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Study on digital twin technologies for Watershed Information Modeling (WIM): A Systematic Literature Review and Bibliometric Analysis

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Abstract

Digital Twin (DT) concept has recently emerged in civil engineering; however, there are fewer applications in water conservancy and hydropower engineering, especially for smart integrated management at the watershed scale. Therefore, this study aims to gather relevant literature on the digital twin in the infrastructure domain and to review and analyse the key technologies and the current state of their integrated application from a pathway to implementation perspective. The review conducted a Systematic Literature Review (SLR) and Bibliometric-qualitative Analysis (BQA) to identify a developing base of digital twins for smart watersheds. The related research gaps were identified from the analysis regarding information integration, alignment of BIM+ processes to constructor business processes & the effective governance and value of information. From this, a novel Watershed Information Modelling (WIM) research strategy utilizing a framework for BIM+ and information governance coupled with knowledge-driven decision-making is outlined to further progress the smart watersheds.

Keywords: Building information modelling (BIM); Digital twin; BIM for hydraulic engineering; Watershed Information Modeling (WIM)

1. Introduction

Digital twin (DT) is a virtual replica of a physical entity that possesses the ability to think (derive conclusions), sense (in real-time), and act (provide optimization suggestions) [1]. It is created by integrating physical feedback data with artificial intelligence, machine learning, and software analysis within an information technology platform [2]. While it shares some similarities with building information modelling (BIM), which models a building's design and construction, a digital twin models how people interact with built environments. The digital twin relies on a series of integrations with IoT, AI, machine learning, and software analytics [3]. Although BIM and digital twin are commonly used in the building sector, they are not as frequently utilized in hydraulic engineering. To explore this issue, we conducted a preliminary survey by searching the Web of

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Science database for papers on BIM/digital twin and their use in buildings, bridges, underground engineering, tunnels, roads, railways, hydraulic engineering, and dams. The results are shown in Fig. 1. As expected, BIM and DT are most commonly used in the building sector, with 8,565 and 1,603 papers, respectively. However, their application in hydraulic engineering and dams is significantly less frequent, with fewer than 50 reports available.

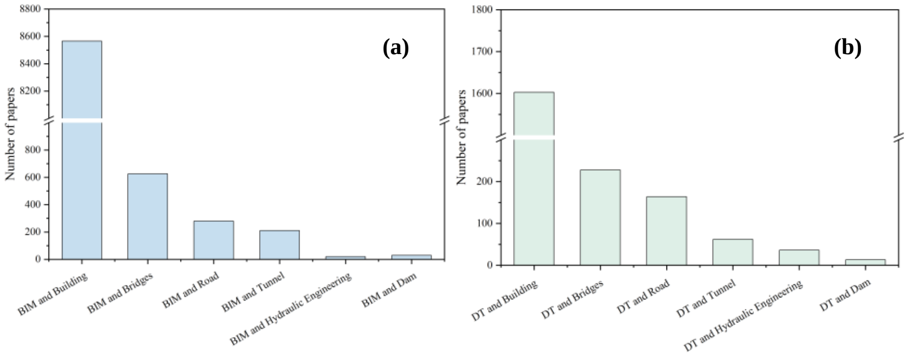


Fig. 1. Number of published papers on BIM and digital twin in different areas of infrastructure.

According to the most comprehensive database in Nature-Scientific Data, the number of dams worldwide currently exceeds 38,000 [4]. Fig. 2 illustrates that these dams are located on various rivers and, together with water and human activities, contribute to the creation of multifunctional watersheds. These watersheds serve critical functions such as flood control, power generation, water supply, and navigation. Therefore, the efficient and scientific management of these dams is crucial for ensuring the safety and effectiveness of the watersheds.

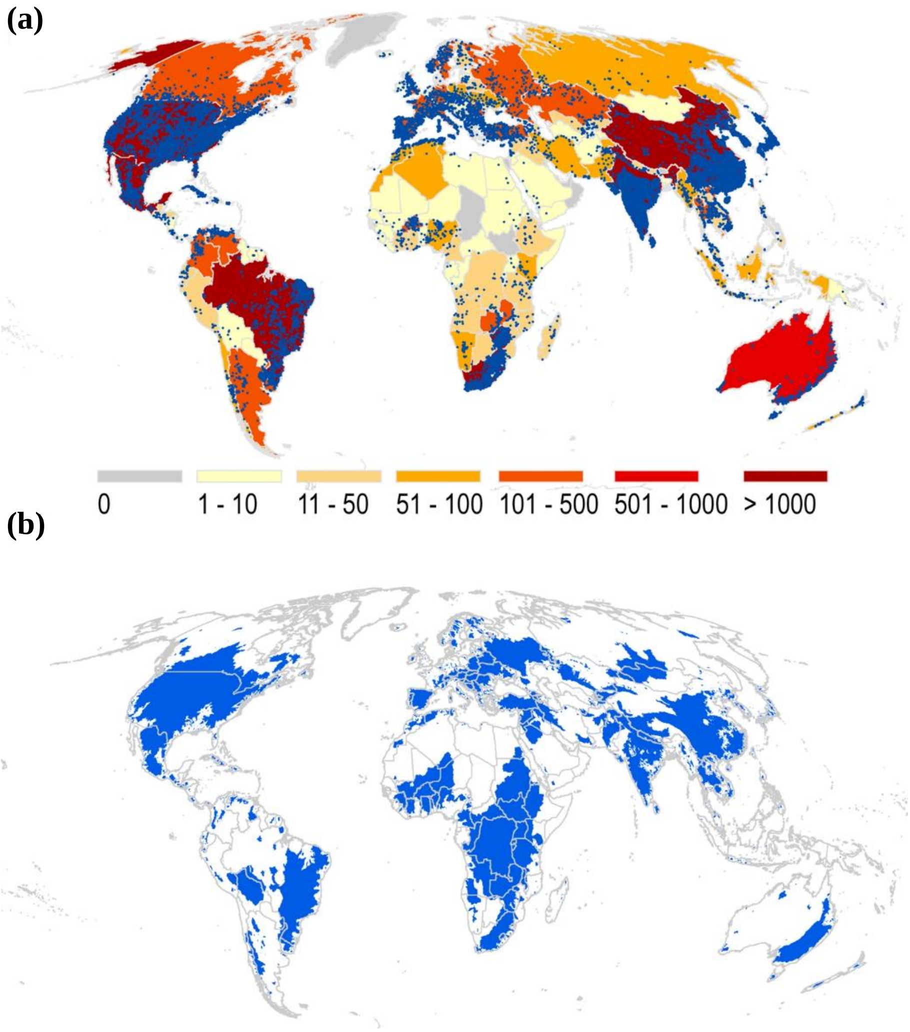


Fig. 2. Dams and catchments in GOODD database. (a) Shows the number of dams in each country (yellow to red colours) and individual dam locations (blue dots) and (b) shows the area of terrestrial land draining into a dam in blue. [4]

In light of the rapid development of network information technology, IBM took the initiative in 2008 to propose the concept of 'Smart Earth', which initiated a global trend in 'smart' construction. To address watershed management challenges in the face of climate change and increased human activities, the Smart Earth concept gave rise to the proposal of 'smart watersheds'. Unlike the digital watershed perspective, smart watersheds place greater emphasis on human interaction with the physical watershed, enabling easy communication between people and water, water and water, and people in the physical world of the watershed. This approach is more akin to the concept of smart cities [5]. City Information Modeling (CIM) technology represents an innovative approach to realizing smart cities by projecting IoT technologies derived from cloud computing, big data, and communication technologies throughout the city. It describes the physical targets above and below ground, indoors and outdoors in a city, and their time-space states, providing a digital representation of the physical and functional characteristics of a city-level group of buildings [6,7]. The success of CIM provides valuable insights for achieving smart watersheds.

In view of the potential benefits of digital twins for smart watersheds, this study aims to provide a review of the path to digital twin implementation in the infrastructure sector to inform research on the application of BIM and digital twins in hydraulic engineering. In order to achieve the above target, this review collects more than 861 key publications in the relevant area and analyses the trends for BIM+ development for infrastructure according to publication time analysis, author analysis, keyword analysis and cluster analysis. And then, analyses the characteristics of BIM, GIS, 3D scanning, 5G and satellite remote sensing and the current status of their integrated application. Finally, based on the evolution from BIM to BIM+ to CIM, we propose a novel framework to realize smart watersheds—the Watershed Information Modelling(WIM).

2. Review Methodology

2.1 Systematic literature review

This study employs a systematic literature review (SLR) approach. The SLR method is an explicit way of conducting a literature review that aims to produce reliable findings with clear research questions, a comprehensive search strategy, well-defined literature inclusion criteria, and comprehensive data analysis. The SLR approach can help reduce research bias introduced by traditional literature review methods [8]. Jill Jesson et al [9] established a precedent for conducting an SLR, proposing six key phases: mapping the field through a scoping review, conducting a comprehensive search, assessing the quality of the included literature, extracting data, synthesizing the data, and writing up the findings. The specific process is illustrated in Fig.3.

Phase 1: Mapping the field through a scoping review.

In this phase, we need to prepare the review plan. This includes defining the research questions, compiling keywords, setting up inclusion and exclusion criteria, and designing the data extraction pro-forma or datasheet.

Phase 2: Comprehensive search.

This phase involves accessing electronic databases and searching using the keywords identified in Phase 1. The search results are documented and checked for relevance. The titles, abstracts, and full papers are screened to determine whether they meet the inclusion criteria.

Phase 3: Quality assessment.

Reading the full papers and applying a quality assessment, using the hierarchy of research. Papers that meet the inclusion criteria are included in the review, while those that do not are excluded.

Phase 4: Data extraction.

Recording relevant data onto the pre-designed extraction sheet.

Phase 5: Synthesis.

Synthesizing the data from each article into one and analyzing the data using bibliometric approaches.

Phase 6: Write up.

Writing a balanced, impartial, and comprehensive report, using a systematic review format, to present the findings of the review.

