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DIGITAL TWINS TO ENABLE SMART BUILT HERITAGE MANAGEMENT: A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

This paper aims to investigate theoretical and practical links between applications of digital twin (DT) and heritage facilities management (HFM) in order to identify future applications of DT in HFM through a systematic review of the rapidly expanding DT literature. A systematic literature review strategy was developed based on three research questions: what are (1) the current relationship between ID and HFM, (2) existing gaps between DT and HFM and (3) future trend of applying DT on BHM? The results of the literature review show that first, the studies on adopting DT in the disciplines architecture, engineering, construction and operation (AECO) have been growing in the past few years, especially from 2018 to 2020; second, among the identified papers, a major portion of the literature focuses on investigating DT's application in maintenance, operation, facilities management and asset management from both the building level and smart city level; third, heritage conservation calls for digital solutions for problems related to performance monitoring and predictive maintenance. The implication of this study is that DT application in HFM is that DT shall be integrated with heritage building information modelling (HBIM) to facilitate efficient data management and HBIM-based mechanism for DT development is needed for future HFM.

Keywords: Digital twin, built environment, heritage facilities management, HBIM, systematic literature review

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INTRODUCTION

Heritage conservation activities are labour-intensive and time consuming. Conservationists have been racing against the clock to prevent the built heritage from dilapidation and to maintain its authenticity at a minimization degree of alteration. In the past decade, technologies have been increasingly used in built heritage documentation, analysis and preservation. Drones, 3D scanning, GPS, satellite imagery and rectified photography, building information modelling (BIM) technologies have helped to build digital representation of built heritage so that comprehensive analysis, predictive maintenance and strategic management can be planned and implemented efficiently. The heritage digitization tools have not only enabled the visual presentation of heritage, but also provided technological solution for efficient conservation management. The adoption of BIM technique in 3D geometric modelling with integration of physical, functional and semantic characteristics is one of the technical breakthroughs in effective heritage documentation and management (José López et al., 2018). Murphy (2009) firstly proposed the concept of HBIM, and described it as “a novel solution whereby interactive parametric objects representing architectural elements are constructed from historic data, these elements (including detail behind the scan surface) are accurately mapped onto a point cloud or image-based survey”. HBIM is used to recreate built heritage for both the disappeared ones and existing ones. As-built HBIM is a process of restoring, modelling and managing historic structures by using reality-based recording data (Yang et al., 2020). The application of HBIIM in heritage conservation is growing and DT is proposed to be developed with integration of HBIM (Jouan and Hallot, 2020).

As digital twin has been widely adopted in built environment life-cycle management, its potential in building digital representation combined with static and dynamic elements for AECO (Architecture, Engineering, Construction, Operation) based on real-time information has manifested (Al-Sehrawy and Kumar, 2020). DT as a concept was brought up to describe as virtual representation of products and was proposed to applied in produce life-cycle management (Grieves, 2015). It has been extensively researched in the field of industrial manufacturing, but its application in built environment management is still scarce.

The aim of this paper is to identify future application of digital twin in heritage facilities management. The main research questions that will be answered in this paper are:

R1: what is the relationship between digital twin and heritage facilities management?
R2: what gaps exist in the literature between digital twin and heritage facilities management?
R3: what are the future studies on applying digital twin on heritage facilities management?

A systematic review approach was conducted, using both Scopus and Google Scholar to extract related journal papers with selected key words. The selected paper were reviewed and categorised based on the contents. Key publications were summerised and introduced in order to answer the three research questions. This study is an preliminary attempt to explore the potential of applying DT in heritage facilities management.

WHY DO WE NEED DIGITAL TWIN FOR BUILT HERITAGE MANAGEMENT?

Angjeliu et al. (2020) approach the role of DT for BHM from the building structural safety perspective, indicating that DT can help to predict the structural condition of historic buildings on a real-time basis based on an accurate simulation model and monitoring system. Specialists in historic building are proposing to embrace digital twin technologies in building lifecycle management for monitoring the building remotely on a real time basis (Tahmasebinia et al., 2019). Rasheed et al., (2020) suggested that DT can not only provide real-time information for monitoring and decision-making, but can also make prediction on how the built structure can perform better in the future. They also highlighted eight value additions of DT, including real-time remote monitoring and control, greater efficiency and safety, predictive maintenance and scheduling, scenario and risk assessment, better intra- and inter-team synergy and collaboration, more efficient and informed decision support system, personalisation of products and services, and better documentation and communication. These eight values demonstrate that the application of DT will provide solutions in built heritage management, including conservation approach and method selection, performance monitoring and prediction, maintenance strategies development, energy evaluation, etc.

Tahmasebinia et al., (2019) conducted a case study of Sydney Opera House and the findings reflect that the conservation focus of the iconic built heritage shall shift from large structural concerns to inspection and maintenance of minor issues of surface cracking and water ingress. The findings imply that a "digital twin" shall be created to develop integrated building information models for the historic buildings. Jouan and Hallot (2020) suggest that the application of DT principles in developing HBIM can support the preventive conservation of heritage places, such as monitoring the change, detecting risks, suggesting possible solution and assessing the potential impact of both threats and interventions on significant elements carrying out heritage values. Khalil et al., (2020) emphasised the importance of the documentation of historic buildings and regarded that DT is the development of digital documentation of historic buildings will lead to the development of DTs and DT is a better tool for historic building digitalisation.

METHODOLOGY

Search strategy and paper retrieval

This paper presents a systematic literature review on the theoretical and practical links between DT and HFM with an aim to identify future trends of DT application in HFM. The literature search was divided into two phases. In phase one, an initial search with the key word "digital twin" was conducted using SCOPUS search engine with the aim to determine the keywords for the systematic literature search. VOS Viewers was used to identify the hot topics of digital twin research based on co-occurrence of keywords. A co-occurrence analytical map of keywords was generated based on Scopus data set, shown in figure 1.

