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Mapping the Evolution of 4D BIM in Construction Digitalisation: A Scientometric Analysis and Review

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ABSTRACT

Project delays are a common challenge in the construction industry and often result in increased costs and inefficiencies. As a solution to these ongoing problems, 4D Building Information Modelling (BIM) has emerged as a powerful tool for improving project planning and project management. However, despite the growing interest in 4D BIM, there is a lack of comprehensive analysis of its development and integration with new technologies in construction. This study aims to address this gap by conducting a scientometric review of 4D BIM, focusing on growth patterns, prominent subject categories, keywords, highly cited studies, influential authors and emerging themes. A total of 558 bibliographic records from the Web of Science core collection database (2007-2024) were analysed. CiteSpace was employed to conduct four scientometric analyses, which included exploring co-authorship, co-word relationships, co-citation patterns and clusters. The study found that the emerging themes include technology integration, construction management, safety and risk management, spatial and urban modelling and digital twin reality capture planning. The study also emphasises the importance of integrating technologies such as artificial intelligence (AI), the Internet of Things (IoT) and augmented reality (AR) with 4D BIM to enhance predictive analytics and support smarter construction management practices. This review not only provides valuable insights into the future of 4D BIM in construction digitalisation but also offers practical guidance for countries looking to adopt 4D BIM and emerging technologies in their construction industries.

Keywords: Scientometric analysis; building information modelling; 4D BIM; construction digitalisation

INTRODUCTION

The global economy is heavily reliant on the construction sector for growth and it significantly boosts the GDP of multiple countries (Dehdasht et al. 2022). However, there are recurring problems in the sector such as project delays and cost overruns (Tahir et al. 2019). These problems arise from inefficient project scheduling, delays in material delivery and frequent changes in project scope. Construction delays has seen as a significant issue in both developed countries (Gomez-Cabrera et al. 2024) and developing countries (Nafe et al. 2024; Rivera et al. 2020; Selcuk et al. 2024; Wuala & Rarasati, 2020), costing the industry billions of dollars annually. In 2019, the coronavirus disease (COVID-19) outbreak posed unprecedented challenges to the global construction sector. The industry encountered significant obstacles due to the implementation of lockdowns, supply chain disruptions and the need to adopt new working methods (Shereen & Elhegazy 2022). According to Alenezi (2020), 95% of construction projects were hampered by delays as supervisors were unable to attend work or monitor progress due to the lockdown. These disruptions have highlighted the need for innovative approaches to monitor construction processes remotely, a role that 4D Building Information Modelling (BIM) can effectively fulfil.

BIM is a collaborative digital strategy that involves generating, organising, and distributing comprehensive building data to all stakeholders throughout the life of the project (Eastman 2011; Mazlana et al. 2022). These models can also be optimised in further stages, such as integrating time elements into a 3D model (known as 4D). It has shown that 4D BIM can address various shortcomings in existing design and planning practices (Sheikhkhoshkar et al. 2019). Autodesk Navisworks is one of the most widely used 4D BIM software, particularly known for its clash detection functionality (Yousaf et al. 2024). Dasovic et al. (2019) and Munoz-La Rivera et al. (2019) stated that 30% of total project expenditures in conventional construction are misallocated due to material waste, managerial inefficiencies, inadequate collaboration and ineffective labour. One study found that 4D BIM achieved cost savings of 20-30% on small-scale projects and reduced project duration by up to 80% in small-scale projects (Munagala & Kone, 2020).

The quality of construction planning has been continuously improved through the development and integration of various scenarios, such as automated flight planning using cameras equipped with unmanned aerial vehicles (UAVs) (Jacob-Loyola et al. 2021), construction waste management (Yousfani et al. 2023), safety management (Zhou et al. 2013), lifecycle management (Li et al. 2021), evacuation path planning (Hosseini & Maghrebi, 2021), virtual construction planning (Hatori et al. 2021), workplace conflict detection (Flores & Mourgues, 2024), supply chain management (Magill et al. 2022), automated structural model generation (Singh et al. 2024), crane simulation and onsite operation management (Tak et al. 2021). To fully realise its potential in the era of construction digitalisation, 4D BIM must be integrated with Internet of Things (IoT) devices, artificial intelligence (AI)-driven technologies, robotics, cloud computing and mobile applications. This is because these technologies can enable immediate data acquisition, advanced data analysis, automated decision-making and continuous communication throughout the construction project. Despite the growing recognition of these potentials, there is still a lack of comprehensive integration of digital technologies into 4D BIM.

In the field of bibliometrics, science mapping is an important research issue because it aims to uncover intellectual connections within the ever-changing terrain of scientific knowledge (Santana & Cobo, 2020). Bibliometric and scientometric analysis are the two common science mapping study techniques (Martinez et al. 2019). In this study, the literature on 4D BIM in the past and current construction industries is examined using scientometric analysis. It explores the landscape of a particular research area by using different techniques such as analysing author connections, common keywords and publication trends (Pooja & Sood, 2024). Several previous studies have explored scientometrics and BIM (Daniel et al. 2024; Pereira et al. 2021; Siccardi & Villa, 2023; Sun et al. 2024; Tanko et al. 2024; Tushar et al. 2023), with only one study explicitly focusing on 4D BIM (Patel et al. 2022). Although previous studies have investigated the benefits and applications of 4D BIM, there remains a significant gap in comprehensive scientometric analyses that systematically map the development and integration of 4D BIM into the digitalisation of construction. To address this gap, the following research questions are proposed:

1. What are the growth patterns and the most active countries and institutions in 4D BIM research within the past and current construction industries?
2. Which keywords have emerged as the most prominent in 4D BIM research?
3. What are the most frequently cited studies in 4D BIM?
4. What are the 4D BIM-related emerging themes and research for the future digitalisation of the construction industry?

METHODOLOGY

This study analysed all publications in the Web of Science (WOS) core collection database, which includes high-impact journals across various disciplines (Liu et al. 2021) and provides robust tools for bibliometric analysis (Caputo & Kargina, 2022). Figure 1 illustrates the study framework including three main stages: preliminary search, data processing and scientometric analysis. The methodological flow of this study was guided by approaches from previous review articles (He et al. 2017; Pereira et al. 2021; Tanko et al. 2024; Zhao 2017).