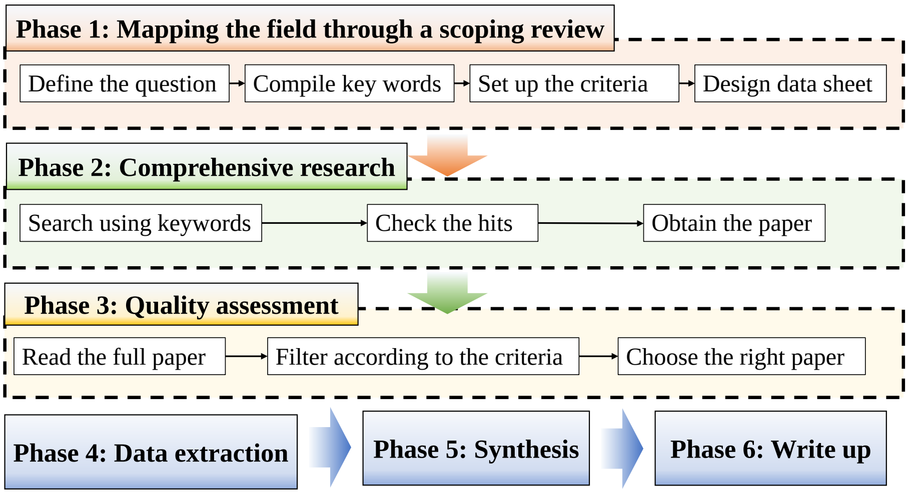


Fig. 3. Flow chart of a systematic literature review.

2.2 Prepare a review plan

2.2.1 Formulating the review questions

The review question is critical to the systematic review. We first propose the mapping review question, and then propose the sub-questions. As Table 1:

Table 1 List of research questions.

Type	No.	Questions
A mapping review question	Q_m	How to realize the digital twin of large-scale hydraulic engineering and watershed?
Sub-questions	Q_1	What technologies can be used to support digital twins?
	Q_2	What are the characteristics of these technologies?
	Q_3	How to integrate these technologies?
	Q_4	What are the forecast and needs for the future trend?

2.2.2 Compiling keywords

Based on the research questions proposed in section 2.2.1, this study aims to investigate the methods for realizing digital twins (DT) in large-scale hydraulic engineering and watersheds. Previous studies in the Architecture, Engineering, and Construction (AEC) industry have identified Building Information Modeling (BIM) as a core technology for DT development[10]. However, the complexity of the environment in which DTs are implemented makes it challenging to rely solely on BIM for their realization. The emergence of new technologies, such as Geographic Information Systems (GIS), the Internet of Things (IoT), 3D scanning, 5G networks, and satellites, resulting from the development of Industry 4.0 and Civil Engineering 4.0, presents additional opportunities for DT realization. In this study, the focused technologies for addressing research question 1 in section 2.2.1 include BIM, GIS, IoT, 3D scanning, 5G networks, and satellites. However, the integration of these technologies into a unified application framework for construction projects has not yet been achieved. Therefore, the study will focus on research question 3 in section 2.2.1, taking BIM as the core technology and exploring the integrated application of BIM with the other new technologies mentioned above. Based on the above analysis, the keywords and search strategy for this study will comprise ‘BIM’ and a combination of new technologies, including GIS, IoT, 3D scanning, 5G networks, and satellites, expressed as “BIM and (GIS or Internet of things or 3D scanning or 5G network or satellite)”.

2.3 Comprehensive search

The comprehensive search phase includes database selection, research time range selection, and types of literature selection. To determine authoritative core intelligence in the focused field of this article, the Web of Science Core Collection, which is the world's largest comprehensive academic information resource covering the most significant number of disciplines, has been selected as a search database. Before beginning the search process, the starting year of the literature range must be specified. Before 2007, the Web of Science database lacked any relevant publications. As a result, while conducting a keyword search in this section, the database's advanced search tool should be used, and the literature search should begin and conclude on 1 January 2010 and 31 December 2022, respectively. Academic publications are classified into the following categories: Brief Report, Case Report, Comment, Commentary, Communication, Concept Paper, Conference Report, Data Descriptor, Editorial, Entry, Expression of Concern, Guidelines, Hypothesis, Opinion, Perspective, Proceedings Paper, Project Report, Protocol, Reply, Short Note, Thesis, Tutorial and Viewpoint. Since the integration of BIM and other new technologies was researched only around 10 years ago, it has received little attention in academic journals of various types. Related keywords appear in the following publications: Article, Review, Conference Report, Proceedings Paper and Thesis. As a result, the five categories of the search were discovered in this study.

2.4 Quality assessment

Using the database's advanced search tool, a total of 1269 preliminary search results (Total Number of Retrieved Documents) were obtained that satisfied the search criteria. The initial search may turn up material that is irrelevant to the research topic. To guarantee that the sample literature is highly relevant to the research issue, it should be checked against the inclusion criteria. The screening criteria developed are shown in Table 2, and suitable papers are selected based on the criteria developed by manual screening. The procedure for selecting research literature consisted of two parts. First, the researcher does an initial screening of the retrieved material by reading the title and abstract parts. This is followed by a secondary screening phase known as the coding phase, during which the researcher examines the whole text of the literature and does an in-depth re-screening using the criteria. The selection process is shown in Fig. 4, and 861 papers were finally identified to complete this review of selected papers.

Table 2 Quality assessment criteria.

No.	Inclusion criteria	Exclusion
1	Full article accessed.	Not the full article accessed.
2	Length of paper at least 2 pages.	<2 pages.
3	The topic is related to the integration of BIM and other new technologies specified in this article.	The topic is not related to the integration of BIM and other new technologies specified in this article.
4	The publication has been peer reviewed.	The publication has not been peer-reviewed.
5	Content with a clear research title, abstract and keywords.	Content doesn't have a clear research title, abstract and keywords.

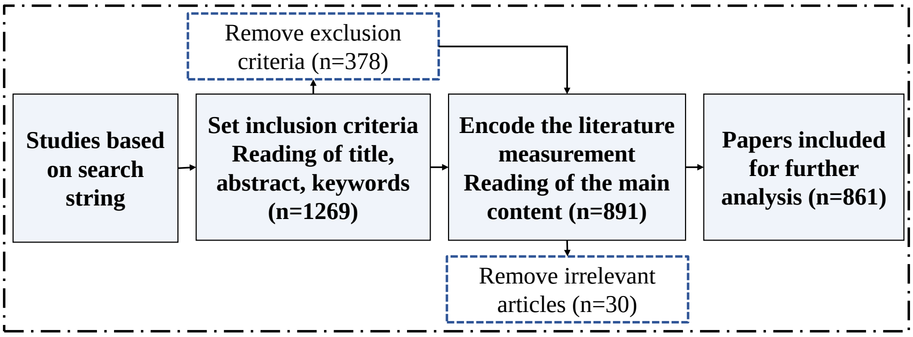


Fig. 4. Paper selection process.

2.5 Reporting

In the reporting stage, include Data extraction, Synthesis and write-up. In this stage, bibliometric analysis is used. Because this study aims to provide an outlook on the future applications of BIM and other technologies integration, it is necessary to make a co-citation analysis of the existing literature to explain, cluster, and anticipate the research field. This is the main function of CiteSpace. The location of clusters and their correlation in a co-citation network view can show the intellectual structure of the science mapping field [11]. After realizing the co-citation cluster mapping, the timeline view of the co-citation network can be obtained using the cluster number as the y-axis and the year of citation publication as the x-axis.

3. Bibliometric analysis of recent studies

3.1 Time series analysis

The articles published in the Web of Science (WOS) core dataset collection from 2007 to 2022 are presented in Fig. 5 in chronological order; there have been 861 papers published in the mentioned period. Since 2013, the number of published articles has increased significantly, indicating an increased interest in this field of research in the past few years. The growth rate of the article number in the WOS core dataset in 2021 has dropped significantly compared with the previous years, indicating a lack of significant breakthroughs in this research area. Thus, the existing research on the BIM and other new technologies integration has achieved preliminary functional and data integration. Still, the integration application area has not yet been completely researched. It can be seen from Fig. 5 that the research of BIM and GIS integration and BIM and 3D scanning integration began earlier. Starting from 2007 and 2008 respectively, the research on BIM and Satellite integration, BIM and Internet of things integration, and BIM and 5G integration started relatively late, starting in 2013, 2014 and 2018. According to the Fig. 5, the research on BIM and GIS integration, BIM and Internet of things integration, and BIM and 3D Scanning integration, accounted for 39%, 25% and 33% respectively, while the research on BIM and 5G integration and BIM and Satellite integration accounted for 1% and 2%. It can be seen that the current research is mainly focused on the integration of BIM and GIS, the Internet of things, and 3D Scanning applications, corresponding to the integration of BIM and 5G, Satellite research is relatively small.

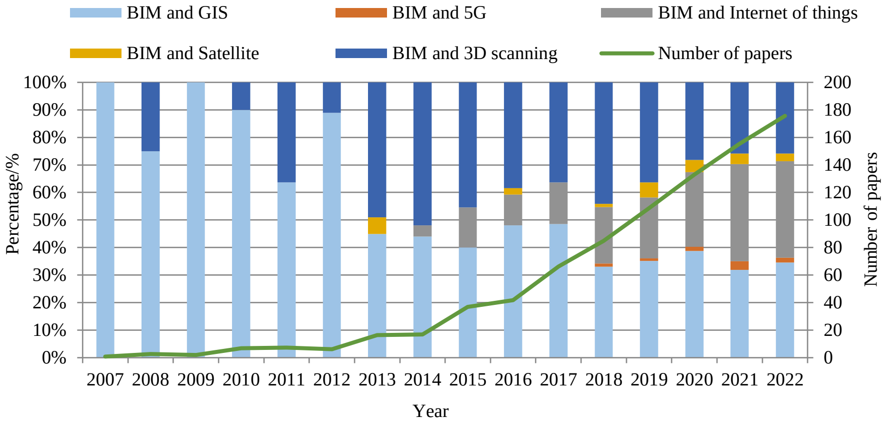


Fig. 5. The number and percentage of published papers in the WOS literature.

3.2 Author analysis

Typically, a small handful of experts set the direction of a research field [12]. Moreover, the most recent research trends can be gleaned by analysing the research patterns of prolific authors. Between 2007 and 2022, the number of authors with >5 publications in BIM and new technologies integration-related research is 19, suggesting that BIM and new technologies integration is studied by a small number of experts. Cheng, Jack C P of Hong Kong University of Science and Technology is the most prolific author, having published twenty publications on BIM and new technologies integration and ranking second in terms of total citations. The top 19 authors are all from universities, indicating that universities are the primary and leading researchers in BIM and new technology integration.

