A Systematic Taxonomic Review of the Application of BIM and Digital Twins Technologies in the Construction Industry

Abstract

Purpose – This study aims to provide a comprehensive analysis of the transition from Building Information Modelling (BIM) to digital twins (DT) in the construction industry, exploring the current state (themes and trends) and future directions of this emerging research domain.

Design/methodology/approach – A multi-stage approach was employed, combining scientometric and systematic review approaches. The scientometric analysis involves quantitative assessment of scientific publications retrieved from the Web of Science database – using software tools like VOSviewer and HistCite. The systematic review involved a rigorous synthesis and evaluation of the existing literature to identify research gaps, themes, clusters, and future directions. The clusters obtained from the scientometric analysis of the co-occurrence network were used as a subject base for a systematic study.

Findings – The findings reveal a rapidly growing interest in BIM-DT integration, with over 90% of publications since 2020. The United Kingdom, China, and Italy are the leading contributing countries. Five prominent research clusters are identified: (1) Construction 4.0 technologies, (2) smart cities and urban environments, (3) heritage BIM and laser scanning, (4) asset and facility management, and (5) energy and sustainability. The study highlights the potential of BIM-DT integration for enhancing project delivery, asset management, and sustainability practices in the built environment. Moreover, the project's life cycle operation phase has garnered the most attention from researchers in this field compared to other phases.

Originality/value – This study is unique in its comprehensive approach, combining scientometric and systematic methods to provide a quantitative and qualitative evaluation of the BIM-DT research landscape. Unlike previous reviews focused solely on facility management, this study's scope covers the entire construction sector. By identifying research gaps, challenges, and future directions, this study establishes a solid foundation for researchers exploring this emerging field and envisions the future landscape of BIM-DT integration in the built environment.

Keywords: Building Information Modelling (BIM); Construction industry; Digital Twins (DT); Systematic review; Scientometric

1. Introduction

After years of manual drawing, the introduction of computer-aided design (CAD), and the evolution of design tools (Afsari et al., 2019), van Nederveen and Tolman introduced a new approach in 1974 in conjunction with construction project management tools after Eastman introduced the description system building (1992). This technique received much interest and was eventually known as "building information modelling (BIM)". BIM is described as "a digital representation of the physical and functional aspects of a facility" by the US National Institute of Building Sciences (NIBS, 2017). This model-oriented approach provides a single database for project assets throughout its life cycle and supports decisions from feasibility studies to demolition. BIM is a project's graphical database of geometric and semantic data, providing access to data from temporary facilities and other sources throughout its life cycle. (Heaton et al., 2019; Pham et al., 2020).

Proper planning and scheduling based on actual site conditions, accurate estimation of expenses, meticulous data collection, classification, and recording during various project life cycle phases, and effective utilisation of this data for project management are crucial considerations before commencing the implementation phase. According to Tang et al. (2019), adopting a model-based database like BIM can facilitate these processes throughout the project lifecycle. However, the utilisation of BIM involves implementing plans for maintenance, environmental impact analysis, and project energy performance simulations. BIM's innovative application of "information" highlights its significance. Historically, the construction industry's adoption of BIM has primarily focused on enhancing information management practices (Hilal et al., 2019). Meanwhile, in recent times, building project stakeholders have leveraged BIM tools and technologies to transform how project information is created, stored, and shared (Kubicki et al., 2019; Howell & Rezgui, 2018).

At each point of a project's life cycle, participants' roles and authority determine how they share information layers (Zhang et al., 2022). This necessitates efficient information-sharing mechanisms for interoperability across the project life cycle. From ISO STEP to IFC to IfcOwl, BIM interoperability solutions have failed to shift from a static building information model to a web-based model (Pauwels et al., 2017). Also, BIM cannot automatically update models with real-time data from the construction project, only static data (Tang et al., 2019). The use of big data, the Internet of Things (IoT), and artificial intelligence (AI) have been offered as feasible options for automating and integrating broader environmental settings as a response to this significant challenge that BIM faces (Bradley et al., 2016). IoT devices are equipped with sensors, communication networks, and processing capabilities. These components enable the provision of intelligent services tailored to the needs of end-users (Asghari et al., 2019). Seamlessly integrating BIM and IoT technologies makes it possible to continuously monitor and track the construction process and the indoor environmental conditions within the building (Natephra & Motamedi, 2019). Despite the potential benefits, the construction industry has been slow in embracing digitisation, with research indicating a low rate of adoption (Haghsheno et al., 2019; Hossain & Nadeem, 2019). This transformation, termed “Construction 4.0,” signifies the advent of the fourth generation of the industry, a concept formally introduced at the Hannover Messe trade fair in 2011 (Coupry et al., 2021).

With the use of sensors and network components, the construction industry is digitally transforming to develop larger physical-cyber connections (Mannino et al., 2021). In recent studies on modern technology’s use in the building sector, cyber-physical systems have emerged as a solution. Digital twins (DT) are hybrid physical-cyber systems (Mannino et al., 2021). The capacity to link sensors in real time has contributed to the rise of DT in building projects (Menassa, 2021). Graves introduced DT in 2002 in a paper on product life cycle management (PLM) as an evolutionary method (Coupry et al., 2021). After ten years of development, the DT was launched as a digital concept (Grieves and Vickers, 2017). The aerospace industry pioneered this notion of remote monitoring, and the industrial sector adopted it (Errandonea et al., 2020). The DT synchronises the real world with a virtual platform to manage and control the building process, facility management, environmental monitoring, and other built environment life cycle operations (Menassa, 2021).

BIM’s ability to gather and aggregate all geometric and semantic data of a construction project, whether for assets already in place or projects still in the planning stages, has led several researchers to employ it to create DTs (Cheng et al., 2020; Tchana et al., 2019). DT research in the construction industry has focused on safety, planning and cost management, monitoring and inspection, maintenance, and energy management throughout project life cycles. Every prior BIM and DT-related review article focused on facility management and maintenance processes and limited their investigations to that theme (Menassa, 2021; Mannino et al., 2021; Grieves & Vickers, 2017).

DT research is still in its early phases. Conducting studies that extensively study the literature and analyse the existing content in this research field will surely have a substantial impact on the establishment of a proper mental base for researchers who will move in this direction and envisage the research future of this subject. In contrast to prior review studies on the BIM-to-DT transition, this study covers the whole construction sector. Second, by combining scientometric and systematic methods – a comprehensive quantitative and qualitative evaluation of current research was undertaken, and the future direction of this research field was forecasted. Based on this, this study's main body is divided into two sections: the first is a quantitative study that uses scientometric approaches to investigate the research process of transitioning from BIM to DT. The second part of this study analyses the data by comparing it to the extant literature and then clustering similar themes together. Predictions for the future of this research area required looking at the strengths and weaknesses of current methods as well as the experts' suggestions for future research.

2. Methodology

The current study employed a multi-stage approach to critically investigate and analyse the transition from BIM to DT in the built environment. The primary objective was to gain a comprehensive understanding of the prevailing research themes, trends, and patterns related to BIM-DT research on a global scale. The research approach consisted of two distinct stages. The initial stage involved conducting a scientometric analysis, which is a quantitative assessment of scientific publications and citations within a specific research domain (Olawumi & Chan, 2018). Subsequent to the scientometric analysis, the second stage involved carrying out a systematic review, a rigorous and structured process of synthesising and evaluating the existing body of literature to address a well-defined research question or set of objectives (Dresch et al., 2015; Olawumi et al., 2022).

2.1 Search and data collection protocols

Most review studies employ the Web of Science (WoS), Scopus, or a combination of these two databases to retrieve relevant documents for further analysis. An evaluation of existing studies that compare scientific databases reveals a strong correlation between the outputs (articles) and impacts (citations) obtained from WoS and Scopus despite differences in their scope, data volume, and coverage criteria (Rastogi et al., 2020). In this study, the WoS database was utilised to identify pertinent research papers and extract data from them.

Choosing an appropriate strategy before commencing an article search is critical in order to identify all related papers, define boundaries for the search results, save time, and keep researchers from becoming bogged down in a vast number of documents and information. To avoid ineffectiveness, "BIM" and "DT" were simultaneously searched in the articles' topic areas during the database search. The retrieved research corpus was limited to "articles," "review articles," and "early access," with English as the only language allowed. According to WoS data, publications in this field began in 2018.

As of May 25, 2022, the database contained 140 articles flagged as potentially relevant to this study and its scope. Each of these articles underwent a thorough examination, during which various aspects – including the topic, title, authors, year of publication, keywords, research aims, methodological approaches, and key findings, were carefully categorised.

After completing these reviews, five articles were deemed less relevant to the current research and were consequently removed from the dataset. After applying the necessary filters and conducting manual inspections, 135 articles were selected for inclusion in the study. The bibliographic information associated with these 135 articles was catalogued from the database. Furthermore, the articles were sorted based on their relevance to the research topic. Both the systematic review and the scientometric analysis utilised the entire set of these 135 identified articles for comprehensive analysis.

2.2 Scientometric and systematic analysis

Science mapping enhances researchers' comprehension of bibliometric data; Scientometric software tools assist in visualising and displaying links between various players (authors, institutions, nations, etc.) involved in a research topic (Moral-Muoz et al., 2020; Olawumi et al., 2022).