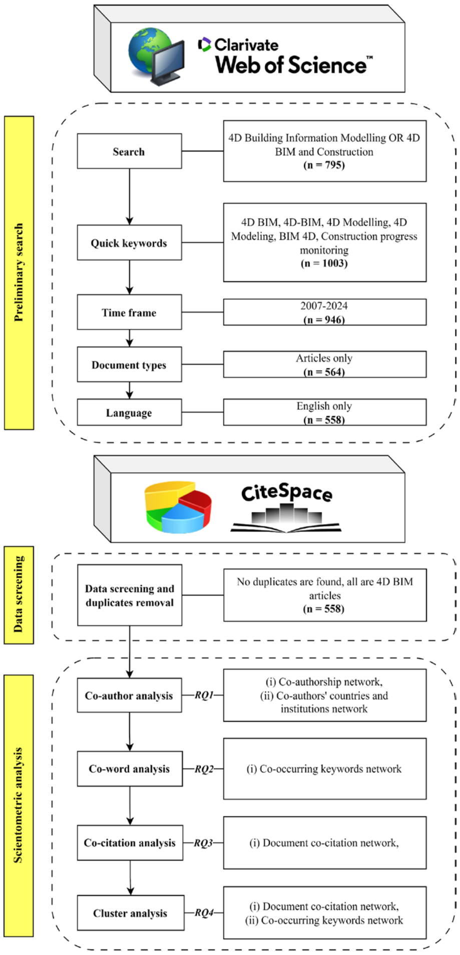

FIGURE 1. Study framework

PRELIMINARY SEARCH

The search strategy used the command "(4D Building Information Modelling OR 4D BIM AND Construction)". To capture more relevant articles, additional keywords like 4D BIM, 4D-BIM, 4D Modelling, 4D Modeling, BIM 4D and construction progress monitoring have been added. Given that fewer than ten articles were published before 2007, the search strategy was limited to publications between 2007 and 2024. The study only considered journal publications, while book chapters, review articles and proceeding papers were excluded from the selection. Most of the research in construction management has focused on journal articles due to their richer and more detailed information, as evidenced by various studies (Radzi et al. 2024; Tanko et al. 2024; Zoleykani et al. 2024). The search was restricted to English-language publications. The final collection process yielded 558 bibliographic records which were compiled and saved in a text document in September 2024.

RESEARCH TOOLKIT

There are some common scientometric toolkits such as CiteSpace (Chen, 2006), ScientoPy (Ruiz-Rosero et al. 2019) and CitNetExplorer (van Eck & Waltman, 2014). These tools enable researchers to study citation patterns, identify research trends, visualise co-cited document networks and understand the evolution of scientific fields over time. CiteSpace (6.3.R1, 64-bit) was selected for this study as it can map knowledge clusters and visualise interdisciplinary research trends (Cheng et al. 2024). Furthermore, CiteSpace can address three fundamental challenges using betweenness centrality, burst detection and heterogeneous network analysis (Chen, 2006; Liu et al. 2019).

DATA SCREENING

Data filtering and duplicate elimination in CiteSpace must be performed on the WOS format before initiating a detailed analysis. This process is important for removing identical and duplicate content. After this pre-processing, a total of 558 valid 4D BIM articles were acquired. No duplicates were found because all the articles were sourced exclusively from the WOS database, without inclusion of data from other databases.

PARAMETRIC SETTING IN CITESPACE

In the CiteSpace front setting, time segmentation was set up between 2007 and 2024, with each slice representing one year. The "Cosine" algorithm was used to determine how strongly network points are connected. The selection criteria were set to "Top 50 objects" and the scale factor was defined as "25". The pruning method was set to "Pathfinder, pruning sliced networks" and the visualisation map was configured as "Cluster view-static, show merged network". Modularity (Q) and silhouette (S) values are typically used to verify whether the visualisation knowledge maps are scientifically true and useful. A Q value above 0.3 indicates a significant network cluster structure, whereas an S value above 0.5 indicates a high reliability of the cluster results (Hu et al. 2020). It was also possible to select the correct node types and create a scientific knowledge map based on the study's needs.

RESULTS AND DISCUSSION

ATTRIBUTES OF DOCUMENT OUTPUTS

Figure 2 shows the distribution of the 558 bibliographic records from 2007 to 2024. The overall trend from 2007 to 2021 indicates a significant increase in interest in 4D BIM, even though there were peak fluctuations between 2014 and 2018. The number of publications peaked in 2021 but started to decline from 2022 to 2024. This suggests that the studies may level off or move to new areas within the larger field of construction management and BIM technologies.

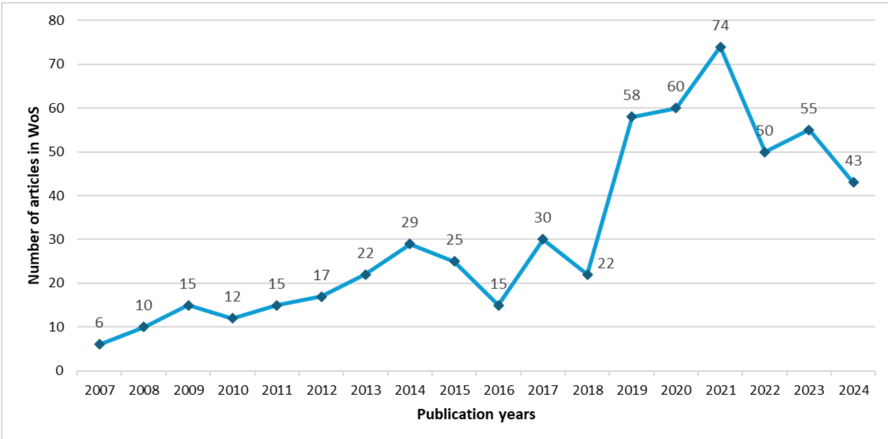

FIGURE 2. Total number of 4D BIM articles collected in the WOS database from 2007 to 2024

CO-AUTHOR ANALYSIS: NETWORK OF CO-AUTHORSHIP

Based on the number of journal articles, 10 authors with the highest publication output were recorded. As shown in Table 1, Mani Golparvar-Fard (University of Illinois Urbana-Champaign), Timo Hartmann (Technical University of Berlin), Vijay Kumar Bansal (National Institute of Technology Hamirpur) and Alaloul Salah (Universiti Teknologi Petronas) occupied the top four positions.

