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Article

Immersive Technologies-Driven Building Information Modeling (BIM) in the Context of Metaverse

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Abstract: At present, considering the novelty of Immersive Technologies (ImTs) associated with Digital Twin (DT), Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) in the context of the metaverse and its rapid and ongoing development in Building Information Modeling (BIM), knowledge of specific possibilities and methods for integrating ImTs into building process workflows remains fragmented and scarce. Therefore, this paper aims to explore the research progress and trends of immersive technology-driven BIM applications, providing a helpful reference for understanding the current knowledge system and stimulating future research. To the best of the authors' knowledge, this is the first attempt to use macro-quantitative bibliometric analysis and micro-qualitative analysis methods to explore the research topic of ImTs-driven BIM. This study obtains 758 related studies in the past decade, year 2013 to 2022, through a series of keywords from the Web of Science Core Collection database and uses VOSviewer software to conduct keywords co-occurrence analysis and overlay visualisation to visualise the relationship between ImTs and BIM, which contains six clusters, namely VR, Internet of Things (IoT), DT, 3D model, design, and AR. The macro-quantitative analysis on ImTs-driven BIM applications throughout all the stages of the building lifecycle reveals the themes, content, and characteristics of the applications across the stages, which tend to be integrated with emerging advanced technology and tools, such as Artificial Intelligence (AI), blockchain, and deep learning.

Keywords: immersive technologies; building information modeling (BIM); metaverse; digital twin (DT); virtual reality (VR); augmented reality (AR); mixed reality (MR); extended reality (XR)

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1. Introduction

The metaverse concept was first introduced in the novel *Snow Crash* by Neal Stephenson [1]. It is characterised as a virtual digital world tightly connected with the physical world, which will further drive the digital transformation across various aspects of people's material lives [2]. After 30 years of development, the metaverse has become a hot topic in research areas such as the Internet of Things (IoT), Blockchain, Artificial Intelligence (AI), and other related technology-driven industries [3].

Over the past four decades in the field of architecture, the development of Building Information Modeling (BIM) has transformed the traditional design paradigm of the architecture, engineering, and construction (AEC) industry [4] whereby BIM has pervaded the entire building's lifecycle [5]. Furthermore, within the current context of the metaverse, Patrik Schumacher posits that future immersive virtual environments should be the purview of architects rather than graphic designers [6]. The metaverse is anticipated to inevitably drive the innovation and development of future BIM technologies [7].

However, BIM has not fully revealed its potential [8]. In current BIM applications, the most common issue is that information is not presented in a way that can be authentically experienced by the user [8]. Adopting BIM poses multifaceted challenges spanning technological, financial, managerial, personnel, and legal dimensions. Among these, the most pressing constraints limiting the broader utilisation of BIM are its limitations in scalability, interoperability, and remote collaboration support [9]. To address the long-term low productivity and unsatisfactory performance of construction projects caused by these challenges, researchers and professionals in the AEC industry actively seek solutions that can be adapted to BIM [10].

Over the past decade, advancements in Building 4.0 and Industry 4.0, together with the pervasive adoption of innovative digital technologies, have facilitated an unprecedented fusion of the digital and physical realms [11–14]. This synergistic integration has ushered in a new era in the construction industry by prompting transformative changes in management strategies during the construction phase, with a primary focus on enhancing efficiency and promoting sustainable engineering solutions [11–14]. This shift enables building data and information to be exchanged, processed, and utilised, which facilitates communication among designers and stakeholders including users [15]. In addition, the widespread adoption of key technologies such as AI, IoT, Digital Twin (DT), Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) have brought unprecedented possibilities to BIM, enabling it to become more intelligent and leading to significant improvements in building performance and user experience [10,16–21]. Concurrently, the extensive utilisation of these pivotal technologies has incited a revolution, at the heart of which lies the convergence of the lifecycle of physical architecture with that of DT architecture [11]. Hence, to effectively utilise this unprecedented digital revolution and achieve data-driven, efficient, and satisfactory intelligent building management for designers and users, the opportunities provided by Immersive Technologies (ImTs) represented by VR and AR must be utilised [22].