According to the analysis of total citations, 11 authors have >1000 citations, with 8 scholars having amassed over 3000 citations. Wang Xiangyu of Curtin University is the most referenced scholar, with 20829 total citations for his study on BIM-based multidisciplinary collaboration platforms (counted as of February 2023). Following that is Anumba, Chimay, a professor at the University of Florida. The majority of Cheng’s writings in this field are co-authored with others, such as Wang, who also has a substantial body of work and citations. As can be observed, various academics join research groups to collaborate on projects; the majority of these scholars are previous supervisors and candidates, and these groups of scholars who have a common direction form a core group of authors. The core group of authors should refer to the collection of authors who have published more papers and have greater influence, as seen in Fig. 6. Price proposed calculating the core group of authors [8]. The calculating equation is as follows:

$$M = 0.749 \times \sqrt{N_{max}}$$

Where M denotes the minimum number of publications by core authors and N_{max} denotes the largest number of publications by the author throughout the statistical year. According to Table 3, the author with the most articles is Cheng, Jack C P, with twenty, indicating that N_{max}=20. The calculation gives M=3.35, indicating that the core group of authors are those with a total number of articles more than or equal to four. The total number of authors with more than or equal to 4 publications is 31. And the total number of publications published by these 31 authors is 188, accounting for 14.81% of the entire data, which, in Price's view, is much less than the required 50% [8]. This demonstrates that BIM and new technologies integration research has not yet developed a stable core group of writers and that the core authors are very few in number. At the same time, the establishment of the core author group is still in its infancy, and author collaboration is rather limited. This is because the study on this topic is still in an early stage of development and change, and there is a dearth of renowned researchers at the forefront.

Table 3 Most productive authors (total number of articles >4).

Author name	Research institution	Country	No. of articles	Total citations	h-index	Proportion
Cheng, Jack C P	Hong Kong University of Science and Technology	China	20	9769	56	14.4%
Wang, Qian	Southeast University	China	14	2070	23	10.1%
Wang, Xiangyu	Curtin University	Australia	9	20829	77	6.5%
Brumana, R	Politecnico di Milano	Italy	8	2414	26	5.8%
Banfi, F	Politecnico di Milano	Italy	8	1540	22	5.8%
Moyano, Juan	Universidad de Sevilla	Spain	7	727	15	5.0%
Zhu, Junxiang	Curtin University	Australia	7	659	12	5.0%
Cho, Yong K	Georgia Institute of Technology	United States	6	4273	35	4.3%
Chen, Keyu	The Hong Kong University of Science and Technology	China	6	608	10	4.3%
Chen, Jingdao	Mississippi State University	United States	6	941	16	4.3%
Lu, Weisheng	University of Hong Kong	China	6	9595	57	4.3%
Bosche, Frederic	University of Edinburgh	United Kingdom	6	3693	28	4.3%
Haas, Carl	University of Waterloo	Canada	6	9958	55	4.3%
Ellul, C	University College London	United Kingdom	5	1390	19	3.6%
Akinci, Burcu	Carnegie Mellon University	United States	5	8240	43	3.6%
Guo, Jingjing	Hunan University	China	5	270	7	3.6%
Anumba, Chimay	University of Florida	United States	5	11068	57	3.6%
Banfi, Fabrizio	Politecnico di Milano	Italy	5	1540	22	3.6%
Leite, Fernanda	University of Texas at Austin	United States	5	2172	27	3.6%

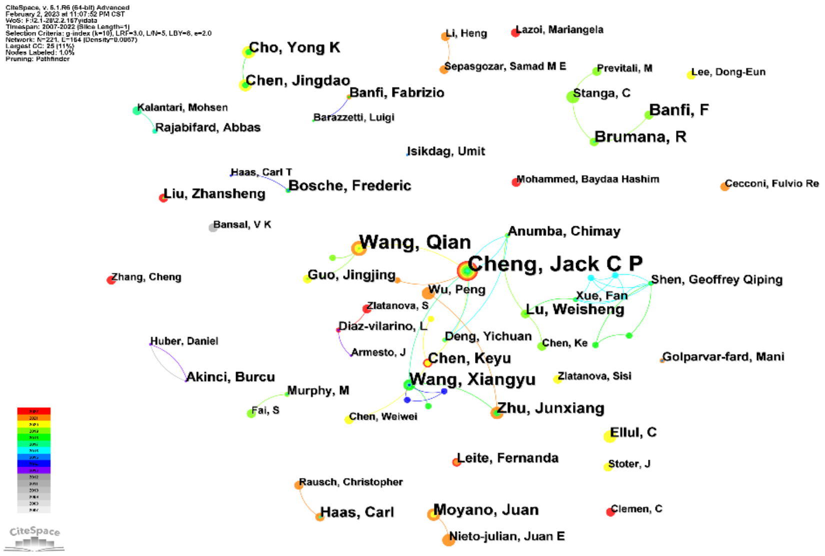


Fig. 6. Core group of authors and Co-citation relationships.

3.3 Keyword analysis

The keywords in a literature review serve as the article's core, serving as a high-level overview of the article's subject, and keywords with a high frequency are often used to identify popular concerns in a research field. CiteSpace software is used to create a visual analysis of keywords in Fig.7. It is a graph illustrating the co-occurrence of BIM and new technologies integration research terms from 2007 to 2022. There were a total of 212 keywords found. Each node represents a keyword, and the size of the node denotes the frequency at which the keywords appear. To aid in visualization, the keywords in the graph are denoted by varied font sizes and highlighted backgrounds. The greater the magnitude of the keyword, the more frequently it appears. The size of the text indicates the keyword's centrality, which is used to determine the direction of popularity in a given research topic. As illustrated in Fig. 7, the keywords with the largest nodes are bim, system, point cloud, management, internet of things, gis, laser scanning, and digital twin, which are also essential phrases in the direction of the study. Furthermore, the connecting lines between the keywords denote their relationship, and the thickness of the connecting lines denotes the frequency with which the keywords occur together.

To visualise the frequency of terms, we statistically analysed all keywords in this research field, as shown in Table 4. The top 10 rated keywords contain all of the research area's fundamental concepts and their associated meanings. Three categories can be applied to the top 10 co-occurring terms. One area is devoted to the description of the BIM and new technologies integration research. For example, BIM and 3D Laser scanning, BIM and Internet of things, and BIM and GIS, which reflects current technological developments. One is about data processing, For example, Big Data, Machine learning, Artificial Intelligence, Deep Learning, and Data Integration, which propose the method of data processing. The other is the Digital twin system, for example, Smart City, Smart Building, Digital Construction, 3D City Model, and Industry 4.0, which reflects the integrated application of technology and data. Therefore, it is important to integrate the results of the preceding research with a subsequent examination of the keywords' features.

Table 4 List of frequency and extracted keywords.

Frequency	Keywords

532	Building Information Modelling (BIM)
301	3D Point Cloud Modelling, 3D Laser Scanning, 3D Reconstruction, Cloud Data Computing
248	Internet of Things (IoT)
247	Geographic Information System (GIS)
167	Management, Facility Management, Construction Management
155	Digital Twin, Smart City, Smart Building, Digital Construction, Digital technology, Smart Underground Construction, Industry 4.0, 3D City Model, Construction Industry
68	Big Data, Machine learning, Artificial Intelligence, Deep Learning
66	Integration, Data Integration
24	Visualization
17	Infrastructure

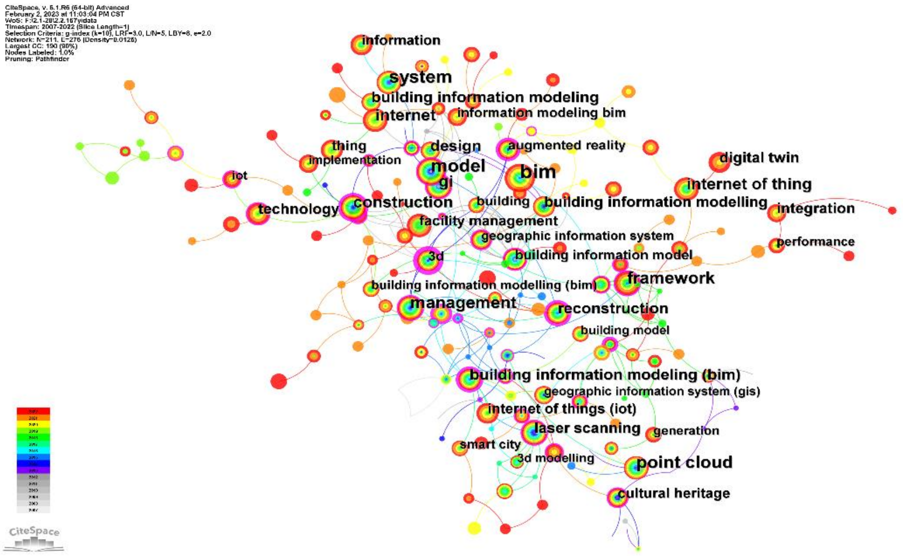


Fig. 7. Topical keywords for each year.

3.4 Cluster analysis

Cluster analysis compares data or information with comparable qualities. CiteSpace enables the visualisation of clustering data in a precise manner rather than through the use of a common prominent grouping network. It emphasises the cluster properties by generating cluster labels that are numbered according to the cluster size. The graph area might also show the cluster density. In the CiteSpace analysis report, 212 keywords were categorised into 8 categories, with circles emphasising each cluster. The diameter of the circle shows the frequency of the terms in the cluster, with a larger circle representing a higher frequency. The greater the range, the more instances of the relevant keywords there are, as illustrated in Fig. 8.

By analysing the keyword density, it is determined that modularity Q=0.7942, weighted mean silhouette = 0.9151 and harmonic mean (Q, S)=0.8503. It is commonly accepted that a clustering module value of Q>0.3 indicates that the clustering structure is important and S>0.5 indicates that the clustering structure is within a tolerable range. It can be concluded that the keyword network clustering structure of the BIM and new technologies integration research is meaningful, and the clustering results are satisfactory. The connections between the terms are logical. This could be because BIM and new technologies integration research is more closely related to computer science and incorporates several established technologies into traditional BIM research, including GIS, computer vision, laser scanning and virtual reality.

The iterations of the keywords can be presented in the form of a time zone diagram by further processing the data from the clusters. As illustrated in Fig. 9 individual keywords and clustering data are shown chronologically, with connecting lines demonstrating their evolution and relationships with other terms. The time zone mapping not only illustrates the distribution of research popularity but also how it has changed over time. Iterations during the last decades have also coincided with the proliferation of popular technology. The left side (2007) is denser and more focused, whereas the right side (2022) is more diffuse and enormous, which corresponds to the emergence and progression of a developing interdisciplinary technological research path.