Figure 3 displays a co-authorship network, where authors are represented as nodes and links between them indicating collaborative work on articles. The network comprises 234 nodes and 180 links. In the network, node sizes are scaled according to the number of publications, while the thickness of the connections reflects the intensity of collaboration across different years. To enhance clarity, the time slices of three years are used because 2007–2024 are very far apart, making it difficult to identify patterns or relationships. The network reveals that the researchers within these clusters have developed strong collaborations. For example, Mani Golparvar-Fard is the central author in one of the largest research communities, which involves Amir Ibrahim, Shang-Hsien Hsieh and Feniosky Pena-mora. Recently, Wesam Salah Alaloul and Abdul Hannan Qureshi have formed robust research connections with multiple co-authors. In terms of betweenness centrality, Mani Golparvar-Fard (centrality = 0.01), Shang-Hsien Kang (centrality = 0.01) and Shih-Chung Kang (centrality = 0.01) are less central in connecting different research groups. Although they remain active within their respective clusters, they do not play a significant role in bridging separate parts of the larger network.

TABLE 1. The 10 authors with the highest publication output in 4D BIM research

Author	Institution	Country	Count	Percentage
Mani Golparvar-Fard	University of Illinois Urbana-Champaign	USA	13	2.3%
Timo Hartmann	Technical University of Berlin	Germany	8	1.4%
Vijay Kumar Bansal	National Institute of Technology Hamirpur	India	7	1.3%
Alaloul Salah	Universiti Teknologi Petronas	Malaysia	6	1.1%
Andre Borrmann	Technical University of Munich	Germany	6	1.1%
Conrad Boton	Ecole de Technologie Superieure	Canada	6	1.1%
Chansik Park	Chung Ang University	South Korea	6	1.1%
Syed Saad	Universiti Teknologi Petronas	Malaysia	6	1.1%
Xiangyu Wang	East China Jiaotong University	China	6	1.1%
Borja Garcia de Soto	New York University Abu Dhabi	United Arab Emirates	5	0.9%

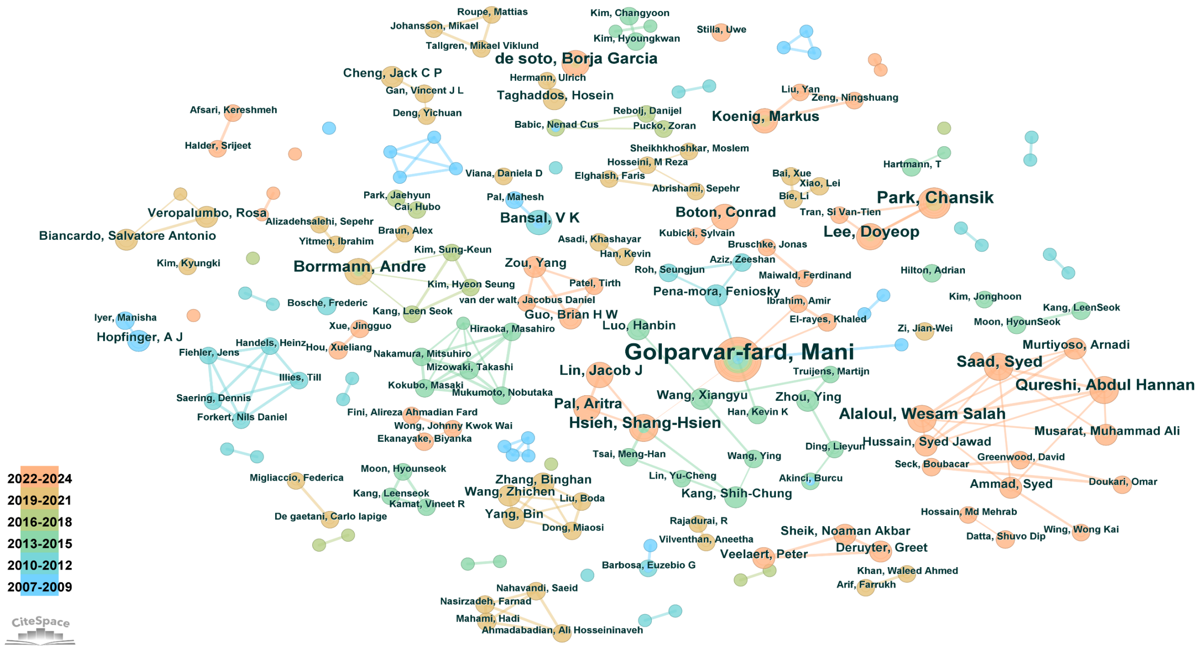

FIGURE 3. Network of co-authorship

CO-AUTHOR ANALYSIS: NETWORK OF COUNTRIES AND INSTITUTIONS

A distribution network for articles related to 4D BIM was established through collaboration among various countries and institutions, as shown in Figure 4. The network comprises 373 nodes and 938 links. The size of the node represents the total number of articles published from 2007 to 2024. Figure 4 illustrates that the USA (116 articles), China (83 articles), England (59 articles), Germany (51 articles), Canada (41 articles) and Australia (41 articles) have made significant contributions to 4D BIM research. The higher volume of journal articles in these countries indicates good progress in the field. The fact that the USA has been the most influential in the development of 4D BIM is closely linked to the General Services Administration (GSA)'s mandate for 4D scheduling and related initiatives on all projects since 2007 (Teicholz, 2013).