At present, the rapid development of ImTs provides an excellent opportunity for various stakeholders to immerse themselves in different stages of a project, offering novel solutions to address the challenges [23,24]. ImTs can blend with the natural world through digital media devices and even simulate the real world to deliver immersive experiences in the virtual world, providing sensory stimuli such as visual, auditory, and tactile senses, which is crucial for achieving immersive experiences in BIM [25]. Currently, VR, AR, and MR are the most common ImTs related to BIM, which can provide architects with more intuitive ways to experience their designs and make user experiences more interactive and realistic. In addition, since the DT technology provides a digital foundation for integrating the physical and digital worlds, DT has wide-ranging applications in a number of areas such as facility management, monitoring, logistics processes, and energy simulation in BIM [20,26–32]. Additionally, BIM is the core of digital transformation in the construction industry, as it forms a good integration with DT as a data management platform [33] that associates with the VR, AR, and MR technologies [34], which is a clear signal for developing the building metaverse [35].

Despite the rapid and sustained growth of ImTs in the BIM domain, which has been widely recognised [23,24], researchers still lack a comprehensive understanding of how to concretely integrate ImTs into the architectural process workflow [22]. This incomplete and fragmented understanding reveals the necessity for a systematic and objective synthesis of ImTs in the BIM domain. Therefore, this paper aims to explore the research progress and trends of immersive technology-driven BIM applications, providing a helpful reference for understanding the current knowledge system and stimulating future research. Based on this objective, this paper firstly aims to initiate a preliminary examination of the application of immersive technologies in the field of BIM, to acquire a clear understanding of their practical usage within this discipline. Subsequently, the paper endeavours to systematically analyse significant research advancements and key discoveries in this field, with the intent to delve deeper into the understanding of how these technologies have influenced and shaped the practice and study of BIM. Ultimately, this paper strives to construct a comprehensive understanding of the current knowledge system in the BIM domain, thereby providing a valuable reference for understanding the existing knowledge structure and stimulating future research.

2. Materials and Methods

This paper employs a mixed research methodology, including a macro-quantitative analysis of relevant studies in the Web of Science Core Collection (WoSCC) database using bibliometric techniques, and a micro-qualitative exploration of the relationship between BIM and ImTs, of which bibliometric methods have been used to determine the research structure and themes in the macro-quantitative analysis. The bibliometric methods provide visualised quantitative analysis of published literature in a specific field and help evaluate research trends in a particular domain [36], by which title, keywords, and abstract can all be analysed to categorise publications in line with specific themes and subject categories [37]. Therefore, the bibliometric analysis enables researchers to understand the past, keep up with the progress of the investigation, and strengthen future research [38]. This paper explores multiple disciplines in the field of BIM and ImTs; considering the amount of relevant literature and the uncertainty regarding future directions and trends in the research field, bibliometric analysis is an effective approach for investigating the relationship between BIM and ImTs.

This study utilises the analysis tools provided by the WoSCC database to create pie charts and bar graphs revealing the quantity and sources of publications related to ImTs in the BIM field. Web of Science (WoS) is one of the world's most authoritative scientific citation indexing databases, and various usage indicators provided by publishers have been extensively researched [39]. This study will utilise the Web of Science Core Collection (WoSCC) to conduct a search using keywords such as "Building Information Modeling (BIM)", "Immersive Technologies (ImTs)", "Virtual Reality (VR)", "Augmented Reality (AR)", "Mixed Reality (MR)", "Digital Twins (DT)", and "Metaverse". In the search results, journal articles and conference papers will be selected, while articles that do not mention BIM and ImTs in the title or abstract will be excluded. The data used in this paper are obtained from the WoSCC database. As shown in Table 1, keyword searching terms such as "Building Information Modeling (BIM)", "Immersive Technologies (ImTs)", "Virtual Reality (VR)", "Augmented Reality (AR)", "Mixed Reality (MR)", "Digital Twin (DT)", and "Metaverse", as well as their abbreviations and other synonymous expressions, have been used to generate a total of 758 search results from year 2013 to November 2022 (10 years).

Table 1. Results of the data collection process for the most relevant literature data from the Web of Science Core Collection (WoSCC) database (generated by the authors).