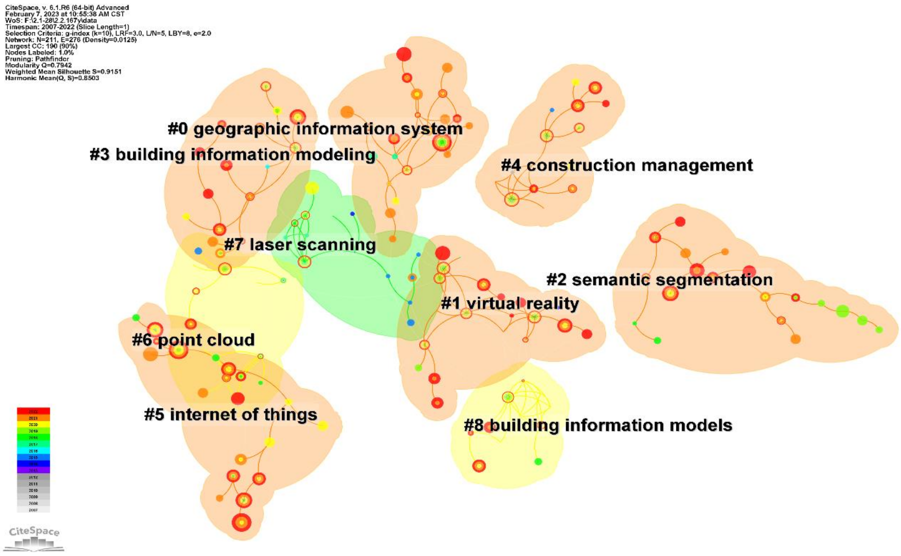


Fig. 8. Keywords cluster analysis visualization.

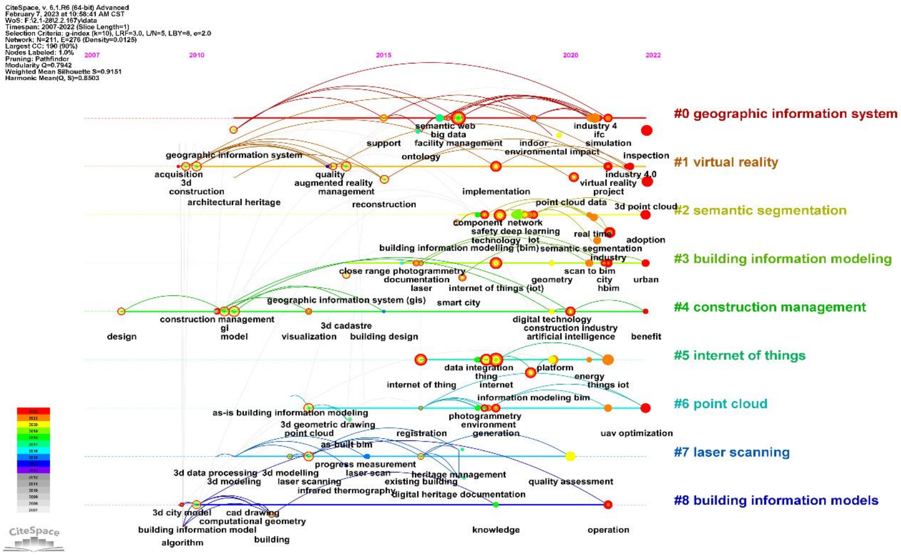


Fig. 9. Iteration of keywords by time zone.

4. Technologies that support the digital twin

4.1 Building information modelling (BIM)

Building information modelling (BIM) was first proposed by Easterman in 1974, under the name Building Description System [13]. BIM is now defined as the provision of rich, integrated information throughout the entire lifecycle of a building, from concept to design and construction [13]. It is considered the second revolution in the construction industry, following the introduction of computer-aided design (CAD) technology [14]. In the last decade, computer-aided design technologies in the AEC industry have advanced from 2D to 3D modelling [15]. The core of BIM is the creation of a virtual 3D model of a building project, which incorporates visualization, coordination, simulation, optimization, and drawing characteristics. This model is created using digital technology and contains a comprehensive and realistic information base for the building project, including not only geometric information and professional attributes describing the building components, but also state information for non-component objects (such as space and movement behaviour). By using this 3D model with building engineering information, the degree of information integration of building engineering is greatly improved, providing a platform for relevant stakeholders in building engineering projects to exchange and share engineering information [16]. What is common among these definitions is that the BIM concept is made up of four key elements: collaboration, representation, process, and lifecycle, which all interact to create an innovative and efficient project environment [10]. (Fig. 10)

In the design phase, BIM’s 3D visualization function facilitates quick evaluation and proposal of changes by reviewers and owners, thus improving decision-making efficiency [17]. BIM enables engineers from various disciplines to collaborate on a single model through web-based tools, ensuring design coordination throughout the design process [18]. The BIM model contains diverse data for building performance analysis, which can be entered into relevant analysis software using exchange formats such as IFC and gbXML for energy efficiency analysis, light analysis, daylight analysis, ventilation analysis, and green building assessment of the current project [12,19].

During the construction phase, BIM's visualization feature helps spatially coordinate the design of various disciplines (architecture, structure, water supply and drainage, electromechanics, fire protection, lifts, etc.) to avoid collisions between pipes of different disciplines and between pipes and structures [20]. Detailed digital information is necessary for digital construction, and BIM models' component information is stored digitally, providing the building with precise positioning information and necessary conditions for digital construction [21].

In the operation and maintenance phase, BIM can integrate building spatial and equipment information with other data to leverage spatial positioning and data recording advantages, rationalize operation, management, and maintenance plans, and minimize operational emergencies [22]. BIM can be used to establish maintenance work history to monitor the operational status of crucial equipment and achieve process management [23]. Additionally, using rich information in the BIM model, the model can be imported into disaster simulation and analysis software in exchange formats such as IFC to analyze the causes of disasters, and develop disaster prevention measures and emergency plans [24].

However, after two decades of growth, traditional BIM technology faces several issues that require attention. Large-scale construction projects such as transportation infrastructure, energy infrastructure, utility infrastructure, recreational facility infrastructure, or water management infrastructure involve an increasing number of parties, and collaborative activities involving all stakeholders are carried out throughout the project's phases. These projects are highly challenging due to their enormous size, adverse site conditions, and complex designs [25].

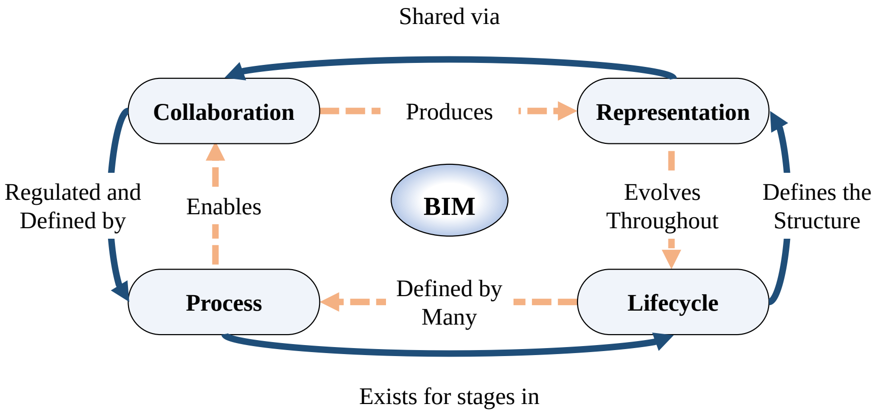


Fig. 10. 4 key elements of the BIM concept.

4.2 Geographic Information System (GIS)

With the rapid advancement of information and communication technologies (ICT), Geographic Information System (GIS) technology is increasingly recognized and accepted by researchers. In particular, the concept of "Digital Earth" has brought GIS technology to the attention of countries around the world. GIS is a computerized database management system designed to acquire, store, retrieve, analyze, and display spatially located data [26]. Research on GIS focuses on five main areas: data acquisition, data processing, data storage and management, spatial analysis, and data visualization [27,28]. GIS data is divided into spatial data and attribute data. Spatial data refers to the entity data of graphics, which is usually obtained using three-dimensional scanners, sensors, laser radar, UAV tilt photography, and other methods. Attribute data is the characteristic data of a spatial entity and is generally obtained using direct input methods.

For data processing, initial data processing mainly includes data formatting, conversion, and generalization [29]. Data formatting refers to the transformation between data of different data structures, which is computationally intensive and should be avoided as far as possible. Data conversion includes data format transformation, change of data scale, etc. The conversion of vector data to raster data is faster and simpler than its inverse. Data scale transformation involves data scale scaling, translation, rotation, and other aspects, of which the most important is the projection transformation [30]. Currently, GIS provides poor data generalization functions, and the requirements of map synthesis still have a big gap, needing further development.

The massive use of geo-referenced data sets in many fields of science, including earth observation [31], environmental sciences [32], city planning [33], and BIM [33], makes data management increasingly a central task in the workflow of GIS data processing [34]. Raster models, vector models, or hybrid raster/vector models have commonly used methods of spatial data management [35]. The choice of spatial data structure determines to some extent the functions of data and analysis that the system can perform. The most critical aspect of geographic data management is how to integrate spatial data and attribute data into one. The common method currently used is to store the two separately, linked by common items (generally defined as feature identification codes) [34]. The disadvantage of this approach is that the definition of data is separated from data manipulation, and the changing attributes of objects in the time domain cannot be effectively recorded.

GIS is extensively used in the infrastructure sector. For example, urban planning involves dealing with many different issues, involving a large amount of data on resources, environment, population, transportation, economy, education, culture, finance, etc [36]. The database management function of GIS facilitates the unified analysis of these data, and finally, the development and planning of the city with multiple objectives [37]. Regarding hydraulic engineering with certain geospatial attributes, the application of GIS is even more extensive. GIS data can be used to build a geographic information platform for hydraulic and hydropower engineering projects to visually display the project environment and help with reservoir site selection, project layout, and project measurement [38]. A GIS-based flood analysis system can be established to assess flood hazards [39], while GIS can be used for effective monitoring of water pollution [40]. In recent years, with the continuous enrichment of data collection methods, the volume of data has exploded, while GIS processing has evolved from single mapping data to spatial big data. A large proportion of big data is likely to be geo-referenced and may be real-time, which is known as geographic big data or spatial big data [41]. This places higher demands on the development of data analysis models and computing power [42].