The contributions of various institutions were also highlighted in the analysis. Institutions such as Chung Ang University (11 papers), Gyeongsang National University (8 articles), National Institute of Technology (7 articles) and Universiti Teknologi Petronas (6 articles) have seen quite active 4D BIM research advancement. These institutions play a central role in driving global research in this field. Additionally, nodes with high betweenness centrality were identified and are marked with purple rings in Figure 4. The network is anchored by countries such as England (centrality = 0.85), Canada (centrality = 0.45), the Netherlands (centrality = 0.44), France (centrality = 0.37) and the USA (centrality = 0.33). Key institutions within this network include Delft University of Technology (centrality = 0.37), Hong Kong Polytechnic University (centrality = 0.27), University of Salford (centrality = 0.24), Curtin University (centrality = 0.22) and University College London (centrality = 0.18).

Furthermore, there were citation outbursts connected to sudden citation surges in countries such as Scotland (burst strength = 2.16, 2008–2012), the Netherlands (burst strength = 3.71, 2012–2016), Iran (burst strength = 3.16, 2018–2021) and Malaysia (burst strength = 3.07, 2021–2024). Similarly, institutions such as Columbia University (burst strength = 2.59, 2009–2012), Gyeongsang National University (burst strength = 3.13, 2012–2016) and Universiti Teknologi Petronas (burst strength = 1.83, 2021–2024) experienced significant citation surges. It is worth noting that Malaysia, as a developing country, is making important contributions to 4D BIM research. Institutions like Universiti Teknologi Petronas in Malaysia have witnessed a remarkable rise in citations in recent years. As a result, Malaysia is playing an increasingly important role in promoting 4D BIM research and suggests that developing countries are starting to make significant contributions to cutting-edge technology research, which could potentially lead to further global innovation and collaboration.

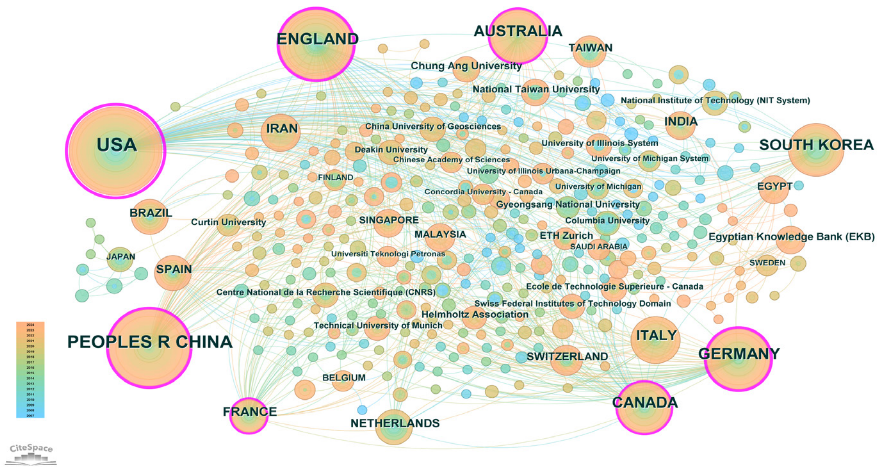

FIGURE 4. Network of countries and institutions

CO-WORD ANALYSIS: NETWORK OF CO-OCCURRING KEYWORDS

Figure 5 presents a network of co-occurring keywords with 524 nodes and 1460 links. The terms “building information modelling”, “building information modeling”, “bim”, “bim (building information modelling) and “building information model” were merged into “building information modelling (bim)”. Besides, “4d building information modelling”, “4d building model”, “4d building information model”, 4d modelling” and “4d model” were merged into “4d bim”.

The top 10 most frequently used keywords in 4D BIM research were “building information modelling (bim)” (frequency = 152), “4d bim” (frequency =80), “management” (frequency = 63), “model” (frequency = 62), “system” (frequency = 53), “construction” (frequency = 47), “visualization” (frequency = 36), “technology” (frequency = 24), “construction progress monitoring” (frequency = 21) and “construction management” (frequency = 15). Additionally, several keywords had relatively high betweenness centrality scores. These keywords included “model” (centrality = 0.26), “4d bim” (centrality = 0.12), “algorithm” (centrality = 0.11), “management” (centrality = 0.09), “building information modelling (bim)” (centrality = 0.07) and “augmented reality” (centrality = 0.04). They are connected to a wide range of research topics and have made significant contributions to the development of 4D BIM research. Besides, seven keywords exhibited citation bursts: “4d cad” (burst strength = 5.42, 2009–2016), “management” (burst strength = 2.63, 2013–2015), “visualization” (burst strength = 4.42, 2014–2015), “evolution” (burst strength = 3.23, 2014-2017), “point clouds” (burst strength = 2.64, 2021–2024), “virtual reality” (burst strength = 2.26, 2021–2024) and “technology” (burst strength = 3.41, 2022–2024). These keywords were central to 4D BIM research during the corresponding year.