Items	Details
Citation	SCI-EXPANDED, SSCI, CPCI-S, CPCI-SSH, CCR-EXPANDED, IC
Search Steps	TS = ("building information model*" OR "BIM") AND ((AR OR "Augmented Reality") OR (VR OR "Virtual Reality") OR (MR OR "Mixed Reality") OR ("Immersive Technology*" OR "ImTs") OR ("digital twin*" OR "DT") OR "metaverse")
Timespan	The year 2013–2022
Qualified Records	758
Source	Web of Science Core Collection (WoSCC)

Subsequently, the data from WoSCC is analysed via VOSviewer, a bibliometric software, employing scientific cartographic methods such as keywords co-occurrence analysis. Scientific cartography, a branch of bibliometrics, is aimed at visually explaining the dynamic changes in a research field through diagrams and charts, which provides the possibility to explore and extend knowledge paths, particularly in interdisciplinary and cross-cutting fields [40]. In addition, VOSviewer is one of the commonly used tools in quantitative science. It was developed in 2019 by the Centre for Science and Technology Studies (CSTS) at Leiden University in the Netherlands, which focuses on extracting essential terms from a large number of scientific documents and generating visual co-occurrence networks [37]. Therefore, using VOSviewer to implement scientific cartographic methods can quickly help researchers identify hotspots and explore future trends [41] for the integration of BIM and ImTs.

However, due to the complexity of scientific development, bibliometric analysis is limited to roughly measuring scientific development's regularities and lacks nuanced qualitative analysis. Thus, in addition to a macro-quantitative analysis, this study further conducted a micro-qualitative analysis based on the results of the macro-quantitative analysis, aiming to comprehensively reveal the existing studies providing deeper insights into the knowledge map of the integration of BIM and ImTs. In the micro-level analysis, the relevant literature on ImTs for BIM from WoSCC database has been explored. Then, the criteria for selecting highly relevant journal articles and conference papers are determined by the following three guidelines: (1) the article is widely cited and recognised within its field, as such articles may significantly influence the development of the field; (2) the article offers unique perspectives or findings, or delves into the integration issues of BIM and ImTs; (3) the relevance of the article to the research theme, with preference given to articles directly addressing the research theme or its major components. These articles will be used for a comprehensive analysis of the research hotspots and future development trends of BIM in conjunction with ImTs (including VR, AR, MR, and DT) at various stages of the building lifecycle.

The research method flow diagram, as shown in Figure 1, is divided into five phases: (1) searching relevant publications by topic in WoSCC; (2) analysing the above search results in time period and journal sources using histograms and pie charts; (3) the keywords co-occurrence analysis using VOSviewer, illustrating the current situation and future directions by network visualisation, high-frequency keyword analysis, overlay visualisation, and hot research keyword analysis; (4) selecting highly relevant studies for mapping their research content to various stages of the building lifecycle with year, research method, and research topic; and (5) analysing the research hotspots and future development trends of ImTs-driven BIM applications.