Eck and Waltman (2014) identified several text-mining tools suitable for conducting scientific map analysis, including CitNetExplorer, CiteSpace, Gephi, HistCite, Pajek, Sci, and VOSviewer. After carefully evaluating the features and capabilities of each software product, VOSviewer and HistCite were selected as the software tools of choice for this study. This selection was based on the assessment that these two tools were best aligned with the specific objectives and requirements of the current research. VOSviewer software is ideal for examining large networks with lots of data (Zabidan et al., 2020). The software is also widely used in building research (Jin et al., 2018). HistCite's robust statistical function makes retrieving and sorting lists of highly cited papers, years, publications, authors, institutions, and countries easy (Stock et al., 2023). This study used various software tools to examine publication trends, author and institution collaboration and communication networks, country involvement, keyword frequency, and keyword organisation.

Concurrently, a careful and methodological analysis of the content within the selected articles was conducted. A systematic literature review is a valuable technique that facilitates data analysis, synthesises existing knowledge, and identifies research gaps within a particular field of investigation (Oesterreich & Teuteberg, 2016). It contributes to the formulation of new ideas and hypotheses (Gharbia et al., 2020). In this study, the principal topic areas within the research domain were determined, and action criteria were established based on the clusters derived from the scientometric analysis of the co-occurrence network of terms. At an early stage of the inquiry, categorised information was gathered by thoroughly examining the subjects covered in the articles, and the findings were presented in tabular format. The articles pertaining to these identified themes were then selected and categorised accordingly. Figure 1 illustrates the research design approach employed in this study.

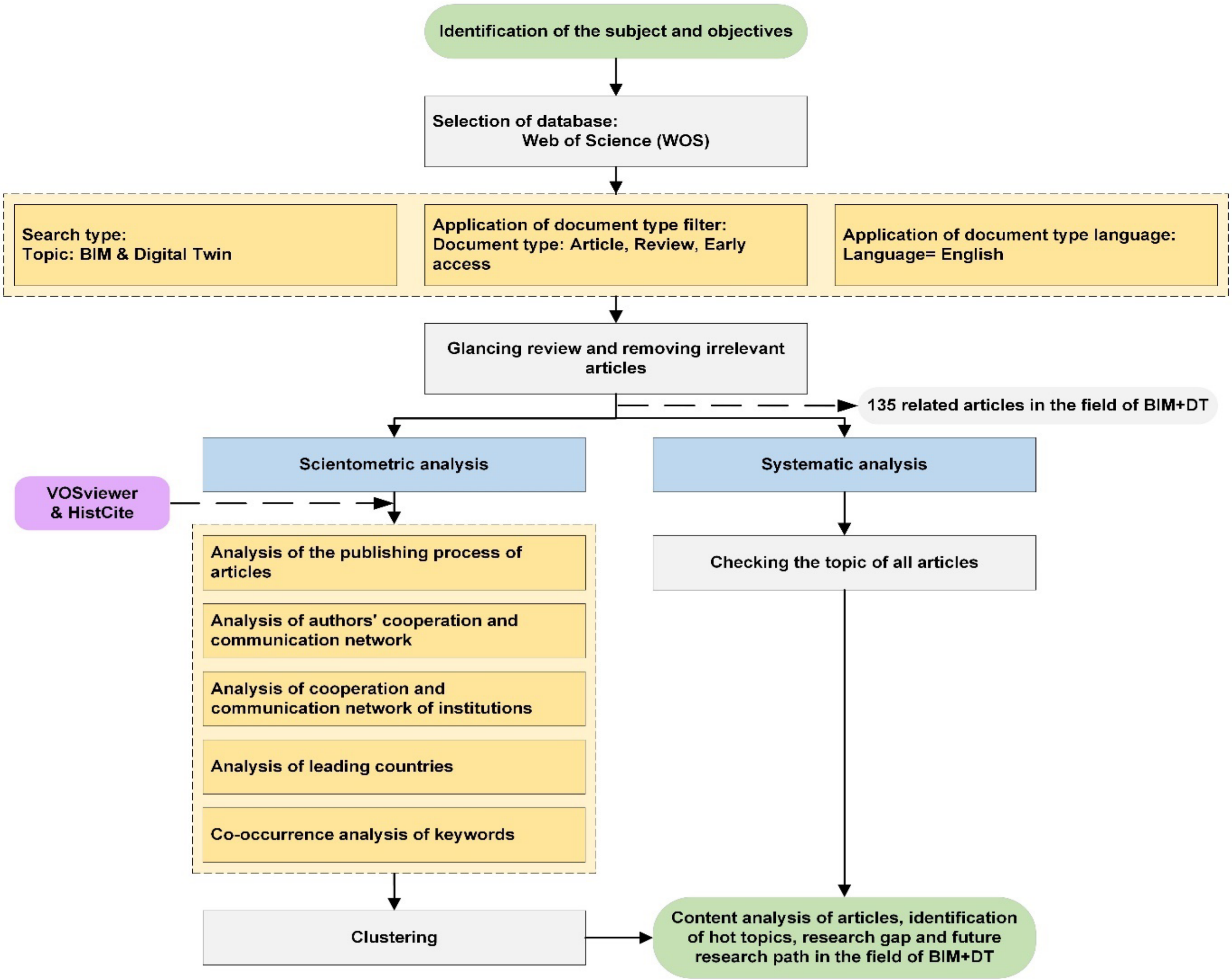

Figure 1. The process of the study

3. Scientometric analysis

This section presents and discusses the result of the scientometric analysis.

3.1 Time trend analysis based on the annual publication of articles

According to WoS statistics, the first journal paper on DT applications in medicine was published in 1994, while the first on DT and BIM was published 25 years later in 2018. This shows how original and innovative this study topic is compared to others. Figure 2 illustrates the trend in the publication of journal articles focusing on the intersection of DT and BIM from 2018 to 2022. The observed publication pattern indicates a widespread acceptance and growing interest among researchers and authors in this field, with over 90% of the articles being published since 2020. Remarkably, despite the challenges posed by the COVID-19 pandemic, the number of publications tripled between 2019 and 2020. Furthermore, the trend observed in 2021 seems to have carried over into 2022, with 27 papers being published in the first five months alone, suggesting a sustained momentum in the publication rate. The pattern in Figure 2 is supported by studies on the annual publishing trend of reviews on DT in construction (Opoku et al., 2022; Mannino et al., 2021; Coupry et al., 2021; Hosamo et al., 2022).

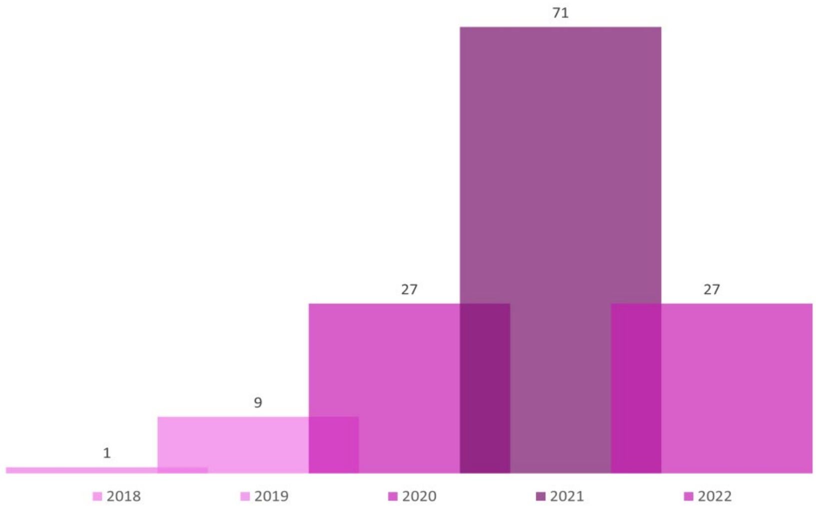

Figure 2. BIM-DT articles publication trend. Source: WoS database

3.2 Analysing the cooperation and communication network of authors.

Figure 3 depicts the network of authors and their collaborative networks within this research field. The visualisation of this author collaboration network was generated using the VOSviewer 1.6.18 software tool. The "co-authorship" analysis used authors as the analytic unit and comprehensive counting. Fractional counting determines each author's contribution, while complete counting assigns one article to each author for each joint work with two or more authors. A joint article is given as a fraction after being divided by the total number of writers. The "*minimum number of documents of one author*" was three (3), and the "*minimum number of citations*" was 5. The display and network were optimised using these settings.

Eleven of the 458 identified writers who fit the criteria were added to the network. In this kind of network, the *node size* represents an author's degree of activity in terms of the number of articles they have produced, and the *edge thickness* represents the strength of the connection between the two writers. By examining the network graph and the strength of the connections between the nodes (representing authors), three distinct groups of writers with a significant level of collaboration can be identified. Within the first group, Sepehr Alizadehsaleh and Ibrahim Yemen exhibit the strongest collaborative relationship, as evidenced by a connection strength of 383, which is the highest in this network. Further analysis reveals that these two authors have co-authored three publications together, indicating a close and productive working relationship.