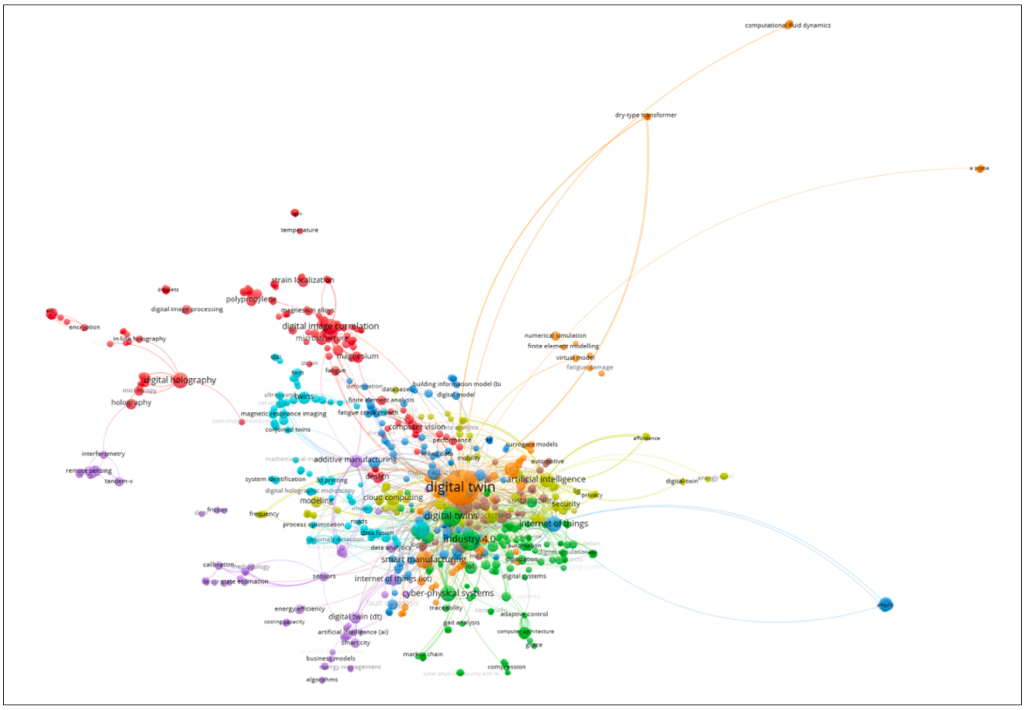

Figure 1. Co-occurrence analytical map of keywords generated based on Scopus data set
Note: the minimum cluster of 60 is considered and 8 clusters include 1000 keywords among 1,758 papers.

A number of 1,758 papers was generated and 1,000 keywords were identified and these keywords are presented in the map in forms of nodes of different size. Nodes that are strongly related with each other are located close to each other while weakly related nodes are located far away from each other (Jan van Eck and Waltman, 2014). Terms that co-occur a lot are located close to each other in the visualisation map. VOS viewer has grouped the terms into eight clusters, of which seven are of significant size (red, orange, yellow, green, sky blue, blue, purple). According to the two-dimensional distance between the terms generated and the size of circle surrounding the searching word “digital twin” shown in figure 1, it is apparent that a major number of papers are dedicated to the investigation on areas related to digitalisation, such as “industry 4.0”, “internet of things”, “cyber-physical systems”, “cloud computing”, artificial intelligence”, “simulation”, “machine learning”, “augmentation”, “blockchain”. “Active manufacturing” and “smart manufacturing” are the two most visible keywords that represent specific DT industry application. Figure 2(a) and 2(b) show the groups of keywords led by “active manufacturing” and “smart manufacture” and their relationships with digitalisation activities. In a literature review paper by Liu et al., (2020a), among all the papers on digital twin and its application, 47% of the journal publication focused on manufacturing. In figure 1, keywords with “buildings” include “building information modelling”, “existing building”, “historic building”, “smart building”, “building energy models”, “smart building”, “technical building service” and “building”. But they only compose a very small fraction in the co-occurrence analytical map and only “building information modelling” has direct connection with “digital twin”.

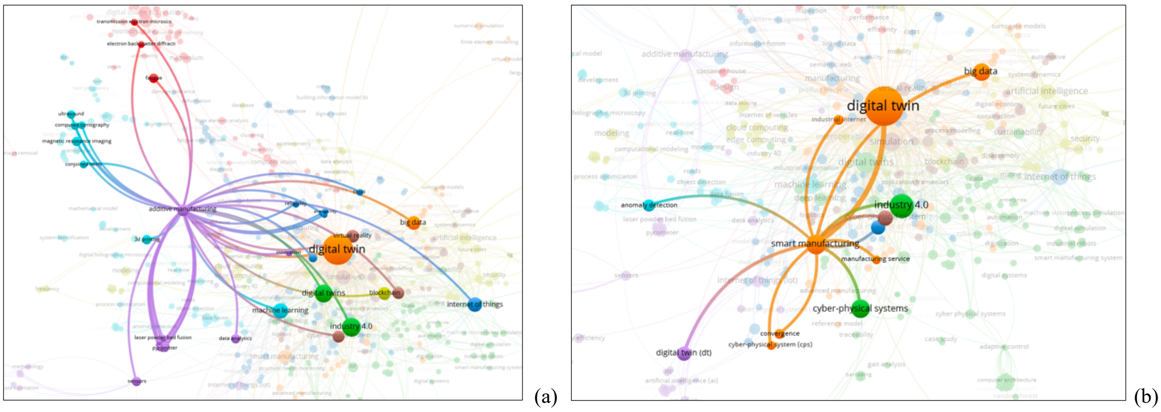

Figure 2. Co-occurrence analytical map of selected keywords created on bibliographic Scopus data for each group of keywords within and outside their individual groups: (a) active manufacturing network map; (b) smart manufacturing network map

Note: the minimum number of co-occurrences of keywords was 60, with a minimum strength of 0.