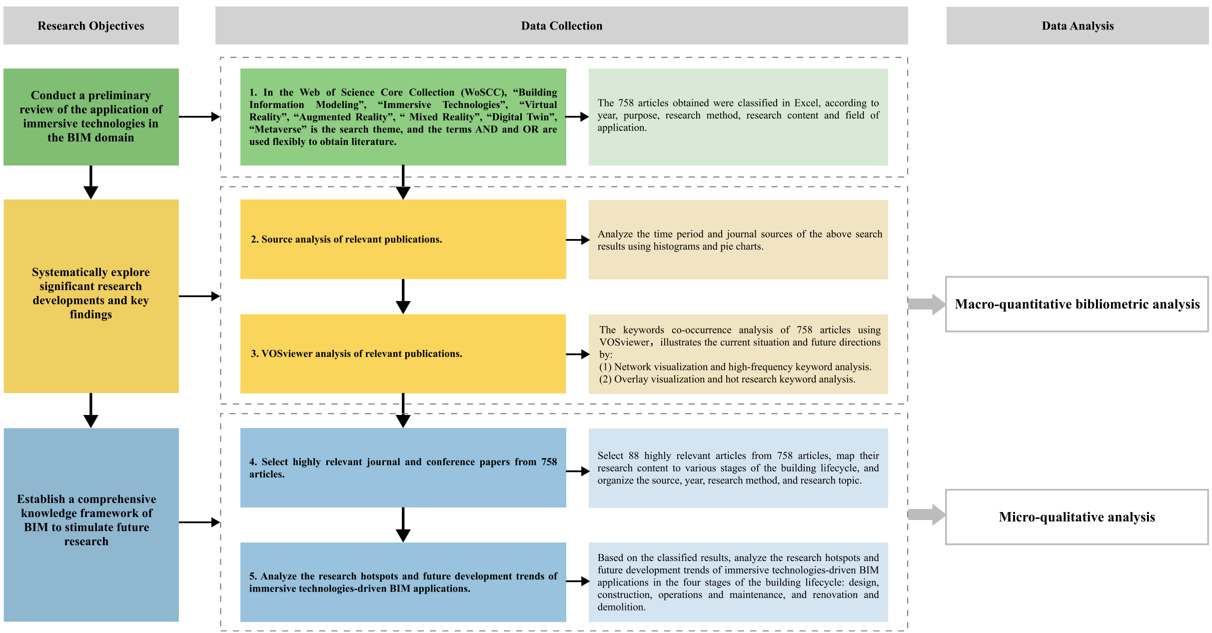

Figure 1. Research method flow diagram.

3. Results

3.1. Results of Macro-Quantitative Bibliometric Analysis Regarding Immersive Technologies (ImTs)-Driven Building Information Modeling (BIM) in the Context of Metaverse

3.1.1. Source

The trend of publication quantity is an essential indicator of scientific research trends. As shown in Figure 2, the number of publications in BIM and ImTs in the context of metaverse increased slowly from 18 articles in year 2013 to 28 articles in year 2016. From year 2017, the number of publications increased rapidly to 47 articles. Then, the number of publications in year 2022 reached 192, more than four times that in year 2017. As such, research on the relationship between BIM and ImTs in the context of metaverse is gaining sustained interest and wide recognition in the field.

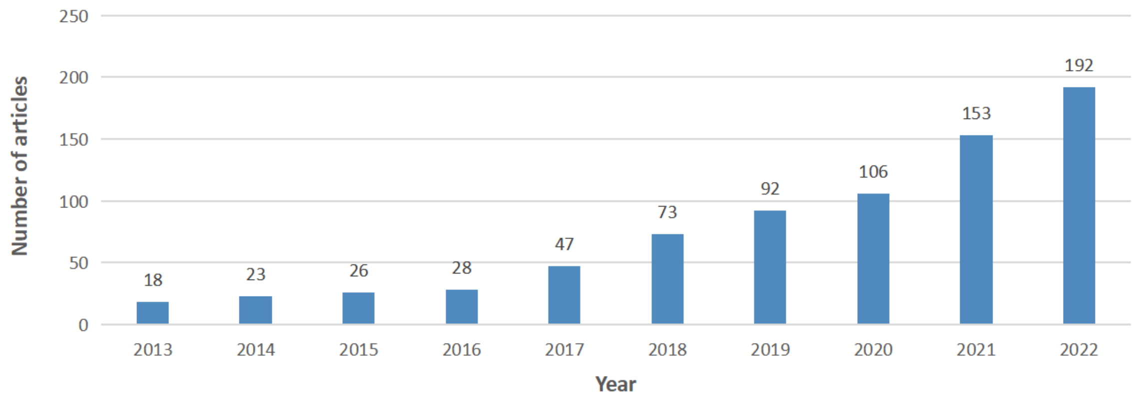

Figure 2. Number of articles published each year on Immersive Technologies (ImTs)-driven BIM within the context of metaverse from year 2013 to 2022 (10 years) in the WoSCC database (generated by the authors).

The publication sources related to ImTs in the field of BIM within the context of metaverse are shown in Figure 3. A total of 758 articles have been published in 377 publications, of which 38.26% of the articles are from nine primary sources which are Automation in Construction, with 11.74% of all the published articles, followed by Buildings (6.07%), Applied Sciences Basel (5.15%), Sustainability (4.75%), International Archives of the Photogrammetry Remote Sensing and Spatial Information Sciences (3.56%), Engineering Construction and Architectural Management (1.98%), Advances in Civil Engineering (1.72%), Lecture Notes in Computer Science (1.72%), and Journal of Construction Engineering and Management (1.58%).