4.3 3D scanning

3D scanning is an emerging technology that integrates optical, mechanical, electrical, and computer technology. Its primary application is to scan the spatial shape, structure, and colours of objects to obtain the spatial coordinates of their surfaces [43]. This technology is gaining popularity due to its fast and accurate measurements, non-contact approach, and ease of use. Using a 3D scanner to scan a model enables the direct interface of its three-dimensional data with CAD/CAM software. The data can then be adjusted and repaired in the CAD system, significantly improving industrial efficiency [44]. There are various types of 3D scanning process areas, including structured light 3D scanning, LASER triangulation 3D scanning, photogrammetry, and coordinate measuring machines (CMM) (contact-based 3D scanning) [45].

In the infrastructure sector, 3D scanning has applications throughout the life cycle of a building. During the design phase, 3D scanning can provide a 1:1 colour 3D point cloud model of the construction site, including topography, traffic routes, and surrounding buildings, providing an accurate basis for design [46]. During the construction phase, key parts of the building can be scanned using a 3D scanner, providing an accurate database for acceptance at a later stage of the project [47]. During the operation and maintenance phase, 3D laser scanning technology can be used to monitor deformation due to its high accuracy. For example, it can be used for dams, bridges, tunnels, and surface deformation monitoring [48]. Georgios Tzortzinis et al. [49] used three-dimensional (3D) laser scanning to evaluate deteriorated steel bridge girders due to corrosion. Popescu, Cosmin et al. [50] compared the performance of three different imaging technologies for the three-dimensional (3D) geometric modelling of existing structures: terrestrial laser scanning, close-range photogrammetry, and infrared scanning. The results suggest that all investigated methods can be used to create 3D models of bridges.

4.4 Internet of Things (IoT)

The Internet of Things (IoT) is a rapidly evolving information and communication technology that enables the rapid connection, transmission, and exchange of data between various devices through embedded sensors and wireless network technology. The use of embedded sensors and wireless networking technologies enables the quick connection and transmission of data between various devices [51]. The basic features of IoT can be summarized as holistic sensing, reliable transmission, and intelligent processing [52]:

- Holistic sensing: Sensing devices such as radio frequency identification, QR codes, and smart sensors can be used to sense and obtain various types of information about objects.
- Reliable transmission: Through the integration of the internet and wireless networks, information about objects can be transmitted in real time and accurately, enabling the exchange and sharing of information.
- Intelligent processing: Various intelligent technologies can be used to analyze and process the sensed and transmitted data and information to achieve intelligent monitoring and control.

In the construction of dams, railways, and other infrastructure projects, a lot of rolling work often needs to be carried out, and IoT access can be used to automate rolling by controlling the sensors in the rolling equipment [53]. The continuous real-time data stream from IoT sensors, combined with historical data from other projects, can be used not only to monitor the current job site but also to provide a growing data set that can be used with machine learning for predictive analysis, making construction smarter [54]. IoT is also used for structural health monitoring to detect vibrations, cracks, and other safety conditions of critical building elements and structures during and after construction [55].

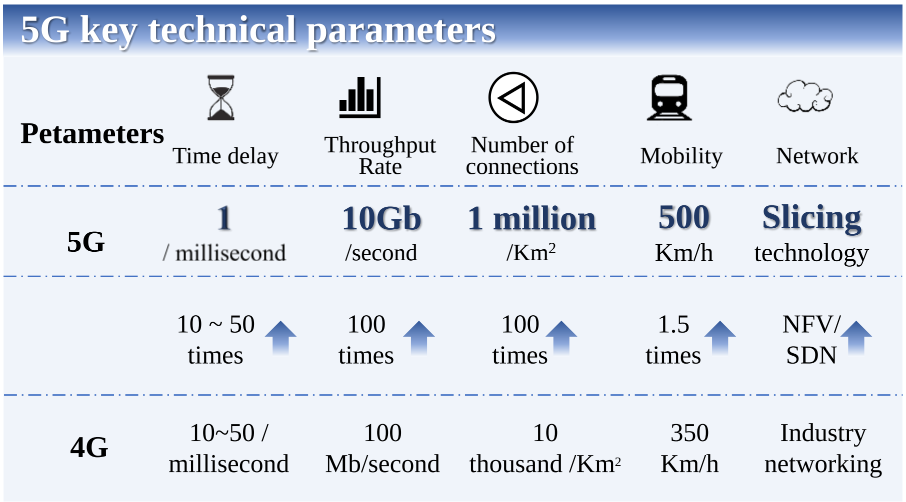
IoT-based location detection and recognition of facility items have great potential for increasing maintenance management efficiency [56,57]. Similarly, Dong and Lam [58] highlighted that IoT could help accurately detect building occupancy, leading to better decisions for building services delivery and energy control. However, the current wireless networks pose a great challenge in tapping into the benefits of IoT devices. With the number of IoT devices set to increase manifold shortly, current wireless networks may not be able to securely connect a vast number of IoT devices [59].

4.5 Fifth generation(5G) wireless networks

5G is the fifth generation of mobile networks, designed to connect everyone and everything, including machines, objects, and devices. As shown in Fig. 11, 5G aims to provide high-bandwidth data (multi Gbps speed), ultra-low latency, better reliability, high cybersecurity, and connection to a high number of devices per square kilometre, with a focus on providing a superior user experience. A comparison of the theoretical benefits of 5G and Wi-Fi/4G is shown in Table 5 [59]. With 5G, new functionalities can be developed to detect environmental changes in real time, which can aid in disaster recovery efforts. By supporting enhanced automation and digitization, from manufacturing to buildings to transportation to agriculture, 5G promises to reduce energy, resource, and material consumption [59].

Due to the significant advantages of 5G communication technology, there is no need for complex bridging and cabling works in the construction of network structures in intelligent buildings, making installation convenient and flexible, and easy to expand and transform. The application of 5G networks in intelligent buildings to integrate distributed subsystems and manage them on a unified platform is a cost-effective system integration solution [60]. In the field of communications, remotely controlled and autonomous machinery are considered mission-critical applications. Fast communication between the machinery and the decision-making entity is vital, as fatal accidents may occur if communication fails or if there are delays in the reception of data. The use of 5G technology for connectivity and its high-speed transmission can effectively prevent such accidents from occurring [61].

Moreover, construction is a very dynamic environment in which, if automation is to be achieved, communication needs to be provided for moving elements such as workers or machinery. Wired communication is not feasible in this scenario because it cannot adapt to changes quickly and does not support user mobility [62]. Therefore, wireless communication is essential in this environment.



5G key technical parameters

Petameters	Time delay	Throughput Rate	Number of connections	Mobility	Network
5G	**1** / millisecond	**10Gb** /second	**1 million** /Km^2	**500** Km/h	**Slicing** technology
	10 ~ 50 times ↑	100 times ↑	100 times ↑	1.5 times ↑	NFV/ SDN ↑
4G	10~50 / millisecond	100 Mb/second	10 thousand /Km^2	350 Km/h	Industry networking

Fig. 11. Key technical parameters of 5G.

Table 5. Theoretical benefits of 5G which overcome the general limitations of Wi-Fi/4G [59].

No.	Wi-Fi/4G(General Limitations)	5G (Theoretical Benefits)
1	Longer wait due to latency, lag, and the application getting stuck at regular intervals.	Low latency, high network speed, no lag.
2	Interference on Wi-Fi/4G connection.	No interference in the 5G connection.
3	Connectivity issues (varied connection strength, intermittent disconnection).	Steady, consistent, and high-speed connection strength.
4	No end-to-end control.	Can be customized specifically to AR/VR end-to-end needs.
5	Less scalable to high device requirements.	Scalable to high device requirements.
6	Unavailability of a consistent high-speed network for remote learning. Fixed to space.	Network speed can be available for all locations with consistency. Does not have to be confined to a pre-determined space.
7	Inconsistent speed leads to high-end PC requirements in VR for local rendering.	High speed enables the use of the all-in-one wireless device (lightweight with mobility) and replaces the PC with a cloud server.

8	No efficient method for locating and resolving Wi-Fi performance issues.	Can be customized for the VR experience.
9	Signal interference, signal attenuation, and mutual influence of services.	No issues with the 5G connection.

4.6 Satellite Remote Sensing

Satellite remote sensing involves using satellites as a platform for remote sensing technology. It provides a high viewpoint, wide field of view, fast data collection, and repeated continuous observation, among other benefits [63]. The results obtained are digital and can be directly entered into a computer image processing system. With ongoing advancements in satellite remote sensing manufacturing and chip process technologies, the resolution of remote sensing satellite data is improving in spatial, spectral, and time dimensions [64]. Furthermore, intelligent processing technologies and computing power for datasets are rapidly evolving, marking the arrival of a new era of remotely sensed big data [65].

In the past decade, the main objective of China, the United States, and the European Union has been to develop a next-generation intelligent remote-sensing satellite system. The development of remote sensing satellites with intelligent components, such as the TacSat-3 (USA, 2009), TET-1 (Germany, 2012), new technology demonstration satellite (China, 2020), and a high-resolution multimode satellite (China, 2020), has been established [66]. With the enhancement of onboard computation, data storage, and other resources, the on-orbit data computation of a single satellite is no longer restricted to simple processes of data compression or preprocessing. Consequently, the processing chain is expanding to provide continuous client applications, including on-orbit target detection and identification. The intelligence level of remote sensing satellites, with one satellite for multiple applications and multi-satellite mission integration, is continuously improving. In addition, new remote sensing information accuracy and time efficiency requirements are being presented by countries, industries, personalized clients, and other users.

Satellite remote sensing is valuable in the field of urban construction. It can be targeted to obtain information on the current situation and changes related to urban buildings, roads, parks, green areas, etc. [67]. Based on the distribution of the current situation of urban construction, can provide suggestions for urban construction planning [68]. Furthermore, radar satellites can be used to obtain information on buildings and surface deformation in the city without interruption, allowing for quick identification of hidden danger locations and providing guidance for on-site inspection to maintain the safe operation of the city [69]. In large-scale hydraulic engineering, satellite remote-sensing technology is more widely used. It can provide a rapid assessment of an area’s water resources and water environment by quickly obtaining the distribution of surface water bodies, sediment, organic matter, chemical pollution, and other information such as water depth and water temperature.

5. Application of BIM- other technologies integration

5.1 BIM-GIS integration

BIM is commonly utilized for managing small-scale information such as interior or single buildings while dealing with large-scale information like streets and cities presents the challenge of information silos [10,11]. Moreover, BIM references a relative coordinate system, which limits its spatial processing ability, making it incapable of expressing the geographical location of buildings

[11]. On the other hand, GIS can process large-scale geographic information but can only represent outdoor information and cannot process building details or indoor information [11]. As such, BIM and GIS have their respective advantages and disadvantages and can complement each other. Based on the available literature, three broad types of integration have been identified: data format transformation [70], data combination to form new models [71,72], and ontology-based concepts [72].