In phase two, a combination of key terms and their synonyms are used in the literature search. The key search terms for literature study were (“digital twin”) AND (“building” OR “architecture” OR “facilities” OR “heritage” OR “historic building” OR “BIM” OR “HBIM”) The search was carried out by using the online journal article databases: Scopus and Google Scholar. The procedure for retrieving papers is shown as follows:

- Stage 1: A number of 892 papers published between 1973 and 2021, were retrieved based on the searching rules mentioned above in the search engines, including journal papers, conference proceedings, and book.
- Stage 2: Paper in non-English languages, and in conference proceedings and book were excluded, leaving 256 articles.
- Stage 3: The abstract of each paper was read. Based on the results of stage 1, paper with focus on manufacturing were excluded.
- Stage 4: The titles, abstracts and keywords of the identified articles were screened for relevance. After screening of the paper selected in stage 3, a number of 55key literature focusing on digital twin application in the built environment lifecycle were identified for critical literature review.

An overview of selected paper

An overview of the 55 papers are shown in table 1. The first and the third columns indicate the journal where the paper was published and the number of identified paper under specific journal. The second and the fourth columns indicate the author(s) and the year of publication.

Table 1. An overview of the selected papers

Journal title (number of paper)	Author(s) and year	Journal title (number of paper)	Author(s) and year
Journal of Management in Engineering (6)	Austin et al., (2020); Lu et al., (2020c); Ham and Kim, (2020); Fransisco et al. (2020); Du et al., (2020); Lin and Cheung, (2020)	Sensors (5)	Liu, Zhang and Wang (2020); Gutiérrez González et al., (2020); Tekinerdogan and Verdouw, (2020); Lee et al., 2020
Automation in Construction (4)	Lu et al., (2020a); Lu et al., (2020b); Wei and Akinci, (2019); Love and Matthews (2019)	Sustainability (4)	Zaballos et al., (2020); Kaewunruen et al., (2019); Park et al., (2019); Kaewunruen et al., (2020)
IEEE Transactions on Industrial Informatics (2)	Turner, Oyekan, Stergioulas, Griffin (2021); Gehrmann and Gunnarsson, (2020)	At-Automatisierungstechnik (2)	Brosinsky, Krebs and Westermann, (2020); Ashtari Talkhesttani and Weyrich, (2020)
Advanced Engineering Informatics (2)	Taraben and Morgenthal, (2021); Ahelerof et al., (2021);	PFG-Journal of Photogrammetry, Remote Sensing and Geoinformation Science (2)	Döllner (2020); Schrotter and Hürzeler, (2020)
Journal of Cleaner Production (2)	Wang et al., (2020); Kaewunruen and Lian, (2019)	Engineering, construction and architectural management (1)	Xie et al., (2020)
Frontiers in Built Environment (1)	Kaewunruen and Xu, (2018)	Thermal Science and Engineering Progress (1)	Trancossi, Cannistraro and Pascoa, (2020)
Sustainable cities and society (1)	Gotz, Karlsson and Yitmen, (2020)	ISPRS International Journal of Geo-Information (1)	Jouan and Hallot, (2020)
Computers and Structures (1)	Angjeliu, Coronelli and Cardani, (2020)	International Journal of Production Research (1)	Huang, Wang and Yan, (2020)
Journal of Building Engineering (1)	Böke, Knaack and Hemmerling, (2020);	Applied Geomatics (1)	Khalil, Stravoravdis and Backes (2020)
International Journal of Safety and Security Engineering (1)	Antonino et al., (2019)	Tunnelling and Underground Space Technology (1)	Gong et al., (2020)
Journal of Ambient Intelligence and Humanized Computing (1)	Guo et al., (2019)	Applied Sciences (1)	Park et al., (2018)
Journal of Intelligent Manufacturing (1)	Jeon et al., (2020)	Annals of Nuclear Energy (1)	Lin, et al., (2021)
Applied sciences (1)	Moretti et al., (2020)	Journal of Airport Management (1)	Oliveira (2020)
Curator: The Museum Journal (1)	Sabiescu (2020)	Designs (1)	Gichane et al., (2020)
ASHRAE Journal (1)	Quirk et al., (2020)	ChemEngineering (1)	Maiwald (2020)
Building Research and Information (1)	Turk and Klinc, (2020)	Smart and Sustainable Built Environment (1)	Götz et al., (2020)
Computers in Industry (1)	Greif, Stein and Flath, (2020)	Advances in Civil Engineering (1)	Peng et al., (2020)
Future Internet (1)	Al-Ali et al., (2020)	Open Engineering (1)	Huynh and Nguyen-Ky, (2020)
Energy and Buildings (1)	Lydon et al., (2019)	Journal of Cultural Heritage (1)	Scalas et al., (2020)
Buildings (1)	Tahmasebinia et al., (2019)	IEEE Access (2)	Barricelli et al, (2019); Khajavi et al., (2019)

RESULTS

Definition of digital twin in the context of built environment

The definition of digital twin (DT) was first provided by NASA (Shafto et al., 2010) after Grieves first mentioned the concept. Grieves (2015) defined the 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., 2019). 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., 2020b; Rasheed et al., 2020). Some researchers focus on the simulation of DT while others argues that DT is composed by three dimensions: physical, virtual, and connection parts. Tao and Zhang (2017) suggested that a complete DT should include five dimensions: physical part, virtual part, connection, data and service. The understanding of DT has deepened along with its increasing industry application. Recently, the inter-relationships between the physical entities or system and the digital model are emphasised in an increasing number of investigations and they are conducted to facilitate the digital models to reflect the changing process. DT is defined as virtual manifestation of both static and dynamic features of physical entities, systems and process; enabling technologies such as IoT, AI, machine learning and data sciences, are used to enable real-time data capture and calculation so that the DT model can reflect the changes of the physical counterparts (Angjeliu et al., 2020; Austin et al., 2020; Döllner, 2020; Lu et al., 2020; Moretti et al., 2020; Tekinerdogan and Verdouw, 2020; Aheleoff et al., 2021). Having gained popularities in applied industries, such as astronautics and aerospace area, manufacturing, mechanical engineering, infrastructure operation (Rasheed et al., 2020), DT has been adopted in built environment industry. The 55 papers are key publications reflecting the how DT can be adopted in the field of built environment.