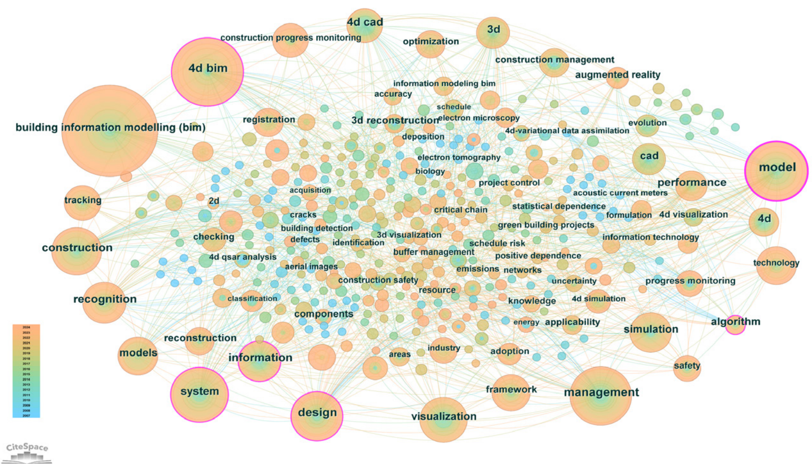

FIGURE 5. Network of co-occurring keywords

CO-CITATION ANALYSIS AND CLUSTER ANALYSIS: NETWORK OF DOCUMENT CO-CITATION

Table 2 summarises the top ten most cited 4D BIM articles, with the top three positions held by Koo and Fischer (2000), Golparvar-Fard et al. (2015) and Turkan et al. (2012), who received 49, 45 and 44 citations, respectively. Koo and Fischer (2000) evaluated the effectiveness of 4D modelling in identifying potential problems in a construction project schedule, highlighting its benefits in visualising the construction process and detecting errors. However, they also noted its limitations in conveying all the necessary planning details. Golparvar-Fard et al. (2015) proposed an approach that integrates both current and planned views to detect progress in construction projects by using a probability-based model for progress detection. Turkan et al. (2012) developed a system that automates the monitoring of construction progress and updates schedules through the fusion of 3D point clouds, 3D CAD models and schedule data.

TABLE 2. The top ten most-cited articles

No.	Total citations	Cluster ID	Betweenness centrality	Article
1	49	#3	0.19	Koo and Fischer (2000)
2	45	#0	0.03	Golparvar-Fard et al. (2015)
3	44	#0	0.05	Turkan et al. (2012)
4	40	#0	0.19	Golparvar-Fard et al. (2009)
5	39	#0	0.15	Han and Golparvar-Fard (2015)
6	33	#1	0.07	Hartmann et al. (2008)
7	32	#1	0.04	Mahalingam et al. (2010)
8	28	#0	0.01	Kropp et al. (2018)
9	25	#4	0.07	Akinci et al. (2002)
10	23	#4	0.03	Moon et al. (2014)

Initially, a network of document co-citations had 611 nodes and 2715 links, but a cluster view was adopted because it could better help identify the main research theme within the body of literature. Figure 6 illustrates how each cluster in the network represents a different aspect of 4D BIM research. It is particularly important to pay attention to articles that have high betweenness centralities, as shown by the purple rings in Figure 6. The representative articles were Koo and Fischer (2000) (centrality = 0.19, cluster #3) and Golparvar-Fard et al. (2009) (centrality = 0.19, cluster #0). These publications are big milestones in 4D BIM research that will have a big impact on the field.

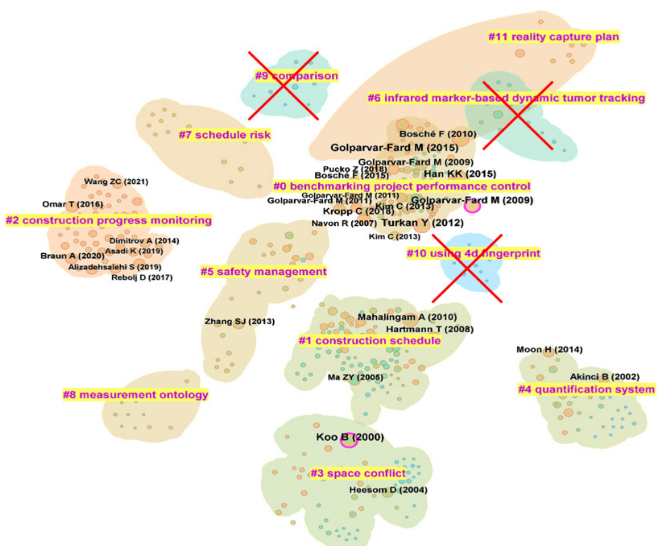

FIGURE 6. Network of document co-citation in the cluster view

TABLE 3. Co-citation clusters of 4D BIM research from 2007 to 2024

Cluster ID	Size	Silhouette	Cluster label	Alternative label	Mean year	Representative document
0	107	0.828	Benchmarking project performance control	Technologies adoption; indoor monitoring	2012	Pal et al. (2023)
1	89	0.816	Construction schedule	Refurbishment process; automated approaches	2010	Ding et al. (2014)
2	58	0.826	Construction progress monitoring	Automated vision-based construction progress monitoring; digital twin	2018	Heigermoser et al. (2019)
3	55	0.935	Space conflict	Construction planning process; spatial aspect	2006	Bansal (2011)
4	43	0.88	Quantification system	Building construction project; strategy management	2006	Mirzaei et al. (2018)
5	27	0.914	Safety management	Site health; effective safety communication	2014	Afzal and Shafiq (2021)
6*	16	1	Infrared marker-based dynamic tumour tracking	Scanned proton beam therapy; predictive uncertainty	2017	-
7	13	0.885	Schedule risk	Buffer management framework; lean management framework	2010	Xiao et al. (2021)
8	11	0.976	Measurement ontology	Ifc software support; new rule	2012	Abanda et al. (2017)
9*	11	1	Comparison	Docking study	1999	-
10*	10	1	Using 4d fingerprint	Treating chemical diversity in quantitative structure-activity relationship (QSAR) analysis	1996	-
11	10	0.977	Reality capture plan	Vision-driven construction monitoring; camera-equipped UAV	2018	Ibrahim et al. (2022)

* irrelevant cluster to 4D BIM research in the construction sector.

By analysing the keywords from the referenced articles in each cluster, the Log-Likelihood Ratio (LLR) algorithm identified 11 important co-citation clusters. The LLR approach was selected because it improves the quality of clustering by making it easier to see how the data is organised and improving the accuracy of cluster assignments (de Amorim et al. 2020). In Table 3, the cluster details are shown in a sequence according to their size, silhouette and cluster label, along with the alternative labels that have the second and third-highest LLR scores. For example, Cluster #0, titled "benchmarking project performance control" had the highest number of members (107), while Cluster #11, labelled "reality capture plan" had the fewest members (10). The silhouette coefficients of the clusters ranged from 0.816 to 1.000, indicating clear distinctions and cohesion within each cluster (Mamat et al. 2018). However, certain clusters need to be removed from the analysis such as clusters #6, #9 and #10, despite their silhouette values being 1. This is because cluster #6 focuses more on medical imaging techniques rather than construction-related applications; cluster #9 focuses on methodologies for comparing different technologies, which does not directly relate to the core objectives of 4D BIM; and cluster #10 deals with chemical diversity in QSAR analysis, which is a topic unrelated to the construction industry.