Type 1: Integration through data format transformation.

Research on data format conversion has focused on converting from IFC to CityGML, with some research focusing on conversion from CityGML to IFC. The conversion from BIM data to GIS data involves coarsening the refined data, including both geometric and semantic aspects. Initially, geometric information conversion was done using conversion rules to define different IFC entity conversion rules for each level of CityGML. In addition to geometric information conversion, mapping semantic information is also essential for integrating GIS and BIM. It is achieved not just by converting the data format but by using the combination of CityGML and IFC standards to create a new data model.

Type 2: Integration through the standard extension.

The integration of BIM and GIS using CityGML and extensions to the IFC standard has two parts: (1) combining IFC and CityGML to form a new data model, and (2) integration based on the CityGML ADE extension. The process in (1) solves the problem of data loss during IFC-CityGML mapping, as there is no data conversion involved, and is more efficient than ADE extensions. It can extract the corresponding information in BIM and GIS models based on different usage requirements, making it highly relevant and flexible.

Type 3: Integration through standard ontology.

Inter-standard mapping and standards-based extensions for integrating IFC and CityGML suffer from the problem of unidirectionality, which disallows bidirectional data exchange between BIM and GIS. To solve this problem, El-Mekawy and Eastman proposed using ontology in 2010. The goal of ontology construction is to create a common understanding of structured information between humans and computers, based on semantic consistency. The key to building an ontology framework is describing architectural or geographical elements and defining their relationships. For example, when modelling an ontology for an area, building elements, spaces, functions, outdoor entities, etc. must be described, and the relationships between them defined appropriately.

In terms of research on the application of BIM-GIS integration, more results are available than theoretical methodological research. During the planning and design stage, BIM technology's advantage is creating a refined model of the building to visualize design results. GIS’s role is in managing and analyzing geographic information of large scenes, providing designers with more GIS data and spatial information to design buildings in macroscopic scenes.

During the construction stage, GIS and BIM technology can be used for building construction progress management, supply chain management, scheduling, tracking, and managing construction materials required from an overall project perspective. Combining various technologies such as RFID, GPS, and the Internet of Things can achieve visual management of construction material suppliers in the general environment of GIS. Regarding the operation and maintenance phase, BIM+GIS technology can be used for applications such as as-built model delivery, maintenance planning, asset management and disaster emergency simulation. For example, in the disaster simulation process, for indoor emergency handling, the indoor spatial and semantic information of BIM needs to be used to define each node in the room, and then the path calculation advantage of GIS is used to carry out scientific escape path planning.

Table 6 summarizes studies on the application studies of BIM-GIS integration in the construction field. The survey contains four key elements: project type, classification of research fields, application and literature year.

Table 6 Application studies on BIM-GIS integration.

Project stage	Classification of research fields	Application	Literature-year
Plan and design	Transport infrastructure	Removing the conflicts that typically arise between the infrastructure design and environmental constraints.	[73]-2020
	Rail projects	Identifying and articulating collaboration requirements during the design stage.	[74]-2021
	Highway infrastructures	Proposing an approach for managing highway alignment in the context of a larger landscape that integrates BIM and GIS.	[75]-2019
	Road projects	Managing highway alignment in the context of a larger landscape that integrates BIM and GIS.	[76]-2014
Construction	Hydraulic and hydropower engineering projects	Building a new construction tool for hydropower project construction.	[25]-2020
	Building infrastructures	Building a system which enables keeping track of the supply chain status and provides warning signals to ensure the delivery of materials.	[77]-2013
	Highway construction projects	Performing real-time and full-process quality evaluation on asphalt pavement construction.	[78]-2022
	Underground projects	Providing real-time three-dimensional spatial information during the construction process.	[79]- 2021
Operation and maintenance	Underground projects	Improving the information-sharing process, utility management efficiency and decision-making.	[80]-2019
	Tunnel engineering	Developing a tunnel maintenance management framework based on BIM and GIS integration.	[81]-2018
	Bridge projects	Developing a bridge management system that contains information management, inspection management, and technical condition evaluation.	[82]-2019
	Disaster prevention	Developing a management system of disaster prevention and relief based on BIM-GIS integration.	[83]-2016

5.2 BIM-3D scanning integration

3D scanning is primarily used to accurately and efficiently capture the 3D surface points of objects, including their spatial shape, structure, and colour. Its benefits include fast measurement speed, high accuracy, and ease of use. Additionally, its measurement results can be directly interfaced with various software [43], making it a popular data source for Building Information Modeling (BIM) [84]. BIM integrates with 3D scanning to compare, transform, and coordinate BIM models with corresponding 3D scanning models to aid in engineering quality inspection, rapid modelling, and efficiency. The process of capturing a physical site or space from the air or ground using scan data and developing an intelligent 3D model by employing BIM software is referred to as ‘Scan to BIM’ [85].

Scan to BIM is crucial for producing as-built models of assets that lack information, have outdated plans, or have incomplete documentation. This process takes a point cloud as input and outputs a final 3D reconstructed model where all assets are classified or labelled. The framework (Fig. 12) is designed to include the following steps [86]:

1. Identification of information requirements: Before starting work, project information needs should be identified and compiled into a scope of work (SOW).
2. Determination of required scan data quality: The scan data quality that can fulfil the identified information requirements should be determined.
3. Data capture: Data is collected in the form of a raw point cloud, and the methods of acquisition are mainly laser scanning and photogrammetry. This step requires clarification of scanning parameters, point cloud resolution, density, and appropriate equipment selection according to the user's application.
4. Semantic segmentation: Once registration of all scans is completed, they are combined into a single 3D point cloud. Then, assets are detected and classified, which can be further processed in BIM software.
5. BIM model: Standards such as IFC and gbXML are applied in this step to exchange information between software applications for BIM [87,88].

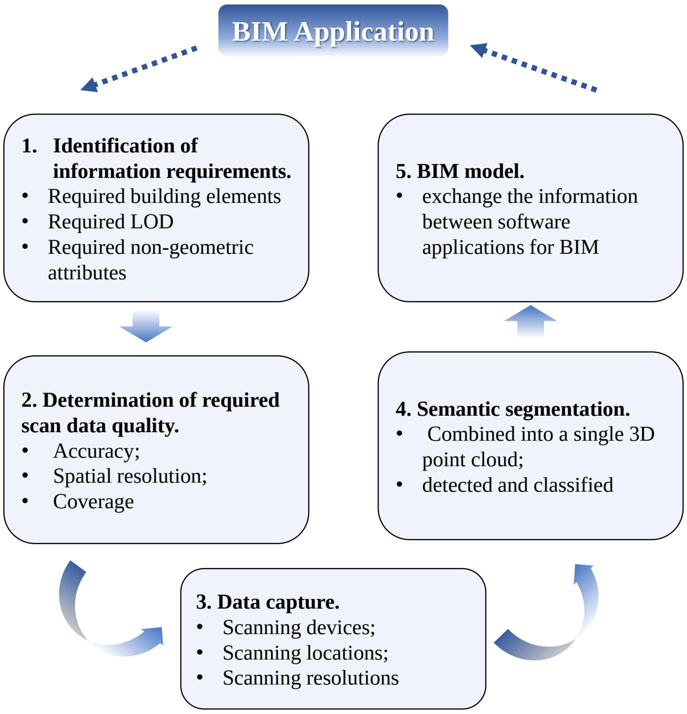


Fig. 12. The framework of Scan to BIM.

The integration of BIM and 3D scanning, also known as scan-to-BIM, has been widely adopted for various applications and has the potential for even more applications in the future. As shown in Table 7, Regarding the plan and design phase, the integration of BIM and 3D scanning allows designers to better understand the topography of the construction site and its surroundings, enabling them to make adjustments to the design accordingly to arrive at the best solution. Regarding the construction phase, the point cloud data obtained from 3D scanning technology is transformed into BIM model data and then compared with the designed model for accuracy. Deviations between the digital model of the construction site and the design model can be identified, ensuring the reliability and accuracy of details during the construction process. Recording building geometry and textures is the most fundamental application of scan-to-BIM in the operation and maintenance phase. Combining 3D scanning and BIM to create an accurate building model and scientifically managing the building's space, equipment, and assets can effectively prevent possible disasters and reduce operation and maintenance costs. At any stage of the project life cycle, 3D scanning and BIM integration can efficiently and completely record the complexities of the construction site, providing great help in project quality inspection and acceptance.

Table 7 Application studies on BIM-3D scanning integration.

Project stage	Classification of research fields	Application	Literature-year
Plan and design	Urban rebuilt projects	Design with 3D site mode.	[88]-2014
	Landscape and decoration	Integrating BIM and 3D scanning for design and decision-making.	[89]-2014
Construction	Large-scale engineering in a complex environment	Integrating BIM and 3D scanning for construction quality control and schedule management.	[90]-2018
	Building Projects	Integrating BIM and 3D scanning to create accurate models during the design phase and construction phase respectively, and determine the construction schedule by comparison.	[91]-2018
	Steel structures	Using a 3D laser scanner obtains the feature data of complex steel structures and their virtual assembly of it in a virtual environment.	[92]-2019
	Removable Floodwall Projects	Integrating BIM and 3D laser scanning technology to improve quality control of prefabricated modular construction projects.	[93]-2020
Operation and maintenance	Precast concrete elements	Using building information modelling (BIM) and 3D laser scanning technology to assess the dimensional and surface quality of precast concrete elements.	[94]-2015
	Large-scale civil infrastructures	Integrating the laser scanning data and the BIM model to determine the degree of deformation of pipe frames (e.g. trusses, columns) for health monitoring.	[95]-2018

5.3 BIM-Internet of things integration

BIM technology provides upper-layer information integration, interaction, display and management, while IoT technology offers bottom-layer information sensing, collection, transmission and monitoring. By combining these two technologies, a "closed loop" of information flow can be established throughout the construction process, enabling seamless integration of virtual information management and physical environment hardware. BIM is currently mainly used in the design phase but is increasingly being applied in the construction and operation and maintenance phases. IoT applications are focused on the construction and operation and maintenance phases, and by using sensors, 2D codes and electronic tags (RFID), real-time monitoring of people, machines, materials, methods and the environment can be achieved. The integration of BIM and IoT can generate significant value throughout the construction lifecycle [96].

