Building Information Modelling in Healthcare Design and Construction: a Bibliometric Review and Systematic Review

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Abstract. Healthcare facilities play a key role in responding United Nations goals, such as sustainability, health and welling. The outbreak of the COVID-19 epidemic has driven much attention to expanding healthcare capacity through advanced digital technologies, such as Building Information Modelling (BIM). Nevertheless, a systematic review of research achievements is lacking. This research uses bibliometric and systemic literature review methods to investigate BIM applications in Healthcare Design and Construction (HDC). The bibliometric investigation focuses on country, journal co-citation, and keyword clustering analyses. The systematic review classifies application domains, BIM actions, and other digital technologies accompanying BIM. Finally, 17 major BIM actions are summarized for six major domains, including operability, resilience, collaboration, sustainability and constructability. This study reveals that the outbreak of COVID-19 has greatly stimulated the academic interest in digital technologies for HDC, and there is geographical uniqueness highly relevant to local government policies and national healthcare services. However, related research is still in a relatively preliminary stage.

Keywords: Literature Review, Healthcare Architecture, Digital Technology, BIM, Healthcare Design and Construction

1 Introduction

According to the World Health Statistics from the WHO [1], more than half of the world's 7.3 billion people cannot access the essential health services they need. Especially in remote and underdeveloped areas, it is hard for people to access healthcare facilities. In response, a United Nations goal aims to improve health-related sustainable development and achieve universal health coverage by 2030. Healthcare facilities will play a critical role [2], although the shortage of healthcare capacity and inefficiency in healthcare building delivery remains a significant challenge [3, 4]. Another serious challenge in terms of sustainability also exists at the same time. The energy consumption and greenhouse gas emissions caused by buildings account for about one-third of emissions. They may double in 2050, while the United Nations estimates that the urban population in 2050 will increase by 2.5 billion. The outbreak of the COVID-19 pandemic has intensified the global consensus on these challenges, as it has exacerbated capacity shortages and a crisis in healthcare facilities. Some countries are trying to expand the healthcare capacity in a short period and smooth the virus's expansion speed through rapid healthcare construction projects. The urgent need for healthcare services has accelerated the development of healthcare facilities world-wide.

However, Healthcare Design and Construction (HDC) has the highest risk of encountering major and unforeseen problems among all project types. A healthcare construction project involves hundreds of stakeholders and suppliers. The initiative of Building Information Modeling (BIM) has become a trend in the literature on HDC to deal with these challenges. BIM can transform traditional information management and integrate data from different disciplines [5]. Namely, horizontal integration among various stakeholders and vertical integration of information at different stages becomes possible with the incentive of BIM [6]. Many studies have shown that BIM has a profound impact on how healthcare projects are designed and delivered. Studies have reported the successful implementation of BIM in healthcare construction in different countries, such as the Netherlands [7], Norway [8], Australia [9], United Kingdom [10], and United States [11]. Many articles describe BIM as incredibly beneficial in designing frontiers of hospital spaces with numerous technical appliances and demanding performance requirements. However, BIM implementation also faces challenges. The reality in HDC is that introducing BIM must be done so alongside a range of complicated design standards and requirements, and so there is a significant need for further review.

This study aims to develop a comprehensive literature review for the application of BIM within the context of HDC to fill the gap. There us no systematic review in this emerging area. The research method combines bibliometric analysis and systematic analysis. Selected literature is illustrated through a country analysis, journal co-citation analysis, and keyword clustering analysis. In addition, application domains will be chategorised along with an analysis of BIM actions in various building stages, and against various techniques for working with BIM. This study will identify the trend towards BIM HDC, and develops propositions and challenges for future BIM applications.

2 Methodology

This study combines bibliometric analysis and systematic review to understand the BIM applications in HDC. Bibliometrics review provides comprehensive and objective statistics of the scholarly output and academic data to accelerate the speed and comprehension in understanding a sample of articles [12]. Systematic review is a labour-intensive method that uses reproducible methods to test hypotheses, summarise existing results, and evaluate the consistency of previous studies to improve the accuracy of the review.