CLUSTER ANALYSIS: CO-OCCURRING KEYWORDS

Figure 7 shows a network of co-occurring keywords in the cluster view, while Table 4 provides the corresponding cluster details. The network displays a strong cluster structure in the clustering results, as indicated by a modularity value of 0.6665 and a silhouette value of 0.8774. However, certain clusters need to be removed from the analysis, such as clusters #5, #6 and #10. This is because the main themes of cluster #5 are supergravity models and super spaces, which are part of theoretical physics; cluster #6 deals with validation in drug design through quantitative structure-activity relationship (QSAR) analysis, which relates to pharmaceutical studies; and cluster #10 focuses on gene automation and annotation, which is part of the bioinformatics and genetic research domain. Therefore, these clusters have no direct connection to the 4D BIM processes in the construction industry.

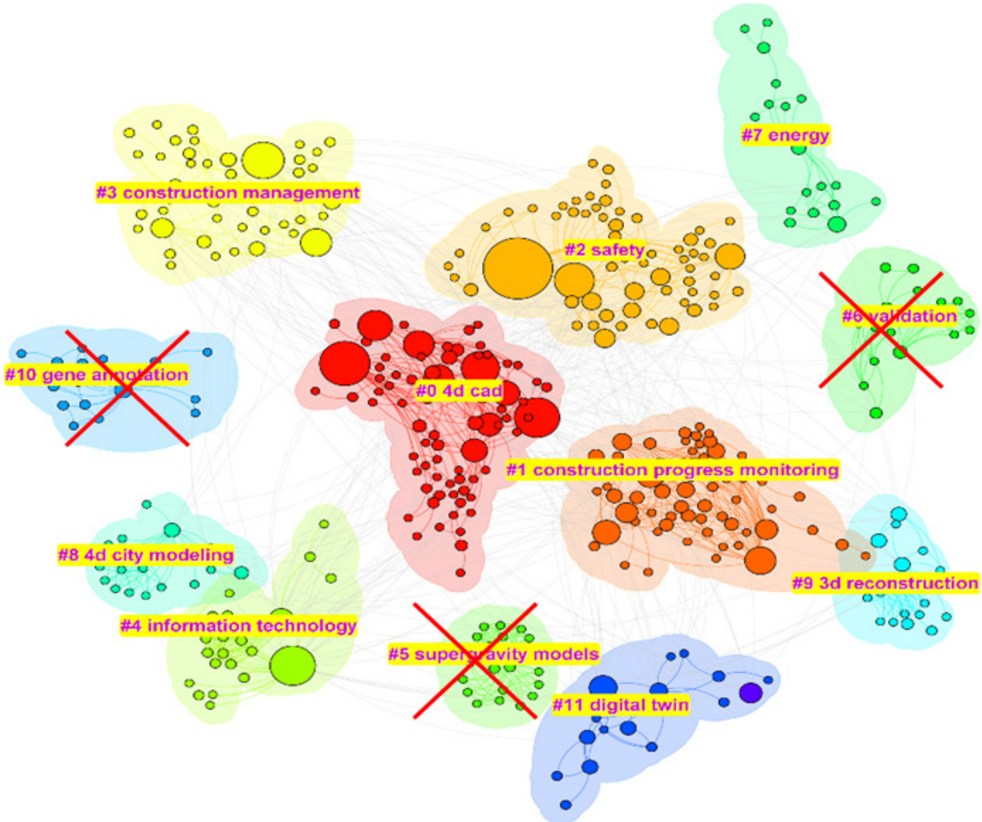

FIGURE 7. Network of co-occurring keywords in the cluster view

TABLE 4. Keyword clusters of 4D BIM research 2007–2024

Cluster ID	Size	Silhouette	Cluster label (LLR)	Alternative label	Mean year
0	80	0.844	4d cad	Construction progress monitoring; 4d modeling	2015
1	64	0.844	Construction progress monitoring	Deep learning; point clouds	2017
2	61	0.788	Safety	4d simulation; clash detection	2016
3	46	0.709	Construction management	Inhibitors; conflict analysis	2015
4	26	0.911	Information technology	Buffer management; 5d bim	2019
5*	21	1	Supergravity models	Extended supersymmetry; superspaces	2007
6*	19	0.987	Validation	4d quantitative structure-activity relationship (QSAR) analysis, drug design	2008
7	19	0.976	Energy	Supergravity; molecular dynamics simulations	2016
8	19	0.958	4d city modeling	Congested sites; 4d urban reconstruction	2011
9	18	0.980	3d reconstruction	4d visualisation; simultaneous localisation	2011
10*	16	1	Gene automation	Virtual gene order; gene annotation	2015
11	15	0.977	Digital twin	Augmented reality; remote sensing	2021

* irrelevant cluster to 4D BIM research in the construction sector.

EMERGING RESEARCH THEMES

Figure 8 illustrates the process of merging and filtering co-citation and keyword clusters. Five main research themes were found such as technology integration, construction management, safety and risk management, spatial and urban modelling, and digital twin reality capture planning.