Appendix 1 provides some definitions appeared in the selected papers, which are listed based on the accepted time to illustrate development of the concept.

The application of digital twin in built environment management

Table 2. Categorisation of identified paper by disciplines in the built environment management

Application of DT in specific discipline		**Paper identified**
Construction		Greif et al., 2020; Turk and Klinc, 2020; Turner et al., 2020
Maintenance, operation, facilities management, asset management	Building level: building operation	Antonino et al., 2019; Kaewunruen et al., 2019; Love and Matthew, 2019; Wei and Akinci, 2019; Gichane et al., 2020; Huynh and Nguyen-Ky, 2020; Liu et al., 2020; Lu et al., 2020c; Moretti et al., 2020; Xie et al., 2020 Zaballos et al., 2020
	City level: smart city development	Park et al., 2018; Austin et al., 2020; Du et al., 2020; Francisco et al., 2020; Lin and Cheung, 2020; Lu et al., 2020c; Schrotter and Hürzeler, 2020
	Heritage conservation	Tahmasebinia et al., 2019; Trento et al., 2019; Angjeliu et al., 2020; Gong et al., 2020; Jouan and Hallot, 2020; Khalil et al., 2020
Others (digital twin development)		Guo et al., 2018; Khajavi et al., 2019; Al-Ali et al., 2020; Böke et al., 2020; Döllner, 2020; Gutiérrez González et al., 2020; Huang et al., 2020; Lee et al., 2020; Lu et al., 2020b; Lydon et al., 2019; Maiwald, 2020; Peng et al., 2020; Scalas et al., 2020; Tekinerdogan and Verdouw, 2020; Wang et al., 2020; Ahelerof et al., 2021

After an extensive reviewing of the identified papers, the papers are categorised into five categories based on their focuses, shown in table 2. The existing literature regarding the application of digital twin in built environment management focus on a few practical disciplines. A brief summary of the topics of the selected papers under the discipline "maintenance, operation, facilities management, asset management" are presented in the following sections.

The application of digital twin in facilities management and asset management

The existing literature regarding the application of digital twin in built environment management focus on a few practical operational disciplines: development of an intuitive interface to visualise a building "digital twin" (Huynh and Nguen-Ky, 2020), evaluation of net zero energy building for existing building (Kaewunruen et al., 2018), indoor safety management system framework based on DT (Liu et al., 2020), open-BIM methodology to support asset management decision making (Moretti et al., 2020), development of image-based localisation and semantic mapping framework (Wei and Akinci, 2019), smart campus development with the integration of BIM with IoT-based wireless sensors networks in the fields of environmental monitoring and emotion detection to facilitate users comforts (Zaballos et al., 2020).

Love and Matthews (2020) proposed a business dependence network (BDN) to visualise the structure of multiple cause-effect relationships that are used to organise the capabilities, changes, benefits that need to be considered prior to adoption. BDN is proposed based on empirical based research and it has been applied in nine case studies to verify the validity of the BDN in evaluating the benefits of adopting digital technologies in asset management. This study does not exert investigation direct on any digital technologies, but has highlighted an issues prior to system digitalisation, which is understanding how digitalisation will bring in tangible benefits to organisations. Antonino et al., (2019) proposed an occupancy detection system to be applied in crowded environment for detecting people's movements using Image Recognition (ImR) sensors and computer vision. The system is proposed to be integrated with BIM to facilitate maintenance management. Digital twin is not the focus of this paper. Yet the occupancy detection is an important part for facilities management and it will bear an additional dimension of meaning in the post COVID-19 pandemics. Accurate detection of occupancy rate provide direction for energy management and workplace safety management. The occupancy detection system is a functional platform as well as a strategic link that connect human activities and building digital models. This has provided significant implication on digital twin development for facilities management. Gichane et al., (2020) presents the design and implementation of a Digital Triplet for a three-floor elevator system. This paper explained the difference among digital model, digital twin and digital triplet. Digital triplet provides an additional intelligent activity layer with machine learning features on top of the typical digital twin design to integrate both physical system and digital twin. The propose of digital triplet highlights the major challenge of digital twin application in practice, which is data analyses and decision execution.

The application of digital twin in built heritage conservation

Jouan and Hallot (2020) reviewed the current challenges of built heritage conservation in its lifecycle and developed a data model that allows integration of semantically enriched HBIM models in the DT environment to support preventive conservation strategies. This paper discussed the potential of DT application in built heritage conservation by delineating the heritage conservation process from social and technical perspectives and suggested that DT can be used to integrate HBIM model and the management process data to implement monitoring and forecasting on built heritage performance management. Stakeholders' role in heritage conservation process are highlighted in the DT and thus related databases are proposed to include in order to provide information to support decision-making. Furthermore, the key mechanism to implement DT for preventative conservation is an integrated risk impact evaluation system. The contribution of this paper lies in that it has mapped out the general process of heritage conservation process and described it from the lens of DT. It has bridged the management activities (dynamic database) and heritage characteristics (HBIM or static database) by explaining what data are needed and provided at certain conservation stage, and their forms of facilitating decision-making. However, the conceptual model appears to be general given that databases (information input) vary significantly by heritage. It is necessary to validate the model by implementing the DT in a specific case to validate the fitting of the model in terms of database input and connection.