However, despite the wide use of sensors in engineering constructions, most of the applications are limited to specific local demands, and there is still a gap between these applications and the concept of IoT. The integration of IoT with BIM is also limited. Previous studies have explored the integration of these two technologies and their application prospects. For example, Teizer et al [97] developed a generic architecture and methodology for integrating real-time environmental and personnel location information into the system. These studies have formed the basic architecture of the IoT-BIM system, which consists of a perception layer, network layer and application layer. Different application scenarios are extended or refined at the application layer, as shown in Fig. 13.

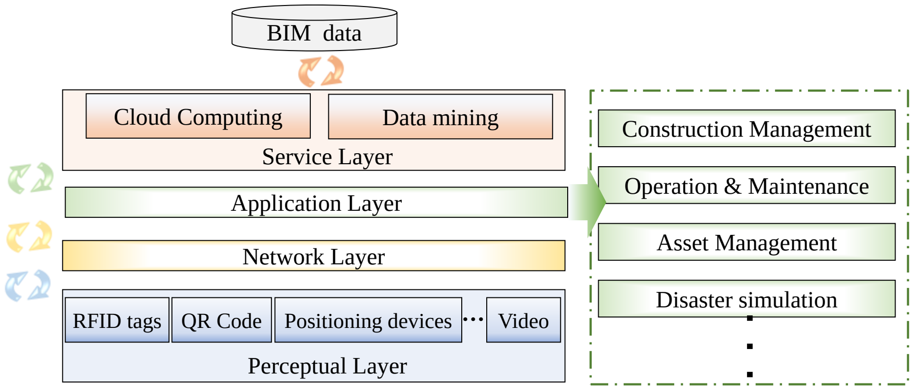


Fig. 13. The framework of BIM-IoT integration.

In the infrastructure sector, the construction and operation and maintenance phase has a longer life cycle and more complex tasks than the planning and design phase. The parties involved in the project exhibit a high degree of decentralization, mobility and mobility, which makes the integration of BIM and IoT more feasible in the construction and operation and maintenance phases of infrastructure. As shown in Table 8, during the construction phase, RFID technology can be used to monitor safety hazards at the construction site, and the monitoring feedback data can be fused with the BIM base data and brought together in a monitoring platform loaded with BIM models to facilitate unified management of the construction site. The construction progress can be monitored remotely through video front-end equipment, and combined with the BIM base data of components and materials, the construction progress can be remotely commanded and dispatched. In the operation and maintenance phase, the combination of BIM and IoT technology can assign a designated RFID tag or 2D code to each facility. An intelligent terminal can then be used to obtain specific information about the equipment and fuse it with the BIM model data, displaying the corresponding BIM model in a visual environment while querying the properties and status of the equipment. This can improve the efficiency of infrastructure operation and maintenance.

Table 8 Application studies on BIM-IoT integration.

Project stage	Classification of research fields	Application	Literature-year
Construction	Utility tunnel construction projects	Integrating BIM and IoT for dust control, temperature sensing and environmental monitoring during tunnel construction.	[98]-2018
	Prefabricated construction	Integrating IoT and BIM for a prefabricated public housing project in Hong Kong, an IoT platform was designed to collect real-time data from the prefabricated building site assembly work process and upload it to the cloud to provide decision support to the relevant site managers and workers.	[99]-2018
	Modular Integrated Construction (MiC) projects	Developing an IoT-enabled BIM platform (IBIMP) for the MiC project based on a real project located in Hong Kong, consisting of Smart Building Objects (SCOs) equipped with smart triple tags (STTs) and GPS sensors, an intelligent gateway system, data source management services, location-based services, rule-based schedule control services, and decision support services for prefabrication production, transportation and on-site assembly processes. Translated with www.DeepL.com/Translator (free version)	[100]-2019
	Underground engineering	Developing a set of underground engineering safety risk early warning and control systems based on BIM technology and Internet of Things technology, which can realise early warning and real-time dynamic monitoring of safety risks during the construction of underground engineering.	[101]-2021
Operation and maintenance	Bridge projects	Integrating BIM and IoT and creating a relational database system (RDBMS) to connect the real model to its digital twin in real time for bridge health monitoring.	[102]-2022
	Building Projects	Developing a data-driven predictive maintenance planning framework for buildings based on BIM and IoT technologies, including a condition monitoring and fault alarm module, a condition assessment module, a condition prediction module and a maintenance planning module.	[103]-2020
	Construction Projects	Integrating BIM and GIS to construct 3D model files, engineering quantity files and construction schedules to achieve fine management of construction materials.	[104]-2022

5.4 BIM-5G integration

Despite the increasing adoption of BIM and support from the government, it has not progressed in terms of advancing to higher BIM maturity levels. One of the reasons for this is the current 4G network's lack of speed and bandwidth capacity to support higher-level BIM use [59]. However, the introduction of 5G capabilities has enhanced data connectivity. The higher bandwidth capacity, increased data speed, and ultra-low latency brought by the 5G network make it possible to integrate

BIM and other technologies, transforming BIM into an immersive tool that allows users to visualize and virtually immerse themselves in the project site on a 1:1 scale of the BIM design [105].

In the design phase, the 3D virtual roaming technology is a breakthrough in BIM technology compared to traditional CAD software. In this model, the impact of other factors on the building can be studied from an external perspective. The 5G network's high speed, large capacity, low latency, and reliability can communicate the change process and the building's actual situation to all parties involved in the project promptly, facilitating the timely correction of unreasonable design loopholes [106]. The traditional method of creating construction archives by classifying and archiving paper versions at the completion delivery stage no longer meets the needs of the information age. The application of 5G network technology can further improve the efficiency of BIM information transmission with high speed, high capacity, and high reliability [107].

In the operations management phase, BIM technology requires accurate descriptions of various parts of the building, including geometric and non-geometric information. BIM models can provide necessary data and information to different stakeholders depending on authorization and update it under license, and changes and modifications based on the 5G network can provide flexibility to the program [108]. For example, if a maintenance unit needs to replace old equipment and facilities, authorized personnel can fully input information about the new equipment into the system to replace the original equipment and facilities information, and with the 5G network, can do so quickly and responsively, recording maintenance times and next maintenance reminders. The use of IoT, Blockchain, unmanned aerial vehicles (UAVs), AI, ML, and DRL-based methods to create smart cities are relatively new concepts that have promising futures within the world of 5G [105].

5.5 BIM-Satellite integration

In addition to retrieving data from existing building databases, BIM for existing buildings can be created using computer vision techniques. Large-scale data acquisition can be achieved through image-based techniques such as photogrammetry and video surveying, range-based techniques like laser scanning, or a combination of both [43,84,85]. Furthermore, satellite remote sensing technology has rapidly advanced, providing images that offer a more detailed and adaptable representation of terrain features on a large-scale infrastructure [63]. For instance, satellite imagery is now available free of charge or can be purchased from commercial providers at a reasonable cost. Street view imagery that contains objects such as buildings, trees and cars can also be obtained for free or at a low cost from mapping service providers like Google Maps. Engineering researchers and social scientists have shown significant interest in satellite and street view imagery, as these resources offer rich visual information [109]. Streetview images have become a valuable resource for various applications, including capturing the social context of the urban environment and estimating the demographic composition of a neighbourhood based on visual cues of cars in streetscape images [110]. Most image-based studies, including applications in building detection, land use classification, etc., have utilised convolutional neural networks (ConvNet or CNN) to extract information from images [104]. Combining satellite information with BIM platforms facilitates comprehensive data analysis, particularly for critical civil engineerings infrastructure such as viaducts, bridges and dams. Furthermore, satellite imagery is useful for both hydrological modelling [111] and water pollution monitoring [112]. Integrating this data with BIM will greatly aid in the creation of digital twin watersheds.

5.6 From Building Information Modelling (BIM) to City Information Modelling (CIM)

The urban environment is incredibly complex, consisting of both static and dynamic objects, as well as various entities such as individuals, companies, organizations, and transportation systems. As a result, a vast amount of information is generated, which can be overwhelming but also highly valuable if properly utilized. In this era of information explosion, it is crucial to sift through the abundance of data sources and extract the necessary information. To achieve this, it is necessary to first organize the information in a structured manner. The use of CIM has been proposed as an effective method for organizing urban information [7]. Similarly, watersheds contain a wealth of complex information related to engineering, rainfall, water quality, power, and flooding. By properly utilizing this information, efficient and integrated management of watersheds can be achieved at a larger scale.

By examining the evolution of City Information Modeling (CIM), it is evident that it is a progression from BIM to BIM+ to CIM. As illustrated in Fig. 14, the BIM concept consists of four fundamental components: collaboration, representation, process, and lifecycle, which work in synergy to create an innovative and efficient project environment. However, as research expands and the demand for intelligence in the infrastructure industry grows, a single BIM is no longer sufficient to digitally represent the building and environment on a large scale, nor can it meet the diverse and complex needs throughout the building lifecycle. Consequently, a new paradigm, BIM+, has emerged, which leverages the integration of BIM with GIS, IoT, 3D scanning, 5G, satellite remote sensing, and cloud computing to provide great value in planning and design, construction, building, and operation phases of large-scale infrastructure.

City Information Modeling (CIM) is a model based on Building Information Modeling (BIM), Geographic Information Systems (GIS), the Internet of Things (IoT), and other technologies. It integrates the above-ground, underground, indoor-outdoor, historical, current, and future aspects of a city, including multi-dimensional and multi-scale information model data such as indoor and outdoor, past, present, and future, as well as urban perception data. It aims to construct a three-dimensional digital space information organic complex of the city that showcases 3D models of urban space at various scales while incorporating attribute correlation information to realize the transformation from digitalization to informatization.