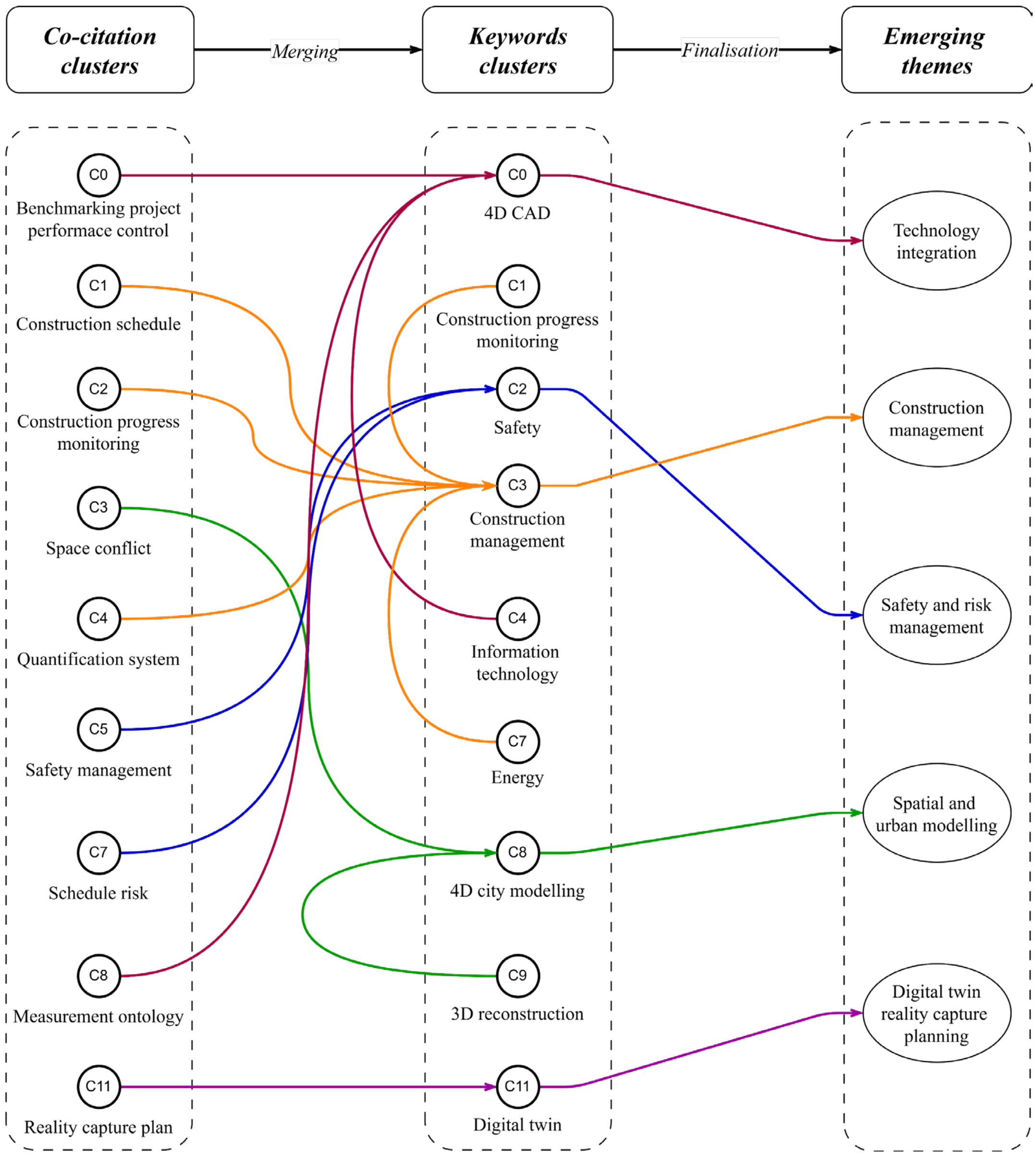

FIGURE 8. Cluster filtering, merging and finalization to identify emerging themes

TECHNOLOGY INTEGRATION

Performance benchmarking is a fundamental aspect of establishing standards and metrics that allow for the continuous monitoring of construction projects. There are five key BIM performance indicators, including accurate quantity take-off, constructability assessments, identifying discrepancies between models from various disciplines, ensuring model data reliability for end users during operation and maintenance, and ease of creating construction documentation (Liu et al. 2017). In India, Ingle et al. (2024) developed a comprehensive project performance assessment model called the Modified Project Quarter Back Rating (MPQR) to evaluate construction projects. Recently, the integration of computer vision and machine learning with BIM and project timelines has improved performance, safety inspections, quality, productivity, operations and building energy efficiency (Lin & Golparvar-Fard, 2020). Automated progress monitoring contributes significantly to project success by ensuring compliance with budget constraints and high quality standards (Alizadehsalehi & Yitmen, 2019).

BIM presents a novel method for defining the measurement ontology used in cost estimation (Abanda et al. 2017). In the past, 4D models only showed the construction progress. However, for successful planning and control of construction site logistics with 4D models, it is essential to identify, classify and create digital representations of logistical requirements for every part of the construction site (Wenzel, 2019). To ensure the ontology works with 4D BIM, experts in cost estimation were consulted to validate the ontology's compatibility with 4D BIM, while logic-based reasoners were employed to verify the syntax. The proposed ontology has been tested on a case study using 4D BIM software. For process automation and the development of 4D tools, Doukari et al. (2022) proposed another ontology which is known as an artificial intelligence (AI) asset for capturing specific subject matter, such as concepts, relationships and constraints.

The backbone that holds all these modern parts together is information technology (IT). Using advanced IT solutions like cloud computing, big data analytics, and AI-driven tools allows for real-time monitoring and decision-making, which makes project management faster and more flexible. The efficiency of quality management during the implementation phase is further enhanced the integration of BIM and cloud computing (Shaban et al. 2024). Marr (2016) illustrated a case where a data-centric BIM system led to cost savings of $11 million and a 12-week reduction in project completion time. Aredah et al. (2021) recommended the development of more sophisticated big data analytics tools for the construction sector and called for a deeper synergy between big data and 4D BIM. Besides, 4D BIM could be integrated with live data from IoT devices (Gao Maggie et al. 2024). The precision and efficiency in managing construction schedules and monitoring would be improved (Pal et al. 2024).

CONSTRUCTION MANAGEMENT

The trend in construction progress monitoring with 4D BIM is shifting towards integrating various sensor technologies and in-placement of cameras. In construction sites, optimising camera placement with 4D BIM and reality models has been shown to significantly improve visual data capture. This method effectively addresses common problems such as occlusion and insufficient coverage. For example, the use of automated visual surveillance systems has been shown to increase camera coverage by 25% (Houng Seau et al. 2024). By integrating additional sensory inputs with the visual data collected through camera monitoring, a more complete picture of the construction site can be achieved. For example, merging 3D point cloud information obtained from LiDAR sensors with camera images can improve the accuracy of volume calculations and detect changes in construction progress (Trzeciak et al. 2023). To track material movement, visual data can be synchronised with radio frequency identification (RFID) tags attached to construction supplies and machinery (Li et al. 2018). To oversee the noise levels, audio sensors can be employed along with visual data (Rashid & Louis, 2020). Thanks to developments in sensor integration, the future digitalisation of construction will advance.