The authors examined several databases including WOS, Scopus, and google scholar, comparing their coverage of disciplines and their suitability for visualisation software. In the end, WOS was selected. The initial search included queries using a combination of healthcare building-related keywords and "BIM", including ("hospital*" or "healthcare*") and ("building*" or "construction*" or "architectur*" or "design") and ("BIM" and "building") or "building information modeling" or "building information modelling". Academic journal papers from SCI, SSCI, and AHCI were considered. In order to understand the overall development of the target field, there was no restriction on the time of publication for the search, but only articles in English were considered. In the end, 71 articles were obtained, all of which were exported as tab-delimited bibliographic data.

For the analytical protocol, the mixed review used in this paper was divided into two phases, the first phase being a bibliometric review to integrate the knowledge structure, evolutionary history and trends of the target domain. The visual analysis in the bibliometric review phase has been followed by country analysis to obtain the current status in various countries' development; journal co-citation analysis to obtain the most influential journals; keyword clustering analysis to explore the main topics. The second phase is a systematic review. The 71 articles were screened according to three principles: (a) the term 'healthcare building' was identified as referring specifically to a building type rather than to the architectural focus on healthcare in general. (b) Some of the articles proposed a generalised digital building technique and selected healthcare buildings as case studies. At this point only the single healthcare building case is retained, rather than being generalised to multiple building types. (c) BIM should be used as the primary digital technology tool in the article, rather than just using BIM as a comparison or padding. Twenty four articles were removed, and the remaining 47 articles were kept for further study. Through a summary of the selected literature, the systematic review phase analysed the application of BIM in the HDC domain, its actions throughout the building life cycle and its integration with other technologies. For the data analysis phase, the six stages of data analysis included: (1) reading the abstracts, keywords and conclusions of the papers; (2) generating codes using Excel; (3) generating initial themes and formulating initial sub-themes; (4) merging and collating the sub-themes once all articles had been read; and (5) defining and naming the themes. Five main domains, 13 supercodes and 28 secondary codes were finally identified.

3 Results

3.1 Country Analysis

As shown in Fig. **1**, among the selection of literature, the earliest academic publications on BIM in HDC was published by the United States (US) in 2010, although prior to this time there was earlier applications of advanced computing in healthcare design and construction. An explosive growth in research in this area across countries began in 2019. In particular, in 2020, due to the prevalence of COVID-19, researchers reached an unprecedented peak in this area, publishing 16 articles, four times the number published in 2018. The country that contributed significantly to the increase in research during the epidemic was China involved in the publication of five and eight articles in 2021 and 2022 respectively. At the same time, China is also the country involved in the most published literature with 17 articles. It is followed by the US and the United Kingdom (UK) with 10 and 8 articles respectively. In terms of inter-country collaboration, China and the US, have the highest number of publications (five). Taken together, it can be seen that the US is a pioneer in the publication of academic research on BIM in HDC. Secondly, the UK and Australia have also been contributing research in related areas. In addition, China has been the most active participant and contributor after its involvement in 2015. It is worth noting that there may be other countries that already have well-established measures and more practice regarding HDC, yet the results may not be published in journal papers, but shared, for example, in some conferences, books or grey literature. In addition, research focusing on HDC is occurring in many countries, reflecting their geographical uniqueness, and is highly relevant to local government policy and national healthcare delivery.