The second group comprises Xiang Xie, Ajith Kumar Parlikad, and Qiuchen Lu, whose positioning within the network is determined by the strength of their connections. Within this group, Ajith Kumar Parlikad and Xiang Xie exhibit a stronger collaborative relationship, as indicated by a link strength of 265. This robust connection may be attributable to these two authors being co-affiliated with the University of Cambridge. In contrast, Qiuchen Lu demonstrates a weaker association with each of them within this group, with a link strength of 205. Notably, the four articles produced by this group are exclusively focused on asset management during the operation phase (Chen et al., 2021; Moretti et al., 2022; Lu et al., 2020; Xia et al., 2020). The third group consists of a larger number of authors with significantly weaker connections than the first two groups.

The third cluster comprises six authors, among whom Fulvio Re Cecconi from Politecnico di Milano stands out as the most connected individual within this group. Cecconi has the highest number of links at 10, with a total link strength of 150, indicating that authors from various groups have taken notice of his work. Notably, Sakdirat Kaewunruen from the University of Birmingham emerges as the most prolific author in this research field among the identified authors, with six published works, making him the largest node within the network. His articles focus on the intersection of BIM and DT, particularly in the context of railway infrastructure, including tracks, stations, and bridges (Kaewunruen et al., 2018a; Kaewunruen et al., 2019b; Kaewunruen et al., 2020; Kaewunruen et al., 2021). Additionally, his research delves into energy and sustainability issues, specifically emphasising the net zero energy approach.

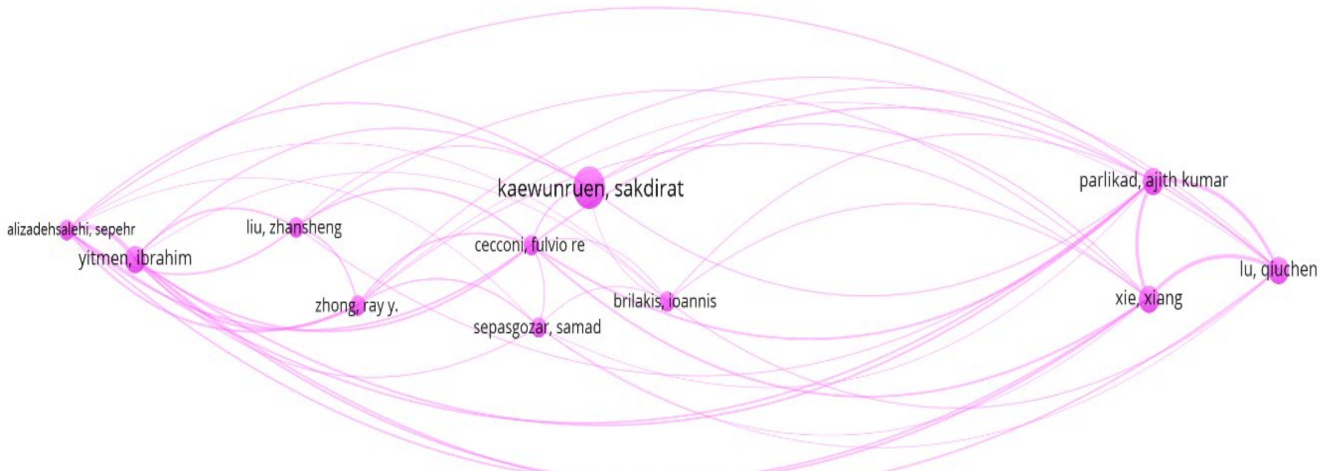

Figure 3. Key authors in the field of the intersection of BIM and DT

3.3 Analysis of cooperation and communication network of institutions

Identifying the network of institutions that are highly invested and actively engaged in a particular research field is beneficial for fostering research collaborations and informing policy-making endeavours (Yan et al., 2020). Figure 4 depicts the network illustrating how organisations interact and collaborate on publications that combine DT and BIM. The analysis was conducted using the VOSviewer software, with the following settings: analysis type - "co-authorship," analysis unit - "organisations," and counting method - "full count." The minimum threshold for inclusion in the network was set at 3 articles and 5 citations for an organisation. Of the 177 identified organisations, 15 met the cut-off criteria and were incorporated into the network visualisation. Based on the strength of the interconnections between the nodes (representing institutions), the University of Cambridge, University College London, and Politecnico di Milano emerge as the three institutions with the strongest collaborative relationships within this research domain.

Among the institutions in this network, the University of Cambridge and University College London (UCL) exhibit the strongest partnership, as evidenced by a link strength of 309. However, an analysis of the list of articles published by each institution, performed on the Histcite software, reveals that the University of Cambridge (9 articles), Politecnico di Milano (8 articles), and UCL (7 articles) have produced the highest number of publications in this area, surpassing other institutions. These three universities dominate the field due to their substantial research output. Cambridge University's scientific and academic efforts to apply digital twins to the built environment gained significant momentum after the establishment of the Cambridge Digital Built Britain (CDBB) in the fall of 2017. CDBB was founded by the University of Cambridge and the UK Department for Business, Energy and Industrial Strategy. It serves as a hub to advance various UK government initiatives, such as the National Digital Twin Programme (NDTP), the UK BIM programme, and others, aimed at improving the nation's infrastructure. Key authors driving this author collaboration network are Xiang Xie, Ajith Kumar Parlikad, and Ioannis Brilakis, who are affiliated with the CDBB Institute and holding faculty positions at Cambridge University. Their research contributions are central to Cambridge's leading role in this domain.

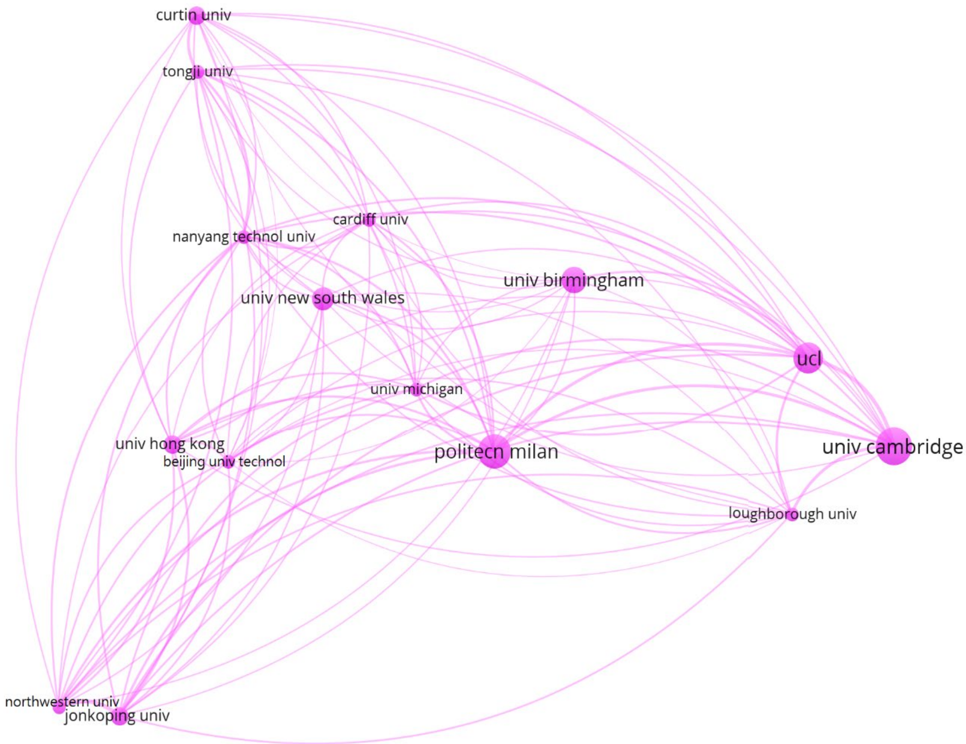

Figure 4. The active institutions and organisations in the research field of the intersection of BIM and DT

3.4 Analysis of countries' participation in this research field

The study analysis of the research corpus revealed that researchers from 34 countries have contributed to the body of knowledge on BIM and DT. Table 1 presents the top ten countries with the most publications in this field. The top three countries leading this domain are the United Kingdom (30 articles), China (27 articles), and Italy (20 articles). While 34 nations have published studies on BIM and DT, the United Kingdom, China, and Italy have produced the most significant research output in this area, with 30, 27, and 20 articles, respectively.

Table 1. Top ten countries in published BIM-DT articles

Country	Number of Documents	Number of Citation
United Kingdom	30	491
People's Republic of China	27	161
Italy	20	59
USA	18	159
Australia	14	134
Spain	10	32
Singapore	6	126
United Arab Emirates	6	24
Sweden	5	34
Canada	4	43

Despite the Chinese government's significant investment in the Internet of Things (IoT) and Digital Twins (DT) to comprehensively develop Industry 4.0 technologies and smart cities until 2025, the United Kingdom's National Digital Twin Programme (NDTP), first introduced by the UK Treasury in July 2018, and Italy's national plan 'Impresa 4.0', launched by the Ministry of Economic Development in 2017, have also contributed to the research output in this field. Notably, scientists from Australia and the United States have published 18 and 14 publications, respectively.