Angjeliu et al., (2020) described the development procedure of a digital model for digital twin applications for an historic masonry building, including building the geometry to structural components material properties, construction technique, and their construction in time, introducing the organisation of DT model (in a hierarchical manner with separate parts and assembled together to create the final model in a later period), and suggesting that a part of the structural geometry can be imported from BIM or CAD models. Angjeliu et al., (2020) focused on the technical aspect of DT development and discussed how the data are recorded, input, organized and structured so to support structural analysis and maintenance prediction.

DISCUSSION

HBIM and DT application in heritage facilities management

BIM and digital twin are two driving forces of built environment digitalisation. Comparing to BIM, digital twin application in built environment management still remains at an initial stage. BIM technologies has been commonly used in design and construction stages in the building life cycle environment while the concept of digital twin is more often to be related to the facilities management stage of a building. According to the selected paper, though "digital twin" is raised as one of the keywords for the paper, the focus of the paper is not about digital twin development or application in specific disciplines. These papers borrowed the concept of digital twin or the principles of digital twin to elaborate operation digitalisation of built environment management. Digital twin concept and principles are more frequently adopted in facilitating facilities management operation to optimise operation efficiency at both building level and city level. Facilities management is the most complicated stage in the built environment life cycle as it involves an integration of multi-system operation and a combination of managing both human activities and system functional activities as well as fulfilling the requirement of sustainable living. As circular economy has been emphasized, facilities management plays an important role in taking the initiatives of demonstrating sustainable development among existing buildings. This main theme has been reflected among all the selected paper.

Heritage facilities management is more complicated than general facilities management activities. Heritage performance monitoring and predictive maintenance are two major concerns in heritage conservation and thus they are the main heritage facilities management issues that urge for digital solutions. BIM technologies have been adopted in supporting heritage conservation activities mainly in terms of producing the digital as-built models and managing the documentation in the digital system. BIM system in heritage management is called HBIM. The application of HBIM is to provide digital solution for heritage documentation, information archiving, repair and maintenance planning, optimising the added-on system efficiency, etc. A series of enabling technologies, such as photogrammetry, laser scanning, virtual reality and augment reality technologies, etc. have been used to produce the digital images and digital models to facilitate the HBIM model development. According to the searching rules, selected paper with HBIM was not many as only those with both “digital twin” and “HBIM” were identified. Thus, HBIM application in heritage management is not elaborated in this paper.

HBIM has well facilitated heritage conservation by developing digital models to present the historic buildings in different stages of their life cycle with integration of historic information. HBIM is still the most applicable digital approach to support heritage conservation. However, the status of HBIM models is static and they require continuous update and programming to reflect the changes. Thus, DT is proposed to be created based on the existing HBIM models to create dynamic digital models that can reflect the dynamic changes of the physical objects. DT integrates artificial intelligence, machine learning and data analytic and it can predict the future heritage performance with both the digital technologies and the data base. Thus, in a near future, HBIM plays an essential role in DT development in the field of heritage facilities management.

Challenges of using DT in heritage facilities management

The challenges of using DT in heritage facilities management can be identified among the selected papers focusing on DT in maintenance, operation, facilities management and asset management. First, the development of a DT requires a huge volume of data and this has presented a big technical challenge on the database development. Multi-layers of data to reflect the contents (historic information, building structure, system functions, building outlooks, etc.) and data from multiple timelines consist a huge volume of digital data; second, the inherent variation in the nature of datasets in terms of semantics, geometry and levels of development requires a development of structured and semantic database (Lu et la., 2020c); third, the provision of data requires adoption of a series of enabling technologies, such as BIM, building simulation, cross reality, IoT, machine learning, etc. to create a building replica; fourth, though existing literature show that researchers have committed effort in designing a process management mechanism to map out the decision-making process, the processes of data management, such as defining the data nature and contents and translating the professional practice into data input-and-output process, require massive input. Thus, HBIM is proposed to be integrated for DT development.

CONCLUSION

This study used a systematic approach to conduct literature review on the digital twin and heritage facilities management to investigate their existing relationships in the current built environment studies. The results show that the studies focusing on integrating DT in HFM is still at a preliminary stage but the numbers of studies on DT application in AECO is growing in the past three years. HFM is seeking digital solution for problems related to heritage performance monitoring and predictive maintenance, and DT is argued to be able to support HFM in facilitating efficient data management. Furthermore, *a* HBIM-based mechanism for DT development is needed for future HFM. This paper has possessed a few limitations: (1) more searching engineers shall be adopted to support a more comprehensive literature extraction; (2) all literature regarding HBIM and digitalisation in facilities management shall be included to have a deeper understanding of the heritage facilities management problems and existing digital solution. A follow-up study will be conducted to consolidate the literature searching and review.

REFERENCE

Aheleroff, S., Xu, X., Zhong, R.Y. and Lu, Y., (2021). Digital Twin as a Service (DTaaS) in Industry 4.0: An Architecture Reference Model. *Advanced Engineering Informatics*, *47*, p.101225.

Al-Ali, A.R., Gupta, R., Zaman Batool, T., Landolsi, T., Aloul, F. and Al Nabulsi, A., (2020). Digital Twin Conceptual Model within the Context of Internet of Things. *Future Internet*, *12*(10), p.163.

Al-Sehrawy, R. and Kumar, B., (2020), August. Digital Twins in Architecture, Engineering, Construction and Operations. A Brief Review and Analysis. In *International Conference on Computing in Civil and Building Engineering* (pp. 924-939). Springer, Cham

Antonino, M., Nicola, M., Claudio, D.M., Luciano, B. and Fulvio, R.C., (2019). Office building occupancy monitoring through image recognition sensors. *International Journal of Safety and Security Engineering*, *9*(4), pp.371-380.