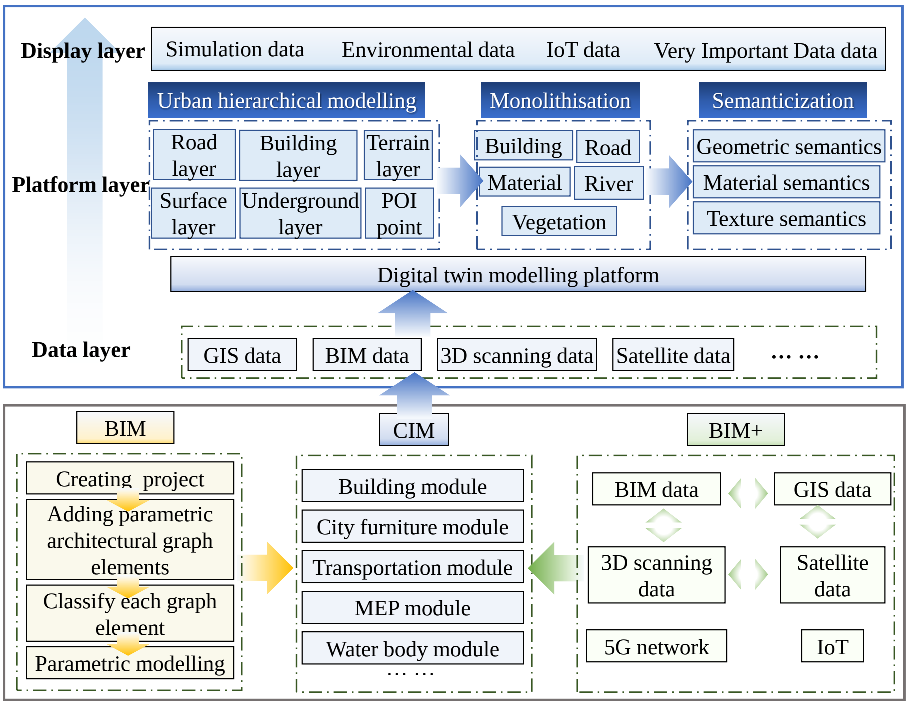


Fig. 14. The Framework from BIM to BIM+ to CIM.

6. Challenges and future directions

6.1 From City Information Modelling (CIM) to Watershed Information Modeling (WIM)

The research on the integration of BIM and other technologies is divided into three categories, evolving from functional integration and data integration to integrated applications. A previous study has proven that CIM is the most important research direction for the future. However, the research on the integration of BIM and other technologies for smart watersheds has not been thoroughly studied. Therefore, the authors suggest that the functional integration of smart watersheds should be a hot topic for future researchers.

As shown in Fig. 15, the authors propose the framework of Watershed Information Modelling (WIM), which integrates BIM, satellite remote sensing data, interferometric radar data, laser point cloud data, and other spatial data. It uses the fast data transmission capability of 5G to build a digital twin basin that combines space and time and realizes the interconnection of human, material, and spatial data in the development and construction of intelligent water conservancy. WIM includes a digital base, an intelligent flood warning model, an intelligent power dispatch model, a hydrological information monitoring system, a water environment information monitoring system, a whole life cycle management system for water conservancy and hydropower projects, a joint dispatching system for terraced water conservancy and hydropower projects (taking into account flood control and power generation), and an information management system for water supply, involving five basic elements: hydrology, environment, engineering, energy, and water services. It forms watershed information modelling.

The sensing layer: This layer uses sensing equipment such as cameras, sensors, laser scanners, robots, and satellite remote sensing systems to collect data at different scales. It connects things to things and things to people according to agreed protocols to create an integrated sky-ground-water resources big data sensing network.

The data transmission layer: This layer provides users with the data transmission, computing, and storage resources they need through 5G technology, private clouds, public clouds, and hybrid clouds. It pools resources through virtualization and other technologies to achieve on-demand allocation and rapid deployment of resources.

The digital support layer: This layer establishes a deep fusion system of multi-source information through the Internet of Things technology. It includes building whole life cycle information, 3D geographic information, 3D point cloud information, and satellite remote sensing information. This layer establishes a digital base for watershed information modelling.

The intelligent water application layer: This layer establishes an intelligent flood control and scheduling system, an intelligent hydropower scheduling system, an intelligent water supply scheduling system, and a basin risk warning system. It achieves comprehensive visualization of key elements of the basin.

1. Intelligent Flood Control and Scheduling System: This system aims to develop a 'four-prediction' simulation platform for flood forecasting, warning, preview, and pre-programming, allowing for dynamic interaction, real-time integration, and simulation of flood forecasting and scheduling results on digital maps. It promotes smart basin flood control, with core functions such as flood forecasting, flood warning, flood pre-show, and flood planning. Real-time rainfall information is used as the basis for forecasting, combined with real-time prediction and analysis of the production and confluence models. For early warning, based on flood forecast data, early warning information is generated and displayed according to the flood warning signal level. To address the pre-event aspect, water monitoring data, rainfall monitoring data, 3D surface, underwater 3D terrain, water conservancy facilities data, and flood control object information are integrated into 3D scenes, to achieve flood prediction evolution, flood inundation model analysis, real-time flood evolution, flood control emergency scheduling pre-event, river reservoir dam failure pre-event, and realistic weir simulation display. In terms of pre-programming, it integrates various flood control schemes, dispatching rules, and expert knowledge to realize the real-time correlation between each pre-programming trigger condition and water monitoring, achieve accurate judgement of current flood water conditions and flood levels, trigger flood control emergency pre-programming in a timely and accurate manner, provide objective and accurate data support, and assist flood control command departments in making emergency dispatching decisions.
2. Intelligent Hydropower Dispatching System: This system builds a model for graded hydropower generation dispatching that considers the overall rainfall and water level changes in the basin. It realizes dynamic interactive mapping of power output and digital maps, improving the efficiency of utilizing clean hydropower resources in the basin and increasing the output of green electricity
3. Intelligent Water Supply Dispatching System: By controlling sluice gates to transfer and replenish water, this system realizes flexible mobilization of water resources in the basin. It achieves flood and drought prevention as well as rational use of water resources while ensuring the safety of reservoir groups, zones, and upstream and downstream.
4. Basin Risk Early Warning System: This system includes a basin ecological safety monitoring system and an engineering safety monitoring system. (a) Through the Internet of Things

platform, it achieves real-time online reception, analysis, and evaluation of multi-parameter water quality monitoring data, supports 5G/NB-IOT/satellite and other networks, performs online monitoring equipment operation, data reception quality benefit analysis, monitoring station distribution visualization, water quality evaluation, water quality ion dynamic trend analysis, river discharge inspection information management, and comprehensive information statistical analysis. (b) The establishment of an Internet of Things platform, a drone inspection platform, and a business system, where the Internet of Things platform provides rapid access to equipment and equipment management services, the drone platform is responsible for the construction of three-dimensional models of reservoirs and dams and inspection support, and the business system mainly realizes real-time monitoring and early warning of water and rainfall conditions and dam safety in small reservoirs. By establishing a basin risk analysis system, effective monitoring and early warning of major catastrophic risk events that may occur in the basin will be carried out to enhance the basin's resilience.

The Integrated decision-making layer: Utilizing the digital twin basin information model, this layer consolidates flood dispatching, power dispatching, engineering safety monitoring, and environmental safety monitoring data. It then incorporates artificial intelligence calculation models to fuse and integrate forecasting data and multi-dimensional information, enabling real-time and rapid collection, analysis, and processing of various information, and presenting a comprehensive visualization display on a single map. By utilizing decision theory, it facilitates unified command and dispatch of flood control, power generation, and risk control within the basin, optimizing the flood control and economic benefits of water conservancy and hydropower projects in the basin.

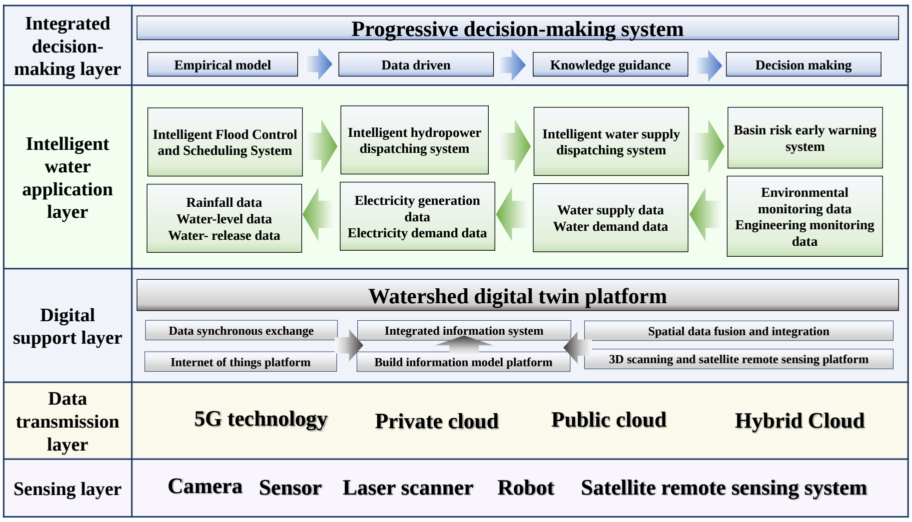


Fig. 15. Framework of watershed information modelling (WIM).

6.2 Challenges for Watershed Information Modeling (WIM)

The application of BIM, GIS, 3D scanning, 5G, and satellite technologies in the development of smart infrastructures has yielded promising results, as evidenced by existing literature. However, several challenges need to be addressed to fully realize the potential of smart watershed technology. These challenges include:

(1) Development of semantic data model.

The development of a semantic data model containing attributes of various components of a watershed is essential for the realization of a smart hydraulic and hydropower engineering system.

The model should contain attributes such as hydraulic and hydropower engineering, hydrological information, water environment information, water ecological information, and hydro-energy. The more semantic attributes the model contains, the more intelligent functions it can realize. Therefore, the development of an integrated platform containing many semantic attributes will be one of the main research areas in the field of BIM+ integration shortly.

(2) Optimization of diverse devices.

Another challenge is how to optimize the advantages of diverse devices. Smart watershed technology integrates a range of subsystems at the application layer to provide reliable and efficient services. Aggregation is worth further analysis, and the WoT concept is considered an ideal element to amalgamate diverse applications due to its universal accessibility. Consequently, smart watershed constituents will be capable of intercommunication regardless of any conflicting components in their communication technologies or operational platforms.

(3) Information technology for integrated watershed management.

From the perspective of smart watershed technology and based on the primary data composition of BIM and other technologies, the theoretical framework of data integration based on data visualization, information spatialization, and attribute structuring compatible with BIM and other technology standards is explored for integrated watershed management. Current challenges include the visualization and integration of the BIM and other technologies' inherent data management, visualization of watershed data, and visualization of invisible data such as red lines and property rights. It is also important to provide essential theoretical support for data integration, storage, analysis, and presentation of the BIM and other technologies and provide a theoretical framework and guidance for the future development of the smart watershed software platform.

(4) Comprehensive decision-making theory system.

A smart watershed system contains several elements such as flood control, power generation, and water supply, and the different elements interact with each other. For example, a conservative approach to flood control will affect the benefits of the basin in terms of power and water generation, while the basin's continuous generation of clean energy and economic benefits are based on the safety of the basin as a whole, creating a complex coupling between these elements. To achieve intelligent and efficient management of the basin and maximize the economic benefits of the basin in terms of energy and water supply while ensuring the safety of the basin, a mature theoretical system of decision-making is needed to support this.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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