The presence of the United Arab Emirates (UAE) among the top ten countries in this emerging field of study is remarkable. This may be attributed to the substantial growth in research efforts in this area. However, compared to other countries on the list, the extremely low number of citations to the UAE's publications suggests that its research has limited global impact (Figure 5). The UAE should leverage the scientific research capabilities of institutions like New York University Abu Dhabi (NYUAD), United Arab Emirates University, University of Wollongong in Dubai, and the University of Fujairah to integrate this cutting-edge technology into its renowned construction sector.

.

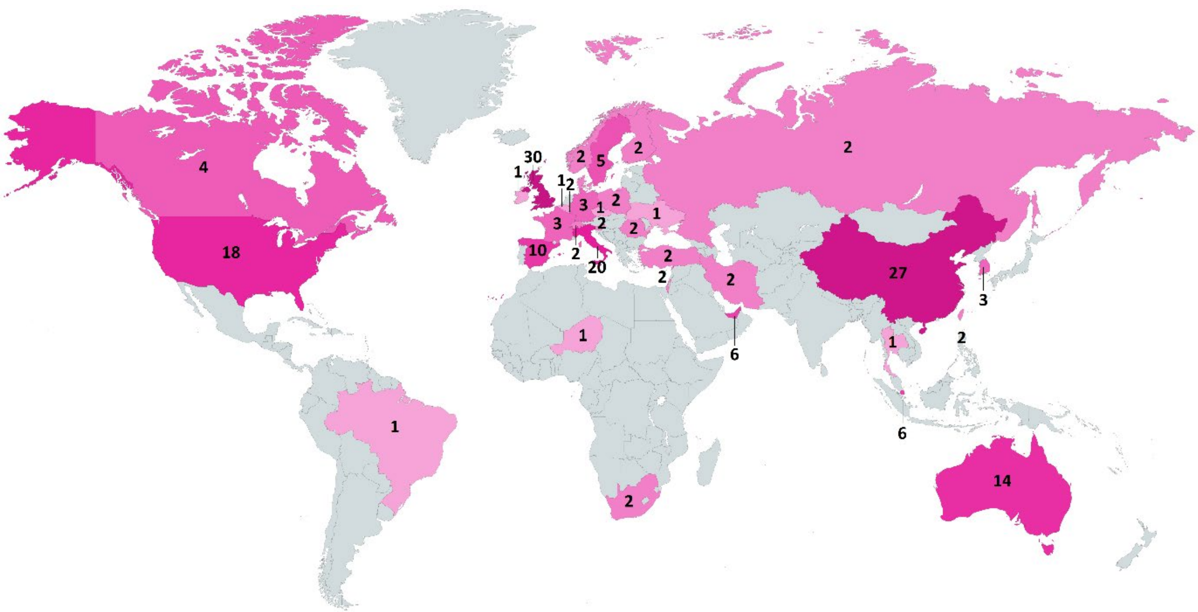

Figure 5. BIM-DT article publication records for Countries

3.5 Analysing the Co-occurrence of Keywords

A network of keywords provides a clear representation of a field of study and elucidates the relationships and intellectual organisation of current research interests (Eck & Waltman, 2014). Figure 6 illustrates a network of co-occurring keywords in this research domain. The analysis was conducted based on co-occurrence, using all keywords as the unit of analysis, and employing a full counting method. Co-occurrence arises when two events—in this case, keywords—appear simultaneously. In a co-occurrence keyword network, nodes represent keywords, and edges represent the relationships between sets of keywords. Previous research that constructed keyword co-occurrence networks acknowledged a significant number of detected studies and the network's congestion due to a large amount of information; however, they only utilised author-assigned keywords (Hosseini et al., 2018a; Pramanik and Maiti et al., 2019; Hosseini et al., 2018b; Yin et al., 2019).

The drawback of this strategy is that it heavily depends on the authors' expertise and experience in selecting the appropriate keywords. All keywords should be used to get around this drawback, including the authors' keywords and keywords plus (Darko et al., 2020; Olawumi & Chan, 2018). The techniques of merging similar words and clearing general concepts were employed to get rid of extraneous information and create a rich, ideal, and understandable network of keywords. A few different words and phrases were combined using the definition in the thesaurus file, and the most popular and expressive word was added to the software as a representation of those words. For instance, the words DT, DT, digital-twin, DT (dt), and DT were combined, and the word DT (dt) was shown on the network as a symbol for all of them. The process resulted in the merging of 203 words, bringing the final word count down from 719 to 599. Some keywords from a related topic area, however, were not combined. For instance, energy-related phrases like net zero energy, renewable energy systems, energy retrofit, and positive energy district were not combined with energy.

Even while these phrases share many similarities (Zhang et al., 2021; Omrany & Agostinelli, 2022), their fusion into the broad category of "energy" makes it impossible to specify and analyse the particular subject of this research field because energy is one of several research subjects. In recent years, it has gained popularity in research on the construction industry, which presents a variety of issues, topics, and methodologies (Yan et al., 2020). The network included 48 terms based on the minimal number of keyword occurrences, which was 5. Next, broad concepts like management, framework, system, model, technology, and the like were deleted from the final terms, leaving 40 keywords with 365 links and a total link strength of 1113. In a keyword co-occurrence network, the strength of the link between two keywords is calculated by the number of publications in which both keywords appear together. This shows how closely the keywords are related to each other in terms of research interests (Eck and Waltman, 2019).

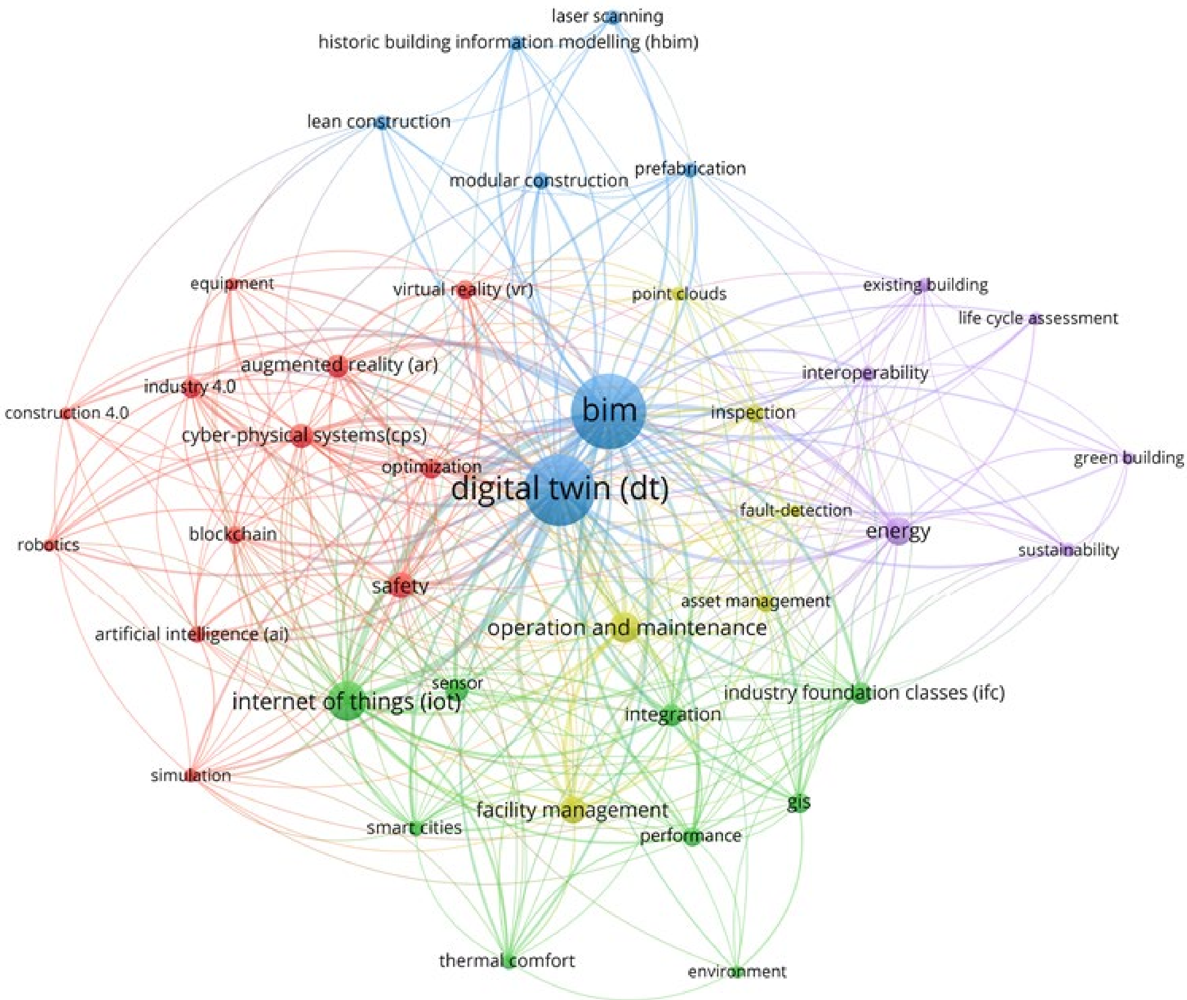

Figure 6. Co-occurrence network of keywords related to the BIM-DT domain intersection

Word clustering is another practical and valuable analysis possible in the keyword network, as seen from the colours produced in the network shown in Figure 6. Five clusters have been found by software analysis, and they are displayed in Table 2. The BIM method (blue cluster), facilities and asset management (yellow cluster), urban affairs and the environment (green cluster), construction industry 4.0 technologies, and energy and sustainability-related challenges (red cluster and purple cluster).