Austin, M., Delgoshaei, P., Coelho, M. and Heidarinejad, M., (2020). Architecting Smart City Digital Twins: Combined Semantic Model and Machine Learning Approach. *Journal of Management in Engineering*, *36*(4), p.04020026.

Barricelli, B.R., Casiraghi, E. and Fogli, D., (2019). A Survey on Digital Twin: Definitions, Characteristics, Applications, and Design Implications. *IEEE Access*, *7*, pp.167653-167671.

Bolton, A., M. Enzer, and J. Schooling. (2018). The Gemini principles: Guiding values for the national digital twin and information management framework. Cambridge, UK: Centre for Digital Built Britain.

Böke, J., Knaack, U. and Hemmerling, M., (2020). Prototype of a cyber-physical façade system. *Journal of Building Engineering,* p.101397.

Brosinsky, C., Krebs, R. and Westermann, D., (2020). Embedded Digital Twins in future energy management systems: paving the way for automated grid control. *at-Automatisierungstechnik*, *68*(9), pp.750-764.

Du, J., Zhu, Q., Shi, Y., Wang, Q., Lin, Y. and Zhao, D., (2020). Cognition digital twins for personalized information systems of smart cities: Proof of concept. *Journal of Management in Engineering*, *36*(2), p.04019052.

Francisco, A., Mohammadi, N. and Taylor, J.E., (2020). Smart City Digital Twin–Enabled Energy Management: Toward Real-Time Urban Building Energy Benchmarking. *Journal of Management in Engineering*, *36*(2), p.04019045.

Gabor, T., Belzner, L., Kiermeier, M., Beck, M.T. and Neitz, A., (2016), A simulation-based architecture for smart cyber-physical systems. In *2016 IEEE international conference on autonomic computing (ICAC)* (pp. 374-379).

Gehrmann, C. and Gunnarsson, M., (2019). A digital twin based industrial automation and control system security architecture. *IEEE Transactions on Industrial Informatics*, *16*(1), pp.669-680.

Götz, C.S., Karlsson, P. and Yitmen, I. (2020), Exploring applicability, interoperability and integrability of Blockchain-based digital twins for asset life cycle management, Smart and Sustainable Built Environment, Vol. ahead-of-print No. ahead-of-print. https://doi-org.tudelft.idm.oclc.org/10.1108/SASBE-08-2020-0115

Gong, C., Ding, W. and Xie, D., (2020). Twin EPB tunneling-induced deformation and assessment of a historical masonry building on Shanghai soft clay. *Tunnelling and Underground Space Technology*, *98*, p.103300.

Grieves, M. (2015). Digital Twin: Manufacturing Excellence through Virtual Factory Replication. White Paper; Dassault Systèmes: Vélizy-Villacoublay, France, pp. 1–7.

Greif, T., Stein, N. and Flath, C.M., (2020). Peeking into the void: Digital twins for construction site logistics. *Computers in Industry*, *121*, p.103264.

Guo, J., Zhao, N., Sun, L. and Zhang, S., (2019). Modular based flexible digital twin for factory design. *Journal of Ambient Intelligence and Humanized Computing*, *10*(3), pp.1189-1200.

Gutiérrez González, V., Ramos Ruiz, G. and Fernández Bandera, C., (2020). Empirical and Comparative Validation for a Building Energy Model Calibration Methodology. *Sensors*, *20*(17), p.5003.

Ham, Y. and Kim, J., (2020). Participatory Sensing and Digital Twin City: Updating Virtual City Models for Enhanced Risk-Informed Decision-Making. *Journal of Management in Engineering*, *36*(3), p.04020005.

Huang, S., Wang, G. and Yan, Y., (2020). Building blocks for digital twin of reconfigurable machine tools from design perspective. *International Journal of Production Research*, pp.1-15.

Huynh, D. and Nguyen-Ky, S., (2020). Engaging Building Automation Data Visualisation Using Building Information Modelling and Progressive Web Application. *Open Engineering*, *10*(1), pp.434-442.

Jeon, B., Yoon, J.S., Um, J. and Suh, S.H., (2020). The architecture development of Industry 4.0 compliant smart machine tool system (SMTS). *Journal of Intelligent Manufacturing*, pp.1-23.

Jouan, P. and Hallot, P., (2020). Digital Twin: Research Framework to Support Preventive Conservation Policies. *ISPRS International Journal of Geo-Information*, *9*(4), p.228.

Kaewunruen, S. and Lian, Q., (2019). Digital twin aided sustainability-based lifecycle management for railway turnout systems. *Journal of Cleaner Production*, *228*, pp.1537-1551.

Kaewunruen, S. and Xu, N., (2018). Digital twin for sustainability evaluation of railway station buildings. *Frontiers in Built Environment*, *4*, p.77.

Kaewunruen, S., Rungskunroch, P. and Welsh, J., (2018). A digital-twin evaluation of net zero energy building for existing buildings. *Sustainability*, *11*(1), p.159.

Khajavi, S.H., Motlagh, N.H., Jaribion, A., Werner, L.C. and Holmström, J., (2019). Digital twin: vision, benefits, boundaries, and creation for buildings. *IEEE Access*, *7*, pp.147406-147419.

Kaewunruen, S., Peng, S. and Phil-Ebosie, O., (2020). Digital twin aided sustainability and vulnerability audit for subway stations. *Sustainability*, *12*(19), p.7873.

Lin, Y.C. and Cheung, W.F., (2020). Developing WSN/BIM-Based Environmental Monitoring Management System for Parking Garages in Smart Cities. *Journal of Management in Engineering*, *36*(3), p.04020012.

Liu, M., Fang, S., Dong, H. and Xu, C., (2020a). Review of digital twin about concepts, technologies, and industrial applications. *Journal of Manufacturing Systems*. https://doi.org/10.1016/j.jmsy.2020.06.017

Liu, Z., Zhang, A. and Wang, W., (2020b). A Framework for an Indoor Safety Management System Based on Digital Twin. *Sensors*, *20*(20), p.5771.