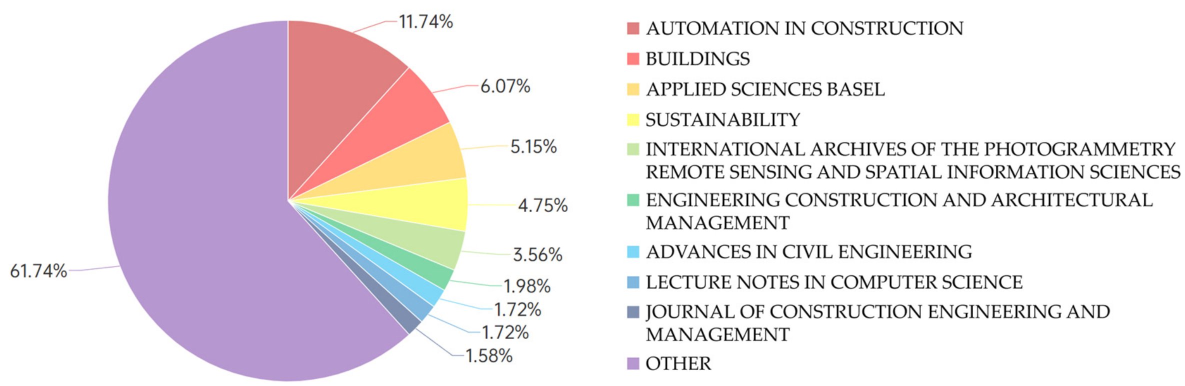

Figure 3. Sources of published articles regarding ImTs-driven BIM within the context of metaverse from year 2013 to 2022 (10 years) in WoSCC database (generated by the authors).

3.1.2. Keywords Co-Occurrence Analysis

The obtained 758 articles from the WoSCC database, as listed in Table 1, were imported into VOSviewer software (version 1.6.18) for keywords co-occurrence analysis. A total of 2623 keywords were generated, from which the minimum threshold for keyword occurrence was set to 'six' to enhance the representativeness of the keyword clustering results. Additionally, a thesaurus file was used to merge similar keywords in the network graph, such as using "VR" to represent "virtual reality", "vr technology", "virtual reality (vr) ", "virtual-reality", and "virtual reality technology", among other synonymous keywords, resulting in 130 co-occurrence keywords that have been identified and classified into six different colour clusters, i.e., red, green, dark blue, yellow, purple, and light blue, as shown in Figure 4.