Table 2. List of identified clusters from VOSviewer software

Cluster one	Cluster four
• Artificial intelligence (AI) • Augmented reality (AR) • Blockchain • Construction 4.0 • Cyber-physical systems (CPS) • Equipment • Industry 4.0 • Optimisation	• Asset management • Facility management • Fault-detection • Inspection • Operation and maintenance • Point cloud

• Robotics • Safety • Simulation • Virtual reality (VR)	
Cluster two	**Cluster five**
• Environment • Geographical information system (GIS) • Industry foundation classes (IFC) • Integration • Internet of Things (IoT) • Performance • Sensor • Smart cities • Thermal comfort	• Energy • Existing building • Green building • Interoperability • Life cycle assessment (LCA) • Sustainability
Cluster three	
• Building information modelling (BIM) • Digital twins (DT) • Heritage BIM (HBIM) • Laser scanning • Lean construction • Modular construction • Prefabrication	

4. Systematic analysis

In the VOSviewer program, Eck and Waltman (2019) developed a clustering tool using an algorithm that assigns keywords to each cluster based on the procedure outlined in the methodology section. In network visualisation mode, colours are utilised to highlight these clusters, as seen in Figure 6.

At first glance, the terms "industry 4.0" and "construction 4.0" are prominently visible among the words in the first cluster, highlighted in ***red***. Other keywords in this cluster refer to modern technologies such as artificial intelligence (AI), augmented reality (AR), blockchain, cyber-physical systems (CPS), robotics, virtual reality (VR), simulation, and optimisation. Experts and researchers consider these technologies as fourth-generation construction tools. The current trend towards digitalisation, automation, and the extensive adoption of information and communication technologies (ICT) in the construction industry is known as Industry 4.0 or "Construction 4.0" (Alaloul et al., 2020).

Terms like geographic information system (GIS), IoT, sensors, and smart cities are visible in the ***green cluster***, and, at first look, the mind may link to the study of these words' contexts. A closer examination of the articles associated with these terms shows that their topic overlaps with "smart cities." BIM has gained traction in recent years as a tool for visualising project data in detail. However, with the integration of BIM with the IoT and DT technologies, the expectations and potential applications have reached new heights, surpassing previous capabilities. A DT differs from other information modelling systems with features like bidirectional data interchange and real-time self-management (e.g., self-awareness or self-optimisation) (White et al., 2021). Smart cities are spreading across China and Singapore-centered East Asian civilisations. By linking BIM with GIS, building and geographic information may be exchanged to create a complete visual database for smart city management, monitoring, and control (Lin & Cheung, 2020).

The primary objectives of the identified articles within the research corpus on smart cities revolve around performance measurement and evaluation of smart city initiatives, information exchange and sharing methods, and enhancing the accuracy and efficiency of IoT sensors. These efforts aim to leverage the potential of this novel concept in areas such as urban sustainability, monitoring, supervision, urban management, visioning and future planning, accident prevention, and urban crisis management. Unsurprisingly, some publications on smart cities address sustainability concepts, as cities host numerous large-scale buildings and play a significant role in the emergence and management of sustainability challenges. It is estimated that cities account for more than 50% of carbon emissions and energy consumption globally (Sepasgozar, 2021).

One of the most well-known instances was when Lin and Cheung (2020) introduced a BIM-based wireless sensor network (BIM-WSN)-based environmental management and monitoring system to manage the environmental conditions of parking lots in smart cities. In this study, a parking lot was equipped with a large number of wireless sensors with sensing and control capabilities to gather real-time data on the levels of carbon monoxide, temperature, and humidity. Different location circumstances were integrated and dynamically shown on the respective spatial components of a BIM model, and all gathered data was communicated through a self-built WSN. A Taipei parking lot was used to test the system's accuracy and practicality. The findings showed that the proposed system is an efficient and effective visual monitoring system for environmental monitoring.

Thematically linked words in the ***blue cluster*** form two unique groupings. The phrases "modular construction" and "prefabrication" stand for the first issue, prefabrication. Another name for one of the prefabricated technologies in buildings is modular construction. Prefabrication, one of the quick construction techniques, has drawn significant attention in the construction industry, particularly in the building sector, because of the rise in prices and decline in productivity of the sector in recent years (Pan et al., 2022). The articles listed in this section may be divided into the following categories: (1) safety-related issues; (2) prefabricated project scheduling and management; (3) project management and information exchange platforms; and (4) procedures for manufacturing and assembling prefabricated pieces.

A dynamic and live 3D model created using BIM and DT helps reduce accidents and increase safety in implementing modular and prefabricated buildings in two ways: first, by enhancing monitoring and dynamic inspections. Safety experts agree that most prefabricated building mishaps occur when moving and lifting parts (Zhao et al., 2022; Liu et al., 2021; Zhou et al., 2021). Also, blockchain technology was often used in BIM research on prefabricated building project information gathering, recording, management, and transfer (Li et al., 2022; Jiang et al., 2021). Accordingly, the authors asserted that prefabricated building projects can be delivered more precisely by using intelligent information exchange and fostering integration between the executive forces of the site, supply chain, and project management. These results may inspire research to develop an automatic framework for scheduling prefabricated building projects (Yang et al., 2021; Lee & Lee, 2021). A good example is a project that uses IFC to construct a live, dynamic information model that reduces timing accuracy in the fourth dimension of BIM and prevents ineffective data from entering a manually run system (Yang et al., 2021).

However, "the collection of historical buildings"—the second issue in this cluster—introduces itself with terms like heritage BIM (HBIM) and laser scanning. The initial and most challenging stage in defining HBIM is the perception of three-dimensional space and the development of a trustworthy model of the architectural elements of a priceless historical structure (Khalil et al., 2021). Depending on the significance of the building, professionals can scan these structures with a high degree of detail using three-dimensional digital measuring technologies like terrestrial laser scanners (TLS) and photogrammetry to achieve these objectives (Banfi et al., 2022). However, edge recognition and positioning, surface reflection uncertainty errors, and blocked area reconstruction are some of the main challenges to tracking parametric objects in a terrestrial laser scanner point cloud (Alshawabkeh et al., 2021). According to a review of the articles in this cluster (Khalil et al., 2021; Moyano et al., 2021; Ramonell & Chacón, 2021; Moyano, 2022), most research in this area focuses on solving the issues above and using DT technology to improve point cloud models from historical monuments created by terrestrial laser scanners (TLS).

The common theme among all the keywords in the ***yellow cluster*** in asset management during project operation shows how closely related the terms in this cluster are to one another and how highly this subject is valued by scholars studying the integration of BIM and DT. However, the measures reveal that this theme has garnered the writers' greatest attention at the nexus of BIM and DT in terms of the number of papers. The facility management process is completed based on the information and data accessible from the assets, which begins upon entering the operating phase. Therefore, the necessary information must have the right degree of detail, be accurate and high quality, be regularly updated, and be accessible as soon as possible to properly conduct this procedure. Most of the facility management studies that have been found have addressed this issue and acknowledged the value of this technology, which has motivated academics to adopt further information technology tools like DT.

By building an integrated model of the project as a database, BIM makes it easier to organise and get rapid access to project information. While IoT technology continuously monitors the project assets and sends instantaneous reports to the database, the asset information is updated continuously as a result. Digital technology should be used by infrastructure management throughout both the data-collecting phase and the decision-making process. There are two steps to the application of such digital technologies in facility management: the information-gathering stage and the decision and action stage (Marra et al., 2022). According to the study of Hosamo et al. (2022), the standardisation of information is the first significant hurdle that must be solved before the actual deployment of DT in the facility management process in the construction sector. According to Zhao et al. (2022), several associated issues, such as a lack of cooperation in data integration and data standards, are limiting the adoption of DT in facility management.

Since managing the assets in these infrastructures is a vital and labour-intensive process, inspections are not just conducted on building sites but also on essential infrastructure. Meanwhile, the administration and upkeep of transportation infrastructures, including bridges, roads, and railroad lines, constitute a sizeable portion of the study. Currently, manual techniques are used to monitor and inspect most bridges constructed worldwide (Keawunruen et al., 2021). This poses several challenges and issues, including rising costs, decreased maintenance operations efficiency, and increased vulnerability. Their publications have also drawn attention to the shortened usable lives of these infrastructures, and they have used a variety of technologies from the fourth generation of the industry, like unmanned birds, DT, and BIM, in concert to address these difficulties (Bono et al., 2022). One of the topics that has drawn the attention of academics is pavement management on roads. The use of machine learning is used to create a pavement performance prediction model based on DT (Yu et al., 2022). One example of this study, the outcomes of which include all the consequences of DT technology, was the integration of DT with PMS to develop a live pavement management system (D'Amico et al., 2022). Digital pavement management was evident.