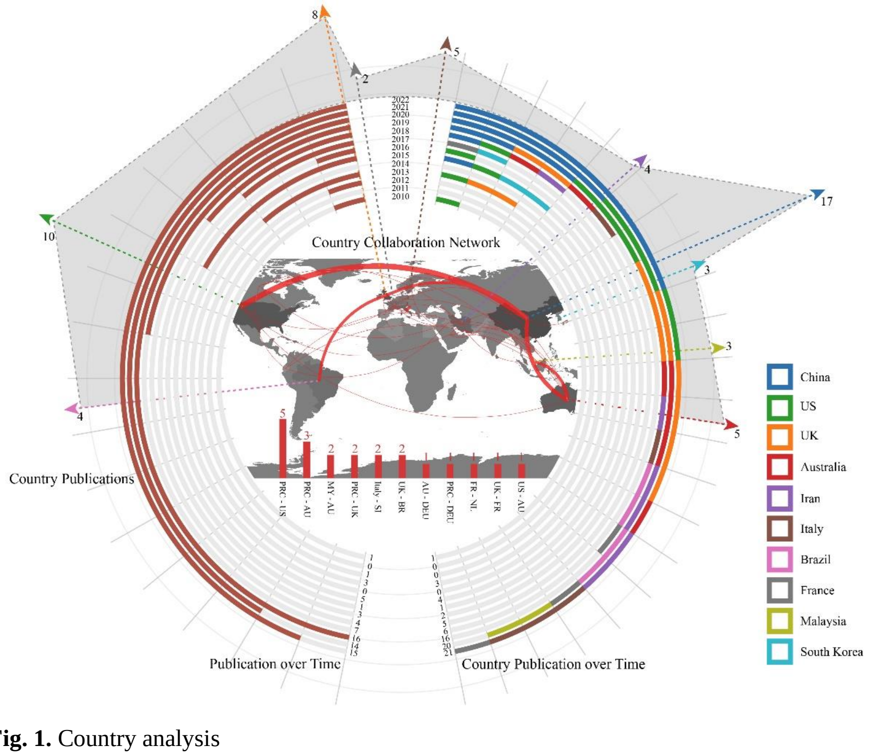

Fig. 1. Country analysis

3.2 Journal Co-citation Analysis

Fig. **2** shows that the journal "Automation in Construction" (AIC) has acted a significant role to share the impacts of research in the target area, with 58 co-citations in 71 publications. This is followed by "Advanced Engineering Informatics" and "Journal of Information Technology in Construction", with 33 and 28 co-citations respectively. Other major journals include "Journal of Building Engineering", "Journal of Construction Engineering and Management" and "Engineering Construction and Architectural Management". Regarding the publication counts, "AIC" published 14 articles, then Sustainability published 11 articles, which accounts for the most, as other journals are all no more than 3 published articles related to BIM in HDC. It can be seen that the AIC contains a relatively comprehensive range of research on BIM in HDC in all phases of the building lifecycle, with the largest number of articles in the construction, operation and maintenance phases. The main focus of its publications is on the advancement and development of digital technology itself. "Sustainability" focuses on how these digital technologies, such as BIM, can be used to make HDC green or sustainable. Other journals also show their own taste for publication. For example, all three articles published in "Journal of Management in Engineering" focuses on the implications of management, especially a perspective on collaboration, from the adoption of BIM in HDC. Compared with other journals, "Building Research & Information" shows more attention on the design studies, as three published papers all investigate the BIM in design stage.

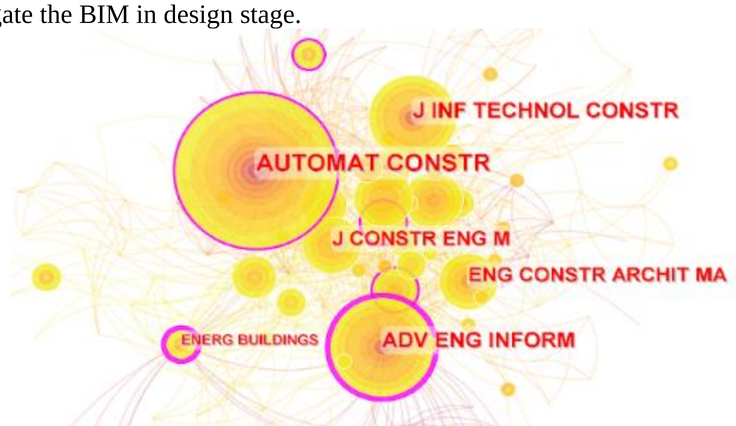

Fig. 2. Analysis of the count of co-citations and betweenness centrality of journals