López, F.J., Lerones, P.M., Llamas, J., Gómez-García-Bermejo, J. and Zalama, E., (2018). A review of heritage building information modeling (H-BIM). *Multimodal Technologies and Interaction*, *2*(2), p.21.

Lu, Q., Xie, X., Parlikad, A.K. and Schooling, J.M., (2020a). Digital twin-enabled anomaly detection for built asset monitoring in operation and maintenance. *Automation in Construction*, *118*, p.103277.

Lu, Q., Chen, L., Li, S. and Pitt, M., (2020b). Semi-automatic geometric digital twinning for existing buildings based on images and CAD drawings. *Automation in Construction*, *115*, p.103183.

Lu, Q., Parlikad, A.K., Woodall, P., Don Ranasinghe, G., Xie, X., Liang, Z., Konstantinou, E., Heaton, J. and Schooling, J., (2020c). Developing a Digital Twin at Building and City Levels: Case Study of West Cambridge Campus. *Journal of Management in Engineering*, *36*(3), p.05020004.

Love, P.E. and Matthews, J., (2019). The 'how' of benefits management for digital technology: From engineering to asset management. *Automation in Construction*, *107*, p.102930.

Lydon, G.P., Caranovic, S., Hischier, I. and Schlueter, A., (2019). Coupled simulation of thermally active building systems to support a digital twin. *Energy and Buildings*, *202*, p.109298

Maiwald, M., (2020). Integrated and Networked Systems and Processes—A Perspective for Digital Transformation in Thermal Process Engineering. *ChemEngineering*, *4*(1), p.15.

Moretti, N., Xie, X., Merino, J., Brazauskas, J. and Parlikad, A.K., (2020). An open BIM Approach to IoT Integration with Incomplete As-Built Data. *Applied Sciences*, *10*(22), p.8287.

Oliveira, P.P., (2020). Digital twin development for airport management. *Journal of Airport Management*, *14*(3), pp.246-259.

Park, S., Park, S.H., Park, L.W., Park, S., Lee, S., Lee, T., Lee, S.H., Jang, H., Kim, S.M., Chang, H. and Park, S., (2018). Design and implementation of a smart IoT based building and town disaster management system in smart city infrastructure. *Applied Sciences*, *8*(11), p.2239.

Park, S., Lee, S., Park, S. and Park, S., (2019). AI-based physical and virtual platform with 5-layered architecture for sustainable smart energy city development. *Sustainability*, *11*(16), p.4479.

Peng, Y., Zhang, M., Yu, F., Xu, J. and Gao, S., (2020). Digital Twin Hospital Buildings: An Exemplary Case Study through Continuous Lifecycle Integration. *Advances in Civil Engineering*, *2020*. https://doi.org/10.1155/2020/8846667

Quirk, D., Lanni, J. and Chauhan, N., (2020). Digital Twins: Answering The Hard Questions. *ASHRAE Journal*. pp. 22-25

Rasheed, A., San, O. and Kvamsdal, T., (2020). Digital twin: Values, challenges and enablers from a modelling perspective. *IEEE Access*, *8*, pp.21980-22012.

Sabiescu, A.G., (2020). Living archives and the social transmission of memory. *Curator: The Museum Journal*, *63*(4), pp.497-510.

Scalas, A., Mortara, M. and Spagnuolo, M., (2020). A pipeline for the preparation of artefacts that provides annotations persistence. *Journal of Cultural Heritage*, *41*, pp.113-124.

Shafto M, Conroy M, Doyle R, Glaessgen E, Kemp C, LeMoigne J, et al. (2010). DRAFT modelling, simulation, information technology & processing roadmap – technology area 11. National Aeronautics and Space Administration.

Schrotter, G. and Hürzeler, C., (2020). The Digital Twin of the City of Zurich for Urban Planning. *PFG–Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, pp.1-14.

Tahmasebinia, F., Fogerty, D., Wu, L.O., Li, Z., Sepasgozar, S.M.E., Zhang, K., Sepasgozar, S. and Marroquin, F.A., (2019). Numerical analysis of the creep and shrinkage experienced in the Sydney Opera House and the rise of digital twin as future monitoring technology. *Buildings*, *9*(6), p.137.

Talkhestani, B.A. and Weyrich, M., (2020). Digital Twin of manufacturing systems: a case study on increasing the efficiency of reconfiguration. *At-Automatisierungstechnik*, *68*(6), pp.435-444.

Tao, F. and Zhang, M., (2017). Digital twin shop-floor: a new shop-floor paradigm towards smart manufacturing. *IEEE Access*, *5*, pp.20418-20427.

Tao, F., Zhang, H., Liu, A. and Nee, A.Y., (2018). Digital twin in industry: State-of-the-art. *IEEE Transactions on Industrial Informatics*, *15*(4), pp.2405-2415.

Tekinerdogan, B. and Verdouw, C., (2020). Systems Architecture Design Pattern Catalogfor Developing Digital Twins. *Sensors*, *20*(18), p.5103.

Trancossi, M., Cannistraro, G. and Pascoa, J., (2020). Thermoelectric and solar heat pump use toward self-sufficient buildings: The case of a container house. *Thermal Science and Engineering Progress*, *18*, p.100509.

Taraben, J. and Morgenthal, G., (2020). Methods for the Automated Assignment and Comparison of Building Damage Geometries. *Advanced Engineering Informatics*, *47*, p.101186.

Turner, C.J., Oyekan, J., Stergioulas, L. and Griffin, D., (2020). "Utilizing Industry 4.0 on the Construction Site: Challenges and opportunities". *IEEE Transactions on Industrial Informatics*, *17*(2), pp.746-756.