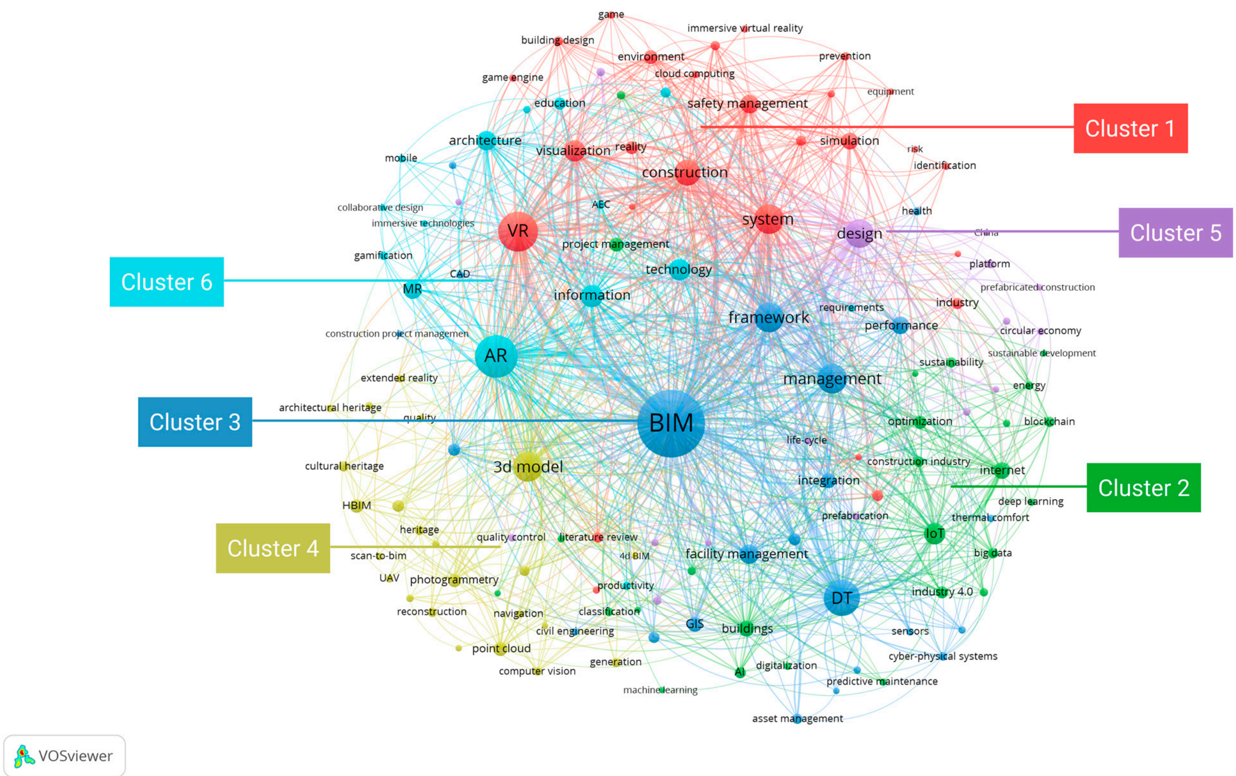

Figure 4. Network-visualisation map of the keywords co-occurrence analysis of published articles regarding ImTs-driven BIM within the context of metaverse from year 2013 to 2022 (10 years) via VOSviewer software (generated by the authors).

In the network visualisation generated by VOSviewer, the size of the node circle represents the frequency of occurrence of a keyword. The larger the node, the higher the frequency of the same keyword appearing in different articles. The keyword "BIM" occupies the most significant node in the centre of Figure 4. The distance between two keywords represents the strength of direct affinity between two topics, while the width of the line represents the strength of the connection between them [42]. Based on the network-visualisation map of the keywords co-occurrence analysis (Figure 4), the knowledge structure and research hotspots of ImTs in BIM can be revealed.

As shown in Figure 4, Cluster 1 (red) focuses on the theme of VR, with main keywords including "system", "construction", "visualisation", "safety management", and "simulation". Cluster 2 (green) is centred on the IoT, emphasising "Internet", "Industry 4.0", "sustainability", "blockchain", and "smart city". Cluster 3 (dark blue) revolves around DT, involving core keywords such as "BIM", "framework", "management", "facility management", and "Geographic Information Systems (GIS)". Cluster 4 (yellow) is themed around 3D modeling, with representative keywords such as "Historical Building Information

Modeling (HBIM)", "photogrammetry", "point cloud", "laser scanning", and "Unmanned Aerial Vehicle (UAV)". Cluster 5 (purple) focuses on design, paying close attention to keywords such as "China", "platform", "lifecycle", "circular economy", and "prefabricated construction". Cluster 6 (light blue) centres on the theme of AR, covering core keywords such as "information", "technology", "architecture", "MR", and "education". As such, the six clusters can be further mapped as shown below:

1. Cluster 1 VR exemplifies the ongoing investigations within the domain of VR for virtual construction. This is typically achieved through 3D real-time computer graphics and advanced display devices, such as head-mounted displays (HMDs) [43]; leveraging VR facilitates with generation of comprehensive virtual construction environments, permitting users to partake in real-time interactions with digital entities [44], which enables project teams to effortlessly conceptualise and visualise their work content, thereby assisting them in making optimal decisions for construction projects [45,46]. Consequently, VR technology is currently employed in BIM to tackle a range of challenges to design, construction, and operation, encompassing design coordination, project planning, construction education, construction operation collaboration, and facility management [8,47–52]. In addition, the visualisation techniques introduced by VR technology have been garnering considerable practical research attention in the realm of safety management [53–57]. These VR-enhanced BIM collectively unveil the substantial potential of visualisation techniques in augmenting the capacity for on-site safety risk identification [58,59].
2. Cluster 2 IoT represents the investigation of IoT within the domains of BIM and smart cities. Industry 4.0, smart city, and blockchain have surfaced as burgeoning keywords in the BIM field in recent years [60–64]. Sensing technology constitutes the pivotal impetus behind the IoT, in which the modeling of sensory information intrinsically influences the quality of smart city systems [65]. Smart cities endeavour to guarantee a salubrious living environment for indoor inhabitants by detecting, processing, and regulating a comprehensive range of indoor and outdoor facilities [66]. As such, smart cities and IoT technology will inevitably be closely linked in the future [67]. In addition, advancement of Industry 4.0 technologies, encompassing pervasive IoT and social media platforms employed for sensor data, services, and intelligent urban applications, may potentially instigate security concerns related to users' private data. Therefore, distributed, intelligent, and secure data management systems composed of blockchain and IoT are widely considered to address data leakage issues [68].
3. Cluster 3 DT epitomises the exploration of DT within BIM domain. In the research within this cluster, clear distinctions are drawn between BIM and DT: BIM aims to enhance efficiency in engineering design and construction at every stage of the building lifecycle [69], while DT focuses more on managing physical assets within a building to ensure their effective, reliable operation and implement predictive maintenance of the related assets [70]. During the literature review, for studies that involve both BIM and DT, we conducted detailed reading and analysis to ensure the authors' main points were understood and properly categorised. The paramount value of DT resides in Facility Management (FM), of which the implementation of DT in FM constitutes a comparatively novel research domain [71,72]. FM predominantly transpires throughout the operation and maintenance stages of a building lifecycle, wherein 85% of the entire lifecycle expense is apportioned to FM [73]. Maintenance management and energy consumption are two essential aspects of daily property management, which engender abundant information [74]. A vast amount of fragmented information is extensively amassed by DT systems and ultimately consolidated and processed via BIM-based FM systems to facilitate the management of buildings throughout the operation and maintenance phases [75–78]. Addressing projects involving large-scale and geographically scattered building assemblages, GIS works as the predominant method within FM [79]. By amassing geospatial data, GIS manages various business procedures and information systems situated within edifices [79].

4. Cluster 4 3D modeling embodies the study of 3D modeling techniques in BIM. The main research focus in this area is HBIM that aims to effectively manage various complex historical heritage scenarios, such as heritage buildings, archaeological sites, ancient infrastructure, and multiple monuments [80–83]. In addition, BIM likewise presents an assortment of new requirements for 3D modeling techniques. Amidst the tide of the digital era, techniques such as photogrammetry, point clouds, laser scanning, and Unmanned Aerial Vehicles (UAVs) have incrementally permeated the scope of 3D modeling, eliciting transformative alterations to conventional and laborious modeling practices [84–89].
5. Cluster 5 design represents the research work of BIM technology in optimising design in the building lifecycle. Digital technology is the pivotal impetus to enhance the circular economy [90]. With the increasing awareness of climate change among people, the application of digital technology, represented by computer simulation and optimisation, to mitigate environmental impacts throughout the lifecycle of buildings has recently attracted more and more attention [91]. In the field of architecture, this interdisciplinary design approach integrating digital technologies has become an integral component of the circular economy [91]. In addition, using prefabricated structures during the construction process significantly contributes to the circular economy through more precise quantitative production and less waste generation [92]. Interestingly, "China" emerges as the sole keyword symbolising a nation amidst all the keywords, as shown in Figure 4, serving as a crucial node in Cluster 5. In recent times, the Chinese architectural sector has fervently engaged with and actively advocated for the development of sustainable building practices and the incorporation of information-driven design [93]. This shift encompasses an array of methodologies grounded in the principles of green construction and enriched by the application of BIM [93]. For example, a large-scale Chinese hospital has been integrated with a sustainable lifecycle forecasting system in DT [94]. The Hong Kong Housing Authority (HKHA) further extensively employs prefabricated construction within its public housing projects to attain sustainability objectives in the building lifecycle [95]. Furthermore, China persistently advocates for proactive economic strategies to foster advancement in sustainability to the construction sector [96,97]. In order to facilitate the implementation of more green building projects, China specifically revised the Design Standard for Energy Efficiency of Public Buildings (GB50189) in 2015 [97]. As such, a sustainable building with a sustained lifecycle based on the concept of the circular economy and BIM has tremendous market potential in China [98,99].
6. Cluster 6 AR exemplifies the research within the realm of immersive BIM environments underpinned by AR. AR allows the integration of virtual 3D objects into reality through devices such as smartphones, tablets, and AR glasses or headphones [100]. These applications enable possibilities for numerous studies, particularly in facilitating construction and improving communication efficiency. For instance, the integration of BIM and AR has been leveraged to provide as-built data directly on-site and offer on-site documentation based on AR devices [101], and to facilitate real-time visualisation of the physical environment for each construction activity or task [102]. In addition, the BIM + AR for Architectural Visualisation System (BAAVS) has been developed to bridge efficient communication among various stakeholders [103]. Furthermore, as an iterative technology of AR, MR offers greater flexibility and provides more possibilities for interaction with the natural world [104].

