optimising the built environment performance in specific contexts (places), such as construction site, office building, industrial building and heritage monument. "Process", "People" and "Place" (viz. 3P model) are also the core components of FM definition (ISO, 2021), with "technology" also integrated into the 3P model of FM definition around a decade ago. Among the identified papers, the virtual DT systems are "products" empowered by various digital technologies. Thus, both physical objects and virtual systems can be regarded as "products" (viz. the 4th "P") in the identified studies. The following elaborates how the four "Ps" are reflected in the existing studies of DT application in HFM.

First, DT has been applied as a tool to combine both static and dynamic data of objects to reflect, monitor and predict the performance of the "product" (component, building, project). The data are extracted and processed based on multi-digital tools, including lasers scanners, sensors, IoT, RFID, WiFi, cloud computing. For component-level DT, the development is relatively straightforward when compared with building-level/project-level DT. A building-level or project-level DT requires inputting a much wider scope and variety of data and thus, BIM and GIS technologies are adopted, upon which a building/project-level DT is built. BIM technology has been proved to be the most powerful and reliable technology that can be integrated to realise the DT development and operation. It is foreseen that BIM-based DT will be the next focus of research in the field of DT in HFM.

Second, while BIM is able to strengthen the multi-party coordination and optimise the operation efficiency, the development of DT, through collecting real-time data, is to form a pool of "possible future scenarios" and to predict the "most likely scenario" for supporting decision-making. Process management (e.g. analysis and diagnosis, asset monitoring) and predictive management (e.g. defect detection) are two major management tasks identified in the literature of DT for HFM. These two management tasks are also two essential management requirements for HFM. Heritage has experienced a long history and its changes shall be closely managed. With the support of digitalisation, the "changes" of heritage can be divided into "processes" based on different time-dimension units, such as hour, day, month and so on. The analyses based on the data of different time-dimension units will help to predict a heritage's possible future scenarios. Also, many HFM activities identified from the existing research papers, such as performance monitoring, maintenance, retrofitting, carbon emission evaluation, are more complicated than common FM activities for newly built, ordinary buildings. The high complexity level of these HFM activities usually result in higher energy consumption. Thus, energy efficiency will be one of the major driving forces for the development of DT application in HFM.

Third, "people" is not only an indispensable component in the DT development but, on an increasing basis, "people" will be integrated in DT application as one form of dynamic data for predicting the human-heritage relationship (Gabellone, 2022). Many heritage facilities have been conserved as special "places" – for example tourism places, whose main mission is to "deliver group-value and knowledge" to a wide scope of society. "People", in the form of visitors, has huge impact on heritage – the "place". Therefore, in future research the role of "people" in the context of "heritage place" are two challenges for DT development. The status of "people" (e.g. visitors, staff) and its relationship with the "place" (e.g. number of visitors, intensity of visitor behaviour) will be absorbed as dynamic data to support DT development.

Fourth, heritage facilities have been considered as urban assets that closely related to the long-term urban development and can to certain extent drive the social development of a city or a country. Some heritage facilities serve as a city's or a country's identity and HFM activities shall be aligned with the city's or the country's development strategies. For example, the planning for certain heritage facilities is to support a city's mega event, such as the opening of Olympic Games. The heritage facilities will be subject to certain levels of adaption. DT can leverage technologies to predict the risks of disasters. Multiple simulations can also be conducted with the support of DT to realise virtual rehearsals.

Figure 6 recaps the main findings illustrated in Figure 5 and highlights the DT application in HFM in future research. Section 5.1 elaborates the identified papers lying in the "DT application in heritage conservation" category (category 4) and Section 5.2 summarises the identified papers in categories 1, 2 and 3. Based on the findings of the systematic literature review, DT application in HFM will expand to the city-level, meaning that DT of heritage facilities will be integrated in the city-level DT systems to harness smart city development. First, heritage facilities, especially national heritage monuments, are one of the economic forces for some regions or cities as they have driven the tourism development by attracting numerous overseas or domestic visitors. In order to leverage the smartness of urban infrastructure and tourism resources, local governments of some countries are committed to developing city-level smart networks/systems to enhance citizens'/visitors' travel experience. Second, advancing the "smart heritage" systems and integrating it to the "smart city" level systems would engage multi-parties in heritage management (Psomadaki *et al.*, 2019). Furthermore, as heritage management activities involve construction activities such as refurbishment and partial redevelopment, it is foreseen that DT application in construction management will be adopted in the studies of DT in HFM. In Figure 6, the coverage of future studies of DT application in HFM is outlined by the dashed lines and the dashed arrows indicate the anticipated expansion of the literature on DT application in HFM in future.