3.3 Keyword Clustering Analysis

Nine keyword clusters were obtained and eight were retained after eliminating invalid clusters. The average size of the clusters was 19.5 and the average silhouette of the clusters was 0.8735. When the silhouette is greater than 0.7, it indicates a high homogeneity of the clusters and the results are convincing [15]. This study analysis six main clusters with silhouette above 0.7, namely value methodology, collaborative design, requirement management, design errors, optimal building design, and Chinese hospital (see Fig. **3**). Specifically, cluster 0 is "Value Methodology". Value methodology, sometimes referred to as value engineering [16] is often defined as a method and process of analysing an entire system to remove unnecessary costs and improve performance and potential [17]. BIM, as a tool capable of integrating various forms of building information, often provides the basic information for analysing value [18]. Cluster 1 is "Collaborative Design". Keywords in the cluster include “construction”, “information” and “maintenance”. The emergence of BIM is itself related to the much greater complexity and fragmentation of architecture projects nowadays, which require a great deal of information exchange and sharing [19]. The discussion of BIM therefore often includes the idea of collaborative working across boundaries and disciplines [20]. The ability to provide collaborative design is also one of the main advantages of BIM, as it enables the exchange of increased information flows between stakeholders in architecture projects [21], alleviate unnecessary duplication of work and errors [22] and ultimately achieve high quality design outcomes and cost effectiveness [23]. As one of the most functionally complex building forms with the most diverse needs, it is promising to apply BIM-based collaborative design in HDC. Cluster 2 is “Requirements Management” referred to as a method of integrating multiple requirements, such as clients, users and government regulations, within a building project to improve project performance. BIM tools are used to assist in the dissemination and processing of information, simplifying the process and increasing efficiency to support the construction industry in demand management. Cluster 4 is “Design errors”. The keywords in this cluster are “management” and “impact”. Errors in the building design process are inevitable in the course of a construction project, but they can lead to delays, rework or cost overruns if not fixed in time. Traditionally, the detection of errors in the implementation of construction projects has often relied on manual troubleshooting, which is inefficient and inaccurate [24]. However, BIM can help save time and costs by warning of potential problems to automatically detect design errors, helping humans to better complete building design projects [24]. As a result, automated BIM-based design error detection is on the rise. Many of the key words in cluster 7 “Optimal Building Design” have ‘early’ as a prefix, such as early design, early decision and early assessment. The overall design and assessment of a project at an early stage is of great importance in achieving the best possible architectural design. BIM may have the potential to significantly assist designers in making decisions in the early stages of design to achieve optimal design. The cluster 8 “Chinese hospital”, which highlights the use of BIM in Chinese hospitals and especially the unprecedented rate of building completion of Huoshenshan and Leishenshan hospitals in Wuhan, China for combating the outbreak of COVID-19. These studies emphasizes the acceleration of digital technologies and off-site construction for speeding advanced hospital construction for health emergencies.