Van Eck, N.J., & Waltman, L. (2014). Visualizing bibliometric networks. In Y. Ding, R. Rousseau, & D. Wolfram (Eds.), Measuring scholarly impact: Methods and practice (pp. 285–320). Springer.

Xie, X., Lu, Q., Rodenas-Herraiz, D., Parlikad, A.K. and Schooling, J.M., (2020). Visualised inspection system for monitoring environmental anomalies during daily operation and maintenance. *Engineering, Construction and Architectural Management*. Vol. 27, No.8, p.1835-1852.

Wang, Y., Wang, S., Yang, B., Zhu, L. and Liu, F., (2020). Big data driven Hierarchical Digital Twin Predictive Remanufacturing paradigm: Architecture, control mechanism, application scenario and benefits. *Journal of Cleaner Production*, *248*, p.119299.

Wei, Y. and Akinci, B., (2019). A vision and learning-based indoor localization and semantic mapping framework for facility operations and management. *Automation in Construction*, *107*, p.102915.

Appendix 1. Definition of Digital Twin based on the selected paper for in-depth literature review

Author, year of publication	Definition
Bolton et al., 2018	"A realistic digital representation of assets, processes, or systems in the built or natural environment."
Du et al., 2020	"Grieves and Vickers (2017) defined a DT to be a set of virtual information constructs that are designed to fully describe a potential or existing physical manufactured product"
Turner, et al., 2020	Digital twin is used to "capture real-time activity and support predictive intelligence for decision-making"
Moretti et al., 2020	"The concept of Digital Twins (DT) aims to address the integration of static and dynamic data, thereby enabling the creation of a digital replica of the physical building that is always up-to-date through its life cycle. DTs are therefore integrated, multifaceted, and multi-scale digital replicas of physical assets, systems, processes, and buildings, that accelerate the development and benefits of BIM in AECO"
Liu et al., 2020	"The DT involves the creation of a virtual object in the digital world that corresponds to a physical object…it can be realized through various technologies, such as the IOT, data/control models, and machine learning"
Lee et al., 2020	"A digital twin is a digital model of a physical entity. It virtually simulates and predicts simulation results by creating digital twins of objects"
Lu et al., 2020	"The concept of DTs evolved as a comprehensive approach to manage, plan, predict and demonstrate building/infrastructure or city assets. The DT is a digital model, which is a dynamic representation of an asset and mimics its real-world behaviour"
Al-Ali et al., 2020	"A smart object, product, system, and process consists of both a physical part and its complementing digital counterpart, also referred to as virtual and cyber part, and more recently referred to as its digital twin."
Angjeliu et al., 2020	"…the DT is an integrated multi physics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, history, etc., to mirror the life of its corresponding twin... he triad (physical model, big data and virtual simulation model) is called the Digital Twin (DT)"
Tekinerdogan and Verdouw, 2020	"A digital twin refers to a digital replica of potential or actual entities (i.e., physical twin). It provides rich representations of the corresponding physical entity and enables sophisticated control for various purposes… Digital twins are made possible through the integration of various technologies such as Internet of Things, artificial intelligence, machine learning, and data science, which enable living digital simulation models to be created that reflect the changes of the physical counterparts"
Böke et al., 2020	"A digital twin gen er ally means the virtual representation of a physical system. It enables the monitoring, real-time optimisations, decision-making and predictive maintenance of the system"
Quirk et al., 2020	"Digital twins in the built environment are digital representations of real-world infrastructure using building information modeling (BIM) software. Applying these tools in a disciplined manner can help built environment professionals find answers sought by building owners and operators pertaining to optimization of capital, efficient operations, change management, resiliency and much more."
Xie et al., 2020	"From the perspective of information richness and analytical/decision-making capability, the concept of Digital Twins (DT) is broader than BIM. In addition to the capabilities offered by BIM, DT is a comprehensive solution that can monitor the as-is status (e.g. condition) of its "physical twin" by integrating multi-source data and data analytics, control and simulation functions."
Austin et al., 2020	"A digital twin is a cyber (or digital) representation of a system that mirrors its implementation in the physical world through real-time monitoring and synchronization of data associated with events."
Lu et al., 2020c	"A digital twin (DT) refers to a digital replica of physical assets, processes, and systems. DTs integrate artificial intelligence, machine learning, and data analytics to create living digital simulation models that are able to learn and update from multiple sources as well as represent and predict the current and future conditions of physical counterparts"

Lin and Cheung, 2020	"Digital twin (DT) is another concept associated with I4.0; it is a dynamic virtual representation of a physical object or system across its lifecycle, using real-time data to enable understanding, learning, and reasoning, and has a similar essence to CPS. Furthermore, DT has the potential to gather and analyze information at different scales, facilitate more efficient construction processes, and allow for informed decision making, which will ultimately promote a safer environment at reduced costs and improved efficiency."
Döllner, 2020	"Digital twins, in general, are composed of three parts, "which are the physical entities in the physical world, the virtual models in the virtual world, and the connected data that tie the two worlds". While the connection between both can be handled by sensors, the virtual models have to be derived from the physical counterparts."
Khalil et al., 2020	"The digital twin in the AEC industry is typically connected with BIM (Building Information Modelling), building simulation, XR (cross reality) and IoT (Internet of Things) concepts in order to build a digital replica of the building, usually with near real-time update, that can help in optimising the decision-making process."
Huynh and Nguyen-Ky, 2020	"'Digital twin', in the scope of building automation development, is a concept related to a physical structure's digital representative carrying real-time properties of the original entity, and thus, the implementation of such is considered beneficial in term of operational management and would gradually raise the premise's assets value."
Aheleoff et al., 2021	"a Digital Twin is a digital replica of a physical entity with the two-way dynamic mapping between a physical object and its digital model, which has a structure of connected elements and meta-information"