SAFETY AND RISK MANAGEMENT

The use of 4D BIM technology has been on the rise in the construction field for safety and risk management purposes, which is crucial for recognising and reducing possible dangers on the construction site. As modular construction becomes more prevalent due to its efficiency and time-saving advantages, there are specific safety hazards to consider, particularly during lifting and the risk of workers falling or being struck by objects (Chatzimichailidou & Ma, 2022). 4D BIM technology can mitigate the dangers linked to modular construction by providing users with real-time data and visual representations of sites. Golparvar-Fard et al. (2011) took this concept further by combining augmented reality with 4D BIM, thereby improving the visualisation of construction processes and their workflows. This integration improves overall on-site security management while also providing explicit attributes for remote project monitoring. Because of 4D BIM's ability to evaluate construction processes over time, safety professionals can identify problems early and implement appropriate safety measures. This means that safety planning can be integrated into the design phase and carried out throughout the construction process (Rodrigues et al. 2022). Furthermore, the creation of a 4D BIM-based benchmark model and safety ontology has resulted in automated safety assessments covering typical hazards such as falls and collisions. This tool supports the comparison of different security strategies and helps select the most effective approaches (Johansen et al. 2023). Despite the numerous benefits, the adoption of 4D BIM for safety management is hindered by challenges such as knowledge gaps, technological barriers and resistance to change, particularly in sectors like oil and gas construction. (Waqar et al. 2023).

SPATIAL AND URBAN MODELLING

BIM has seen widespread application across various infrastructure sectors such as transportation, energy generation, environmental initiatives, recreational spaces and utility networks (Cheng et al. 2016). One ability of 3D BIM is its ability to assess the damage to infrastructure facilities and support individuals in making better decisions for maintenance and management (McGuire et al. 2016).

In contrast, 4D BIM allows users to identify spatial conflicts in construction projects and make essential alterations before commencing the project (Tran et al. 2021). One argument made by Marzouk and Othman (2020) is that there are not enough studies on how BIM can be used in smart city development and connected to GIS. The integration of BIM and GIS has been particularly effective in infrastructure management, such as drainage systems (Ahmad et al. 2024). There have been limited research efforts on integrating BIM and GIS for urban development, and none of them have discussed the use of BIM for smart city development or large-scale horizontal growth. For instance, the integration of 4D BIM with GIS has been shown to improve coordination and communication among project stakeholders in urban cities. This has led to reduced delays through the integration of 4D BIM with GIS for smart utility relocation management (Vilventhan et al. 2021).

DIGITAL TWIN REALITY CAPTURE PLANNING

The introduction of the digital twin paradigm has led to impressive developments in the construction field, building on the groundwork laid by 4D BIM and location-based scheduling (Sacks et al. 2020; Teizer et al. 2022). Digital twins are virtual replicas of physical systems or environments that are continuously updated with real-time data, often sourced from Internet of Things (IoT) sensors and digital signal processing technologies. It is proving to be particularly valuable for applications like structural health monitoring and indoor environment quality evaluation (Hu & Assaad, 2024; Hu et al. 2024). Using the sensor data, the scan-to-BIM method is important in developing an accurate digital rendering of the building (Banfi et al. 2022). After that, a 4D BIM model with temporal data and sensor inputs was made using the digital twin, which provided valuable insights into the structural behaviour of the building as time progressed. Moreover, location-based digital twins are becoming increasingly important in overcoming interoperability issues (Ellul et al. 2024). However, the integration of digital twin and 4D BIM encounters challenges, such as data integrity, bidirectional interoperability and security. To fully exploit the possibilities of digital twin applications in building and city management, overcoming these obstacles requires continuous research and development.

CONCLUSION

This study employed a scientometric analysis to investigate both the past and current global 4D BIM research, as well as the potential emerging trends in the field. The total number of bibliographic records retrieved from the Web of Science (WOS) core collection database was 558. Through co-author, co-word, co-citation and cluster analyses, the study provided a comprehensive overview of the field's evolution.

Mani Golparvar-Fard, Timo Hartmann and Vijay Kumar Bansal were identified as the primary contributors and influencers in the field. The USA, China and England were the main sources of 4D BIM-related journal articles geographically. Additionally, Chung Ang University, Gyeongsang National University and the National Institute of Technology emerged as the leading institutions in 4D BIM research.

The most frequently used keywords such as "building information modelling (bim)", "4d bim", and "management" were identified, while "point clouds", "virtual reality" and "technology" experienced citation bursts more recently. In the document co-citation analysis, Koo and Fischer (2000), Golparvar-Fard et al. (2015) and Turkan et al. (2012) were widely cited, with Mani Golparvar-Fard contributing to three highly influential publications in the 4D BIM field among the ten most cited articles. Additionally, nine co-citation clusters and nine keyword clusters were merged. Five key research themes were identified which are technology integration, construction management, safety and risk management, spatial and urban modelling, and digital twin reality capture planning. These themes represent the key focus areas and emerging trends for the future of construction digitalisation.

Despite its contributions, this study has several limitations. First, the Web of Science database forms the basis of this research. Although this provides valuable insights, it may not fully reflect the global 4D BIM research landscape. Future research could consider other databases such as ScienceDirect and Scopus to provide a more comprehensive analysis. The study focuses on 4D BIM journal publications in the construction industry but does not analyse case studies, which could limit its usefulness to practitioners. Future research could address this gap by implementing case studies and industry insights. Furthermore, the integration of Internet of Things (IoT) and Artificial Intelligence (AI) technologies into 4D BIM for predictive analytics and smart construction management might be an important avenue for future studies.

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DECLARATION OF COMPETING INTEREST

None.

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