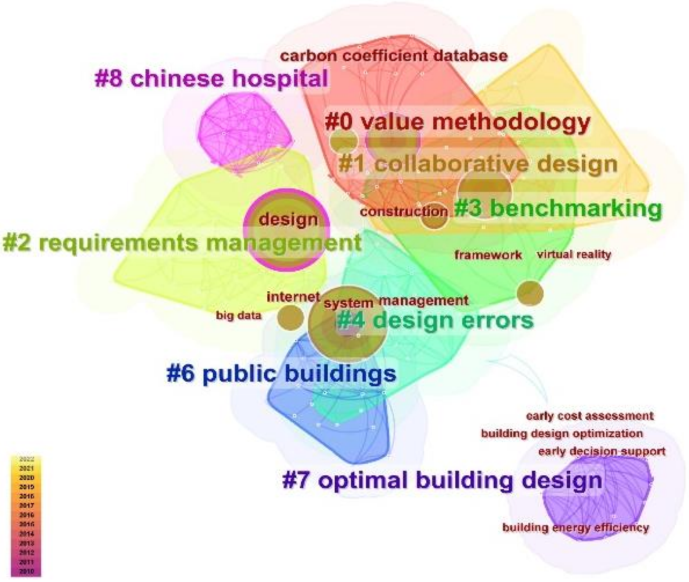

Fig. 3. Keyword clustering analysis

3.4 Classification of Application Domains

As shown in Table 1, the five main application domains of BIM for healthcare were identified: operability, resilience, collaboration, sustainability, and constructability. Twelve of the reviewed papers were related to operability, accounting for 25.5%, with a focus mainly on the post-completion phase of hospital operations, including facility management, user-friendliness optimisation, and benchmarking. Eleven of the papers reviewed were related to resilience, accounting for 23.4%, focusing on the adaptability of healthcare buildings to external disasters such as epidemics, fires, earthquakes and other disturbances, including health emergency and conventional disaster response. The most significant proportion of health emergencies is based on the practical experience of responding to COVID-19 to explore the BIM application in healthcare buildings. There are eleven papers related to collaboration (23.4%). Collaboration in the design phase was mainly related to the use of Virtual Reality (VR) technology to create virtual working environments. In addition, nine articles (19.1%) are related to sustainability, focusing mainly on energy consumption in buildings. And two articles were related to constructability, accounting for 4.3%.

Table 1. Classification of application domains

Domain	Code/super codes	Second Code
Operability (12)	Facility management (8)	Facility management improvement
		Facility maintenance
	User-friendliness optimisation (2)	Patient natural view analysis
		Indoor navigation sign optimisation

	Benchmarking (2)	KPI benchmarking system development
Resilience (11)	Health emergency (7)	Emergency hospital design and construction
		Emergency hospital design
		Emergency hospital construction
		Facilities interconnection hospital
	Conventional disaster response (4)	Resilience performance analysis
		Fire rescue simulation
		Emergency evacuation
		Emergency decision support
Collaboration (11)	Design collaboration (7)	Virtual design work environment
		Integrated design systems
		Co-design tool development
		Client requirement management
		Construction collaboration network
	Construction collaboration (1)	Construction collaboration
	Design-construction collaboration (2)	Design-construction collaboration
Sustainability (9)	Energy consumption (6)	Energy consumption analysis
		Green Building Early Design
	Building component recycling (2)	Building component recycling
	Resource allocation optimisation (1)	Resource allocation optimisation
Constructability (2)		Rule checking
		Error Management
Other(2)		

3.5 BIM Actions for HDC

This paper classifies the full lifecycle stages of a building according to the role of BIM in 47 articles, divided into four stages: planning, design, construction and post completion (see Table 2). Design and post completion, especially detailed design and operation, are two major phases adopting BIM actions. With the explosion of COVID-19, many studies have begun to focus on the integration of modular hospital with BIM, and BIM-enabled design for manufacture and assembly in HDC. BIM actions embody the capabilities that drive rapid healthcare construction in these research. In addition, the study shows that current research mainly focuses on the BIM as a digital tool to support the databases or modelling functions. However, there is few studies about BIM as an innovative digital process for HDC. In the context of HDC, it does not perform the adoption of BIM features that are different from other building types. Therefore, in this part, the study of BIM-driven healthcare facilities have more generalization capabilities than uniqueness. As can be seen, the existing literature tends to take a reductionist view for BIM research. That is, if the HDC is viewed as a process of building a complex system (i.e. a hospital), these studies attempt to single out parts of the overall system, i.e. a particular sub-system, as a specific scenario for the study of BIM technology. This approach although has specific benefits, for example by reducing the complexity of the overall technology application scenario. The negative situation is that this way of attention and research is also hindering the application of BIM, i.e. these fragments or small snapshots of implementation prohibiting a full understanding of a whole system/whole-project process approach to BIM implementation.