The phrases arranged in the final cluster, which is ***purple***, naturally conjure up the idea of "sustainable" in the building business and distinguish it from other fields. The World Commission on Environment and Development introduced the idea of sustainability in 1987 in response to the impact of human interference on the environment, which became more pronounced (Saieng et al., 2018). Studies done up to 2020 show that most of the studies on sustainability in the building sector have only addressed its environmental pillar, ignoring its two other pillars, the economic and social (Lima et al., 2021; Olawumi et al., 2020). This assertion is supported by the studies undertaken for this study; the most attractive issues for researchers in sustainability research are "carbon emission," "zero energy buildings," "green buildings," and "thermal comfort."

Global energy consumption has grown recently, and issues like rising greenhouse gas production and emissions and global warming have garnered increased attention (Onat and Kucukvar, 2020). Measurements show that the building industry contributed more than 30% to the current global crisis (Sizirici et al., 2021). As a result, it is only natural that the topic of reducing energy consumption and greenhouse gas production has drawn a sizable portion of studies on the construction industry in recent years. Numerous researchers worldwide, especially in developed countries, have focused on finding a solution to this global challenge.fv

One of the most significant constituents in this respect is carbon, which is between 30 and 40% of greenhouse gases (Sizirici et al., 2021). Although the cited articles (Kaewunruen and Lian, 2019a; Kaewunruen et al., 2020; Kaewunruen and Xu, 2018a) identified numerous factors in the production and emission of carbon during the life cycle of a project in the construction industry, the review and evaluation of the project life cycle show the stage of material production in the implementation and the stage of benefit. The highest production and emission of carbon over the project's life cycle comes from the removal of assets. The operational phase represents a more significant portion of the process (Kaewunruen et al., 2020). According to the study, technical advancements in the fourth generation of the construction industry will significantly contribute to lowering carbon emissions and other greenhouse gases produced by the sector's operations.

Energy-saving and consumption-reduction strategies have been taken into consideration throughout the project's life cycle, particularly during the operating phase, as part of researchers' ongoing efforts to address the worldwide challenge. "Zero Energy Buildings" and "Green Buildings" have taken a more prominent role in research that has benefited from the usage of DT and BIM. This is due to the widespread use of IoT sensors, their relationship to BIM, and their use to advance these methodologies. DT technology is often used with net zero energy buildings (NZEB) to increase energy-saving innovations (Kaewunruen et al., 2019b; Kaewunruen et al., 2018b). Moreover, green construction practices are being incorporated into project, construction, and operating processes due to the need to reduce energy usage and the rising cost of energy (Saieg et al., 2018). On the other hand, even though the introduction of various thermal comfort models since the 1970s should be seen as a starting point for the development of a research foundation in this area (Zhao et al., 2021), research in the field of thermal comfort, particularly in the research of the construction industry, has undoubtedly flourished.

Shahinmoghadam et al. (2021) argued that DT technology's rich and user-friendly representations of real-time building monitoring data should be explored in thermal comfort. Thermal comfort studies are impacted by two categories of personal and environmental elements; which can be determined from a thorough evaluation of the research in this area. The key problem in this area is ongoing access to relevant data. Previous studies proposed integrating BIM and IoT sensors to create a dynamic spatial model to forecast and quantify thermal comfort using DT technology (Abdelrahman et al., 2022; Shahinmoghadam et al., 2021).

The comprehensive examination of the articles' content demonstrated, to some extent, the correctness of the findings produced by the clustering tool, regardless of the identification and analysis of the issues of interest to scholars in a certain study field. The resultant clustering separated the terms that had a stronger thematic link from one another while being based on judgment based on subjective data, even though they were anticipated to be viewed together in a cluster. The terms "existing building" and "point cloud" were more intricately connected to the words "historic BIM" and "laser scanning" in the blue cluster than the words "environment" and "thermal comfort" were to the words "sustainable" in the purple cluster.

5. Conclusions and future research areas

This study provided an in-depth analysis of the construction industry's transition from BIM to DT. In order to achieve this goal, various research and review publications in the fields of BIM and DT were retrieved from the WoS database. The output data was then evaluated using scientometric tools such as VOSviewer and HistCite. By employing a combined scientometric and systematic approach, the study has revealed several key findings and insights regarding the current state and future directions of this emerging research domain. Also, the themes of each article were identified, explored, and evaluated concurrently with the scientometric analysis. The systematic analysis section examined the articles' themes and derived clusters from the scientometric analysis to discuss the findings of these articles.

The scientometric analysis unveiled a rapidly growing interest in the integration of BIM and DT technologies, with over 90% of the identified publications being published since 2020. The United Kingdom, China, and Italy emerged as the leading countries contributing to this field, reflecting the influence of national initiatives and research programs. Furthermore, the co-occurrence network of keywords highlighted five prominent research clusters: (1) construction 4.0 technologies, (2) smart cities and urban environments, (3) heritage BIM and laser scanning, (4) asset and facility management, and (5) energy and sustainability.

The systematic review further analysed the content within each of these clusters. It revealed that the operation phase of the project life cycle has garnered the most attention from researchers, particularly in areas such as facility management, asset management, and sustainability. The integration of BIM, DT, and IoT technologies has enabled the continuous monitoring and optimisation of building performance, energy efficiency, and environmental impact during the operation phase.

This study significantly contributes to the body of knowledge by providing a comprehensive understanding of the research trends, patterns, and thematic areas within the BIM-DT integration domain. The identification of key authors, institutions, and countries actively engaged in this field facilitates future collaborations and knowledge-sharing opportunities. Additionally, the systematic analysis of research themes and clusters provides a solid foundation for researchers and practitioners to explore specific areas of interest and identify potential research gaps.

Research implications. The study's findings have practical implications for the construction industry and the built environment. Integrating BIM and DT technologies offers numerous opportunities for enhancing project delivery, asset management, and sustainability practices. The identified research clusters, such as facility management, energy efficiency, and smart city applications, provide valuable insights for industry stakeholders to leverage these emerging technologies and address real-world challenges in the built environment. More so, this research contributes to the advancement of knowledge by synthesising the current state of research and highlighting potential future research directions. The identified research gaps and challenges, such as the need for standardisation, data integration, and interoperability, provide a roadmap for researchers to address these issues and advance the theoretical and practical applications of BIM-DT integration.

The increasing focus on facility and asset management in buildings and infrastructure, coupled with the emerging challenges of energy supply, cost escalation, and environmental concerns in many developed countries, suggests that operational phase issues will remain a high priority for researchers in this field. Consequently, sustainability and facility management are expected to be developing areas of study. Additionally, with the advent of Construction 4.0 and the growing digitalisation trend in construction research, it is anticipated that new technologies like drones, robots, laser scanners, and LiDAR sensors will be increasingly integrated with BIM and DT to implement digital twins in the industry.

It is important to note that while the Web of Science is a reputable scientific database, this study's findings are limited to the papers available in that database. Despite the thorough review of article topics to ensure comprehensive identification, some relevant papers may have been inadvertently missed during the search process and excluded from the research corpus.

Meanwhile, based on the identified gaps in the BIM-DT research domain, future studies could focus on developing algorithms and machine learning techniques for real-time data processing, analysis, and decision-making in DT environments. Research should also examine issues related to cybersecurity and data privacy concerns associated with the widespread adoption of DT in the built environment. By addressing these areas of further research, the construction industry can leverage the full potential of BIM-DT integration, unlocking new opportunities for innovation, efficiency, and sustainability in the built environment.

References

Abdelrahman, M. M., Chong, A., & Miller, C. (2022). Personal thermal comfort models using DT: Preference prediction with BIM-extracted spatial–temporal proximity data from Build2Vec. *Building and Environment*, *207*, 108532.

Afsari, K., Florez, L., Maneke, E., & Afkhamiaghda, M. (2019, May). An Experimental Investigation of the Integration of Smart Building Components with Building Information Model (BIM). *In Proceedings of the 36th International Symposium on Automation and Robotics in Construction (ISARC) (pp. 578-585). International Association for Automation and Robotics in Construction (IAARC).*

Agostinelli, S., Cumo, F., Nezhad, M. M., Orsini, G., & Piras, G. (2022). Renewable Energy System Controlled by Open-Source Tools and DT Model: Zero Energy Port Area in Italy. Energies, 15(5), 1817.

Alaloul, W. S., Liew, M. S., Zawawi, N. A. W. A., & Kennedy, I. B. (2020). Industrial Revolution 4.0 in the construction industry: Challenges and opportunities for stakeholders. *Ain Shams Engineering Journal*, *11*(1), 225-230.

AlRyalat, S. A. S., Malkawi, L. W., & Momani, S. M. (2019). Comparing bibliometric analysis using PubMed, Scopus, and Web of Science databases. *JoVE (Journal of Visualized Experiments)*, (152), e58494.

Alshawabkeh, Y., Baik, A., & Miky, Y. (2021). Integration of laser scanner and photogrammetry for heritage BIM enhancement. *ISPRS International Journal of Geo-Information*, *10*(5), 316.

Archambault, É., Campbell, D., Gingras, Y., & Larivière, V. (2009). Comparing bibliometric statistics obtained from the Web of Science and Scopus. *Journal of the American society for information science and technology*, *60*(7), 1320-1326.