Based on the identified literature, the existing challenges of DT application in HFM are revealed. First, multi-layer digital data of heritage buildings, including those about historic

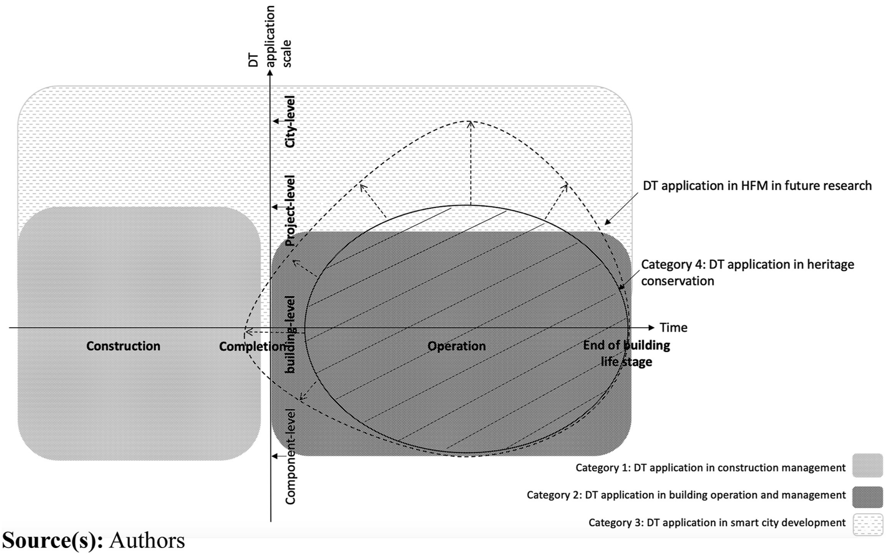


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Figure 6.
Anticipated development of DT application in HFM research

information, building structure, system functions, building outlooks, are at multiple temporal scales and voluminous. Thus, the development of a DT requires the support of big data which presents a technical challenge on database development. Second, the inherent variation in the nature of datasets in terms of semantics, geometry and levels of development requires development of structured and semantic database (Lu *et al.*, 2020c), which needs a scientific resource allocation mechanism and legal justification on collecting and using private data. Third, data provision requires adoption of a series of enabling technologies, such as BIM, building simulation, cross reality, IoT, machine learning, to create a building replica. Thus, the integration of the different digital systems and professional training is desperate. Fourth, although the literature shows committed efforts in designing a process of management mechanism to map out the decision-making process, the data management processes, such as defining the nature and contents of data and translating the professional practice into data input-and-output processes, require massive resource input.

8. Conclusions

Using a systematic approach to conduct a literature review on DT and HFM, this study sheds light on the life cycle management of heritage buildings and investigated their relationships based on the literature that discusses the DT application in built environment management. The identified literature (published in internationally acknowledged peer-review journals), after analysis using VOSviewer – a systematic literature review analysis tool, was categorised into four groups covering different stages and scales of built environment management activities, namely, construction management, building operation and management, heritage conservation and smart city development. These four groups of literature were reviewed in detail.

The review results show that DT has been mainly adopted to support decision-making on conservation approach and method selection, performance monitoring and prediction, maintenance strategies design and development and energy evaluation and management. Even though many researchers attempted to develop DT models for part of a heritage building at component or system level and testify the models using real-life cases, their works appear to be constrained by availability of data. Also, their studies mainly focus on how to utilise DT to facilitate heritage conservation while the DTs developed in their studies cannot fulfil HFM activities – life cycle management for heritage buildings.

The theoretical contributions of this study are as follows: first, it demonstrates how DT technology can be used to support decision-making, monitoring and management activities in the context of heritage building management. It contributes to a better understanding of the potential uses of DT technologies in this field. Second, this study identifies gaps in the literature on the application of DT in heritage building management, specifically the lack of attention to life cycle management of heritage buildings and provides a roadmap for future research in this area. Third, this study provides a conceptual illustration of how DT technologies can be integrated into HBIM to facilitate life cycle management of HFM. Finally, this study emphasises the importance of considering social dynamic aspects in the development of DT application for heritage conservation, such as adaptive reuse and revitalisation.

While this study helps to broaden the scope of future research and inform the development of best practices for the use of DT in HFM, it is not without limitations. First, although the literature databases are credible and have been widely regarded as representative, they may not cover all the publications in the area under investigation. Second, due to the limited literature of DT application in HFM, this study could only analyse the DT application in general built environment management activities to predict the future trend of DT application in both research and practice in HFM. Therefore, further effort should be endeavoured to address these limitations in similar studies in future.

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