Table 2. BIM actions for HDC

Stages		BIM actions for HDC				
Planning (3)		Modelling client requirements using BIM tools	As a data source of both geometric and semantic information			
Design	Concept Design (3)	Modelling of the model objects using BIM software	As a data source for predictive analysis of performance			
Design	Detailed Design (12)	Automated clash checking to send BIM warnings	Technical support for green performance assessment of buildings	As a data source for design optimisation		
Construction (7)		As a data source to support construction coordination	Provision of construction site spatial data	Digital simulation of construction details		
Post-completion	Operation (17)	As a data source for facility management	Modelling occupant semantic data models	As a data source for resilience optimisation and assessment	As a data source and modelling for digital twin	As a data source to analyse energy consumption
Post-completion	Maintenance (3)	As a data source searching or filtering various facility maintenance data				
Post-completion	Renovation (1)	Modelling existing structures				

3.6 Other Digital Technologies Working with BIM

Other digital technologies were investigated alongside BIM to facilitate HDC. As shown in Fig. **4**, emerging digital technologies including VR, Radio-Frequency Identification (RFID), Cyber-physical systems (CPS) and Internet of Things (IOT), 5G, Geographic Information System (GIS), Artificial Intelligence (AI), Mixed Reality (MR), Unmanned Aerial Vehicle (UAV) site track, robotic assembly and cloud computing. Among them, VR appears five times, accounting for one-third of the total. and often promoting it use to visualise and enhance stakeholder spatial awareness and simplify the amount of BIM data [25]. Specifically in the identified literature, the role of VR is mainly in providing a new approach on design, visualisation and immersive experience. For example, Lin, Chen [26] developed a semi-immersive VR and BIM-based design for healthcare design, and Roupe, Johansson [27] developed an immersive VR-based virtual co-design environment. In terms of the different building stages, digital technologies are concentrated in the detailed design, construction and operation stage. The most frequent occurrence was in the operation stage (7 times) and with a high variety (6 sub-types). On average, 0.41 other digital technologies appear per article and 60% of other digital technologies types appear in the operations stage. Building operations are often combined with digital information and digital technologies to achieve more efficient management, with specific benefits in terms of personnel use, response speed, work efficiency and management models [28]. For example, Zhou argue that IOT and cloud computing combined with BIM have changed the data management model of intelligent hospitals [29]; Peng, Zhang [30] used AI engines to improve the speed of response to operational status anomalies in smart hospitals, and MR to improve the work efficiency of staff in checking for operational status anomalies. In terms of application domains, apart from "Collaboration - Design collaboration - Virtual design work environment" using VR, other digital technologies that appear more frequently are "Sustainability - Building component recycling - Building component recycling" (3 times). The digital technologies used in this domain are RFID, CPS and IOT, GIS, all of which are used to monitor abandoned or temporarily non-functional building components and create digital virtual models for them.