Asghari, P., Rahmani, A. M., & Javadi, H. H. S. (2019). Internet of Things applications: A systematic review. Computer Networks, 148, 241-261.

Banfi, F., Brumana, R., Landi, A. G., Previtali, M., Roncoroni, F., & Stanga, C. (2022). Building archaeology informative modelling turned into 3D volume stratigraphy and extended reality time-lapse communication. *Virtual Archaeology Review, 13(26), 1-21.*

Bono, A., D'Alfonso, L., Fedele, G., Filice, A., & Natalizio, E. (2022). Path Planning and Control of a UAV Fleet in Bridge Management Systems. *Remote Sensing*, *14*(8), 1858.

Bradley, A., Li, H., Lark, R., & Dunn, S. (2016). BIM for infrastructure: An overall review and constructor perspective. *Automation in construction*, *71*, 139-152.

Büchi, G., Cugno, M., & Castagnoli, R. (2020). Smart factory performance and Industry 4.0. *Technological Forecasting and Social Change*, *150*, 119790.

CDBB, (2022), Available online: https://www.cdbb.cam.ac.uk/AboutCDBB (accessed on 3 july 2022).

Chen, L., Xie, X., Lu, Q., Parlikad, A. K., Pitt, M., & Yang, J. (2021). Gemini principles-based DT maturity model for asset management. *Sustainability*, *13*(15), 8224.

Cheng, J. C., Chen, W., Chen, K., & Wang, Q. (2020). Data-driven predictive maintenance planning framework for MEP components based on BIM and IoT using machine learning algorithms. *Automation in Construction*, *112*, 103087.

Coupry, C., Noblecourt, S., Richard, P., Baudry, D., & Bigaud, D. (2021). BIM-Based DT and XR devices to improve maintenance procedures in smart buildings: A literature review. Applied Sciences, 11(15), 6810.

D'Amico, F., Bianchini Ciampoli, L., Di Benedetto, A., Bertolini, L., & Napolitano, A. (2022). Integrating Non-Destructive Surveys into a Preliminary BIM-Oriented Digital Model for Possible Future Application in Road Pavements Management. *Infrastructures*, *7*(1), 10.

Darko, A., Chan, A. P., Adabre, M. A., Edwards, D. J., Hosseini, M. R., & Ameyaw, E. E. (2020). Artificial intelligence in the AEC industry: Scientometric analysis and visualization visualisation of research activities. *Automation in Construction*, 112, 103081.

Dresch, A., Lacerda, D. P., & Antunes, J. A. V. (2015). Systematic Literature Review. In A. Dresch, D. P. Lacerda, & J. A. V. Antunes (Eds.), *Design Science Research* (pp. 129–158). Springer International Publishing. https://doi.org/10.1007/978-3-319-07374-3_7

Eastman, C., Fisher, D., Lafue, G., Lividini, J., Stoker, D., & Yessios, C. (1974). An outline of the building description system. *Research Report*, 50, 1974.

Eck, N. J. V., & Waltman, L. (2014). Visualizing Visualising bibliometric networks. In Measuring scholarly impact (pp. 285-320). Springer, Cham.

Errandonea, I., Beltrán, S., & Arrizabalaga, S. (2020). DT for maintenance: A literature review. *Computers in Industry*, 123, 103316.

Gharbia, M., Chang-Richards, A., Lu, Y., Zhong, R. Y., & Li, H. (2020). Robotic technologies for on-site building construction: A systematic review. *Journal of Building Engineering*, *32*, 101584.

Grieves, M., & Vickers, J. (2017). DT: Mitigating unpredictable, undesirable emergent behavior in complex systems. In Transdisciplinary perspectives on complex systems (pp. 85-113). Springer, Cham.

Haghsheno, S., Deubel, M., & Spenner, L. (2019). Identification and description of relevant digital technologies for the construction industry. *Bauingenieur*, *94*(2), 45-55.

Heaton, J., Parlikad, A. K., & Schooling, J. (2019). Design and development of BIM models to support operations and maintenance. *Computers in industry*, 111, 172-186.

Hilal, M., Maqsood, T., & Abdekhodaee, A. (2019). A hybrid conceptual model for BIM in FM. *Construction Innovation*, 19(4), 531-549.

Hosamo, H. H., Imran, A., Cardenas-Cartagena, J., Svennevig, P. R., Svidt, K., & Nielsen, H. K. (2022). A Review of the DT Technology in the AEC-FM Industry. *Advances in Civil Engineering*, *2022*.

Hossain, M. A., & Nadeem, A. (2019, April). Towards digitizing digitising the construction industry: State of the art of construction 4.0. In *Proceedings of the ISEC* (Vol. 10).

Hosseini, M. R., Maghrebi, M., Akbarnezhad, A., Martek, I., & Arashpour, M. (2018a). Analysis of citation networks in BIM research. *Journal of Construction Engineering and Management,* 144(8), 04018064.

Hosseini, M. R., Martek, I., Zavadskas, E. K., Aibinu, A. A., Arashpour, M., & Chileshe, N. (2018b). Critical evaluation of off-site construction research: A Scientometric analysis*. Automation in Construction*, 87, 235-247.

Jiang, Y., Liu, X., Kang, K., Wang, Z., Zhong, R. Y., & Huang, G. Q. (2021). Blockchain-enabled cyber-physical smart modular integrated construction. *Computers in Industry*, *133*, 103553.

Jin, R., Gao, S., Cheshmehzangi, A., & Aboagye-Nimo, E. (2018). A holistic review of off-site construction literature published between 2008 and 2018. *Journal of Cleaner Production, 202, 1202-1219.*

Kaewunruen, S., & Lian, Q. (2019a). DT aided sustainability-based lifecycle management for railway turnout systems. *Journal of Cleaner Production*, *228*, 1537-1551.

Kaewunruen, S., & Xu, N. (2018a). DT for sustainability evaluation of railway station buildings. *Frontiers in Built Environment*, *4*, 77.

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

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

Kaewunruen, S., Sresakoolchai, J., & Kerinnonta, L. (2019b). Potential reconstruction design of an existing townhouse in Washington DC for approaching net zero energy building goal. *Sustainability*, *11*(23), 6631.

Kaewunruen, S., Sresakoolchai, J., Ma, W., & Phil-Ebosie, O. (2021). DT aided vulnerability assessment and risk-based maintenance planning of bridge infrastructures exposed to extreme conditions. *Sustainability*, *13*(4), 2051.

Kaewunruen, S., Sresakoolchai, J., Ma, W., & Phil-Ebosie, O. (2021). DT aided vulnerability assessment and risk-based maintenance planning of bridge infrastructures exposed to extreme conditions. *Sustainability*, *13*(4), 2051.

Khalil, A., Stravoravdis, S., & Backes, D. (2021). Categorisation of building data in the digital documentation of heritage buildings. *Applied Geomatics*, *13*(1), 29-54.

Kubicki, S., Guerriero, A., Schwartz, L., Daher, E., & Idris, B. (2019). Assessment of synchronous interactive devices for BIM project coordination: Prospective ergonomics approach. *Automation in Construction*, 101, 160-178.

Lee, D., & Lee, S. (2021). DT for supply chain coordination in modular construction. *Applied Sciences*, *11*(13), 5909.

Li, X., Lu, W., Xue, F., Wu, L., Zhao, R., Lou, J., & Xu, J. (2022). Blockchain-enabled IoT-BIM platform for supply chain management in modular construction. *Journal of construction engineering and management*, *148*(2), 04021195.

Li, Y. J., Hou, H. Q., & Pei, X. Y. (2006). Introduction and evaluation to HistCite—A citation historiography visualization visualisation software. Library and Information Service, 50(12), 135-138.

Lima, L., Trindade, E., Alencar, L., Alencar, M., & Silva, L. (2021). Sustainability in the construction industry: A systematic review of the literature. *Journal of Cleaner Production*, *289*, 125730.

Lin, Y. C., & 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), 04020012.

Liu, Z., Meng, X., Xing, Z., & Jiang, A. (2021). DT-based safety risk coupling of prefabricated building hoisting. *Sensors*, *21*(11), 3583.

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

Mannino, A., Dejaco, M. C., & Re Cecconi, F. (2021). Building information modelling and internet of things integration for facility management—Literature review and future needs. *Applied Sciences*, 11(7), 3062.

Marra, A., Trizio, I., Fabbrocino, G., & Savini, F. (2021). Digital Models for e-conservation: The HBrIM of a bridge along the Aterno river. *SCIRES-IT-SCIentific RESearch and Information Technology*, *11*(2), 83-96.

Menassa, C. C. (2021). From BIM to DT: A systematic review of the evolution of intelligent building representations in the AEC-FM industry. *Journal of Information Technology in Construction (ITcon),* 26(5), 58-83.

Moral-Muñoz, J. A., Herrera-Viedma, E., Santisteban-Espejo, A., & Cobo, M. J. (2020). Software tools for conducting bibliometric analysis in science: An up-to-date review. *Profesional de la Información*, *29*(1).

Moretti, N., Xie, X., Merino, J., Brazauskas, J., & Parlikad, A. K. (2020). An openbim approach to IoT integration with incomplete as-built data. *Applied Sciences*, *10*(22), 8287.