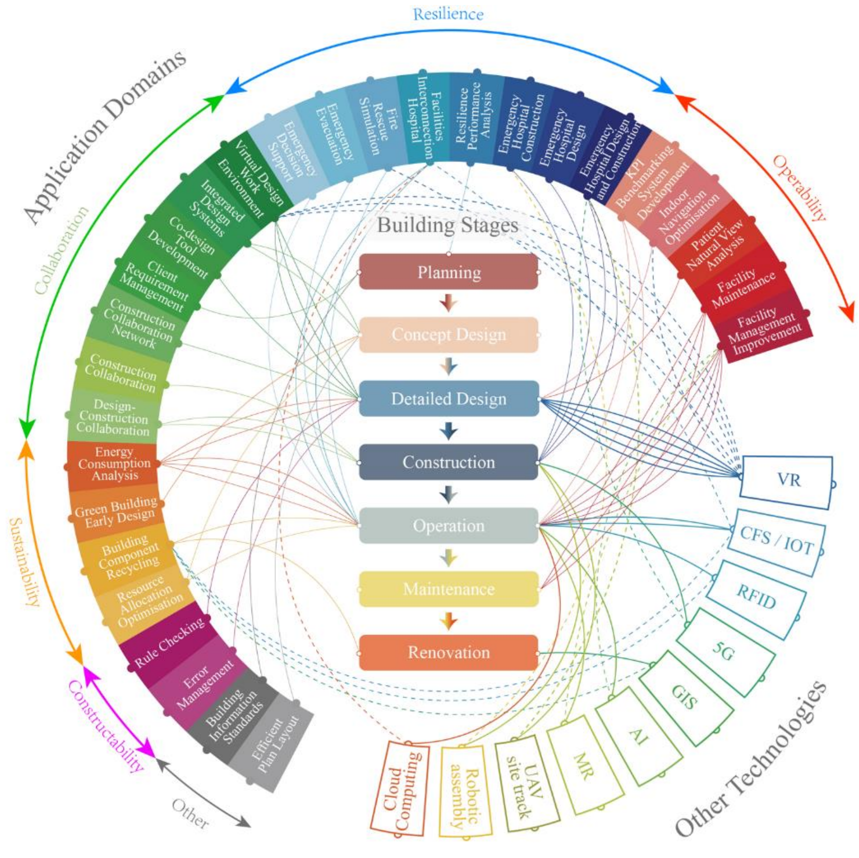

Fig. 4. Other digital technologies working with BIM

4 Discussion and Conclusion

Emerging BIM techniques for HDC include functionalities embodied in BIM and new BIM-enabled techniques. Pikas, Koskela [31] summarised 12 BIM functionalities in healthcare construction through multiple case analysis, including visualisation of form, model changes tracking, predictive analysis of performance, automated generation of drawings and documents, modelling temporary structures (scaffolding) and existing structures, automated clash checking, online communication of product and process information, online meeting sessions, reuse of model information, site planning, 4D and 5D scheduling, information for survey and scanning systems, project statues tracking, and as-built model. Many studies have shown the BIM's profound impact on how healthcare projects are designed and delivered. Many articles describe BIM as incredibly beneficial in designing frontiers of hospital spaces with numerous technical appliances and demanding performance requirements. BIM's wide range of usability and versatility allows it to be combined with a variety of advanced information technologies to better realise project expectations and drive the digitalisation of buildings [32]. However, implementing BIM also faces challenges. The necessity and evidence to introduce BIM to cope with complicated design requirements, such as hygiene, safety, and equipment, need further review and discussion.

This review shows that the outbreak of the COVID-19 epidemic has greatly contributed to an explosion of research related to HDC, especially digitization, in terms of the number of publications. Research focusing on HDC is occurring in many countries, reflecting its geographical uniqueness that is highly relevant to local government policies and national healthcare services. Despite the national differences, commonalities remain in the way digital technologies are used and in their capabilities. Mainstream journals in the field of AEC assume the main role of disseminating relevant literature and are gradually gaining popularity to the attention of an increasing number of journals.

A proportion of the studies do not examine healthcare buildings as a specialised field, but only use them in case selection as empirical scenarios to test their theories and techniques. Some studies, on the other hand, have specifically chosen healthcare buildings for specific BIM studies. Both cases reflect the uniqueness and representativeness of HDC. In detail, healthcare buildings can represent complex engineering, complex projects and complex building functions. As such, healthcare buildings are often used as a case study when examining these complexities. This complexity comes from two aspects: on the one hand, it is the diversity of functions, which represent a wide range of knowledge, design expertise and the hundreds of suppliers and stakeholders involved. The second aspect is that the functions have a huge impact, i.e. the daily use of building functions that affect health, well-being and safety.

The study shows that 17 major BIM actions are applied for six major domains, including operability, resilience, collaboration, sustainability and constructability. These BIM actions represent common BIM functions that match the functions summarized in the case study by Pikas, Koskela [31]. However, it can be seen by the phase division that many building lifecycles are not fully studied regarding BIM. For example, in the planning, conceptual design and renovation phases, the application of BIM functions is still relatively homogeneous, and many BIM functions do not exist in the literature. Therefore, future research can do more research on these building phases that lack attention. Among the many accompanying technologies, VR is the digital technology most highly associated with, with all focus on the design phase. As seen from the results, there are a wide range of real-life scenarios for applying digital technology in HDC. Future research could try to combine more technologies, such as IOT, robotics, UVA and etc., with BIM to address the capacity challenges of healthcare delivery.

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