Motawa, I.; Almarshad, A. Case-Based Reasoning and BIM Systems for Asset Management. Built Environ. Proj. Asset Manag.2015, 5, 233–247.

Moyano, J., Gil-Arizón, I., Nieto-Julián, J. E., & Marín-García, D. (2022). Analysis and management of structural deformations through parametric models and HBIM workflow in architectural heritage. *Journal of Building Engineering*, *45*, 103274.

Moyano, J., León, J., Nieto-Julián, J. E., & Bruno, S. (2021). Semantic interpretation of architectural and archaeological geometries: Point cloud segmentation for HBIM parameterisation. *Automation in Construction*, *130*, 103856.

Natephra, W., & Motamedi, A. (2019, May). Live data visualization visualisation of IoT sensors using augmented reality (AR) and BIM. *In 36th International Symposium on Automation and Robotics in Construction (ISARC 2019).*

National BIM Guide for Owners. NIBS, 2017; 46p, Available online: https://www.nibs.org/files/pdfs/NIBS_BIMC_NationalBIMGuide.pdf (accessed on 20 july 2022).

Oesterreich, T. D., & Teuteberg, F. (2016). Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *Computers in industry*, *83*, 121-139.

Olawumi, T. O., & Chan, D. W. M. (2018). A Scientometric Review of Global Research on Sustainability and Sustainable Development. *Journal of Cleaner Production*, *183*(May), 231–250. https://doi.org/10.1016/j.jclepro.2018.02.162

Olawumi, T. O., Chan, D. W. M., Chan, A. P. C., & Wong, J. K. W. (2020). Development of a building sustainability assessment method (BSAM) for developing countries in sub-Saharan Africa. *Journal of Cleaner Production*, 263(August), Article Number 121514, 17 pages. https://doi.org/10.1016/j.jclepro.2020.121514

Olawumi, T. O., Chan, D. W. M., Ojo, S., & Yam, M. C. H. (2022). Automating the modular construction process: A review of digital technologies and future directions with blockchain technology. *Journal of Building Engineering*, *46*(April), Article ID 103720. https://doi.org/10.1016/j.jobe.2021.103720

Omrany, H., Chang, R., Soebarto, V., Zhang, Y., Ghaffarianhoseini, A., & Zuo, J. (2022). A bibliometric review of net zero energy building research 1995–2022. *Energy and Buildings*, *262*, 111996.

Onat, N. C., & Kucukvar, M. (2020). Carbon footprint of construction industry: A global review and supply chain analysis. *Renewable and Sustainable Energy Reviews*, *124*, 109783.

Opoku, D. G. J., Perera, S., Osei-Kyei, R., Rashidi, M., Famakinwa, T., & Bamdad, K. (2022). Drivers for DT Adoption in the Construction Industry: A Systematic Literature Review. *Buildings*, *12*(2), 113.

Pan, M., Yang, Y., Zheng, Z., & Pan, W. (2022). Artificial Intelligence and Robotics for Prefabricated and Modular Construction: A Systematic Literature Review. *Journal of Construction Engineering and Management*, *148*(9), 03122004.

Pauwels, P., Zhang, S., & Lee, Y. C. (2017). Semantic web technologies in AEC industry: A literature overview. *Automation in Construction*, *73*, 145-165.

Pham, K. T., Vu, D. N., Hong, P. L. H., & Park, C. (2020). 4D-BIM-based workspace planning for temporary safety facilities in construction SMEs. International journal of environmental research and public health, 17(10), 3403.

Pramanik, P., & Maiti, M. K. (2019). An inventory model for deteriorating items with inflation induced variable demand under two level partial trade credit: A hybrid ABC-GA approach. *Engineering Applications of Artificial Intelligence*, 85, 194-207.

Ramonell, C., & Chacón, R. (2021). Open-source terrestrial laser scanner for the virtualization virtualisation of geometrical entities in AEC classrooms. *Computer Applications in Engineering Education*.

Rastogi, T., Backes, A., Schmitz, S., Fagherazzi, G., van Hees, V., & Malisoux, L. (2020). Advanced analytical methods to assess physical activity behaviour using accelerometer raw time series data: A protocol for a scoping review. Systematic Reviews, 9, 1-8.

S. Howell, Y, Rezgui, Beyond BIM, Knowledge management for a smarter built environment, 2018https://www.brebookshop.com/details.jsp?id=327975 (978- 1-84806-476-8).

Saieg, P., Sotelino, E. D., Nascimento, D., & Caiado, R. G. G. (2018). Interactions of BIM, lean and sustainability on the architectural, engineering and construction industry: a systematic review. *Journal of cleaner production*, *174*, 788-806.

Sepasgozar, S. M. (2021). Differentiating DT from digital shadow: Elucidating a paradigm shift to expedite a smart, sustainable built environment. *Buildings*, *11*(4), 151.

Shahinmoghadam, M., Natephra, W., & Motamedi, A. (2021). BIM-and IoT-based virtual reality tool for real-time thermal comfort assessment in building enclosures. *Building and Environment*, *199*, 107905.

Sizirici, B., Fseha, Y., Cho, C. S., Yildiz, I., & Byon, Y. J. (2021). A Review of Carbon Footprint Reduction in Construction Industry, from Design to Operation. *Materials*, *14*(20), 6094.

State Council of China, 2015. Made in China 2025. State Council of China, Beijing, China. Sung, T.K., 2018. Industry 4.0: a Korea perspective. Technol. Forecast. Soc. Change 132, 40–45.

Stock, W. G., Dorsch, I., Reichmann, G., & Schlögl, C. (2023). Counting Research Publications, Citations, and Topics: A Critical Assessment of the Empirical Basis of Scientometrics and Research Evaluation. Journal of Information Science Theory & Practice (JIStaP), 11(2).

Tang, S., Shelden, D. R., Eastman, C. M., Pishdad-Bozorgi, P., & Gao, X. (2019). A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends. *Automation in Construction*, 101, 127-139.

Tchana, Y., Ducellier, G., & Remy, S. (2019). Designing a unique DT for linear infrastructures lifecycle management. *Procedia CIRP*, *84*, 545-549.

Van Eck, N., & Waltman, L. (2019). VOSviewer manual. Manual for VOSviewer version 1.6. 11. Universiteit Leiden.

van Nederveen, G. A., & Tolman, F. P. (1992). Modelling multiple views on buildings. *Automation in Construction*, *1*(3), 215-224.

Vanlande, R., Nicolle, C., & Cruz, C. (2008). IFC and building lifecycle management. *Automation in construction*, *18*(1), 70-78.

White, G., Zink, A., Codecá, L., & Clarke, S. (2021). A DT smart city for citizen feedback. *Cities*, *110*, 103064.

Xie, X., Lu, Q., Rodenas-Herraiz, D., Parlikad, A. K., & Schooling, J. M. (2020). Visualised inspection system for monitoring environmental anomalies during daily operation and maintenance. *Engineering, Construction and Architectural Management*.

Yan, H., Yang, N., Peng, Y., & Ren, Y. (2020). Data mining in the construction industry: Present status, opportunities, and future trends. *Automation in Construction*, 119, 103331.

Yang, B., Dong, M., Wang, C., Liu, B., Wang, Z., & Zhang, B. (2021). IFC-based 4D construction management information model of prefabricated buildings and its application in graph database. *Applied Sciences*, *11*(16), 7270.

Yin, X., Liu, H., Chen, Y., & Al-Hussein, M. (2019). Building information modelling for off-site construction: Review and future directions. *Automation in Construction*, 101, 72-91.

Yu, G., Zhang, S., Hu, M., & Wang, Y. K. (2020). Prediction of highway tunnel pavement performance based on DT and multiple time series stacking. *Advances in Civil Engineering*, *2020*.

Zabidin, N. S., Belayutham, S., & Ibrahim, C. K. I. C. (2020). A bibliometric and scientometric mapping of Industry 4.0 in construction. *Journal of Information Technology in Construction (ITcon).*, *25*, 287-307.

Zhang, Q., & Hao, S. (2022). Construction project manager's emotional intelligence and team effectiveness: The mediating role of team cohesion and the moderating effect of time. Frontiers in Psychology, 13, 845791.

Zhang, X., Shen, J., Saini, P. K., Lovati, M., Han, M., Huang, P., & Huang, Z. (2021). DT for accelerating sustainability in positive energy district: a review of simulation tools and applications. *Frontiers in Sustainable Cities*, 3, 35.

Zhao, J., Feng, H., Chen, Q., & de Soto, B. G. (2022). Developing a conceptual framework for the application of DT technologies to revamp building operation and maintenance processes. *Journal of Building Engineering*, 49, 104028.

Zhao, Q., Lian, Z., & Lai, D. (2021). Thermal comfort models and their developments: A review. *Energy and Built Environment*, *2*(1), 21-33.

Zhao, Y., Cao, C., & Liu, Z. (2022). A Framework for Prefabricated Component Hoisting Management Systems Based on DT Technology. *Buildings*, *12*(3), 276.

Zhou, Y., Wei, X., & Peng, Y. (2021). The modelling of DT technology in the construction process of prefabricated buildings. *Advances in Civil Engineering*, *2021*.