As shown in Table 2, the cluster terms that are more closely related to the topic of ImTs in BIM are BIM, AR, VR, DT, and system. Moreover, the high-frequency keywords are derived by keywords co-occurrence analysis in the VOSviewer, which specifies a minimum number of keyword appearances of 30 times, including their colour representation, cluster, occurrence frequency, and total link strength. Furthermore, the keywords listed in Table 2 are grouped in line with the six clusters as follows:

1. Cluster 1 (occurrence: 471, total link strength: 1276.5): VR, system, construction, visualisation, safety management, and simulation;
2. Cluster 2 (occurrence: 82, total link strength: 274): IoT and internet;
3. Cluster 3 (occurrence: 909, total link strength: 2148.5): BIM, DT, framework, management, FM, and performance;
4. Cluster 4 (occurrence: 98, total link strength: 264): 3D model;
5. Cluster 5 (occurrence: 92, total link strength: 270.5): design;
6. Cluster 6 (occurrence: 349, total link strength: 912): AR, information, technology, and architecture.

Table 2. High-frequency keywords of ImTs-driven BIM within the context of metaverse from the year 2013 to 2022 (10 years) via network visualisation in VOSviewer (generated by the authors).

Colour *	Cluster	Keyword	Occurrence	Total Link Strength
	3	BIM	495	2050
	6	Augmented Reality (AR)	201	924
	1	Virtual Reality (VR)	173	704
	3	Digital Twin (DT)	144	624
	1	system	100	611
	3	framework	95	600
	3	management	97	589
	5	design	92	541
	4	3d model	98	528
	1	construction	76	453
	6	information	57	335
	6	technology	50	333
	1	visualisation	50	319
	2	Internet of Things (IoT)	49	306
	1	safety management	40	275
	3	facility management	43	243
	2	internet	33	242
	6	architecture	41	232
	3	performance	35	191
	1	simulation	32	191

* The colours in the table align with those from Figure 4.

3.1.3. Overlay Visualisation

The research hotspots of each year can be mapped in the overlay visualisation, which helps to predict future research trends. The results in Figure 5 indicate a visualisation of the keywords, presenting the past to the present in colours from purple and blue gradient to green and yellow. Additionally, the weight, total contact strength, and the colour of the keywords are illustrated in Figure 5, in which the research hot spots of each year are summarised in Table 3.

As shown in Figure 5, the dark blue nodes are the architecture, engineering, construction, and Computer Aided Design (CAD), which are the earliest areas of focus for BIM integrated with ImTs. From year 2018 to 2019, AR started to gain prominence as a research point in the industry, while digital construction began to draw attention. Concurrently, ImTs in BIM spurred research into laser scanning and mobile technologies. Between year 2019 and 2020, two leading ImTs, i.e., VR and MR, progressively emerged as hot topics in BIM. A number of subject areas closely associated with these technologies, such as project management, quality control, architectural heritage, safety management, management systems, and 3D reconstruction, have been extensively investigated via the upsurge of VR and MR applications. From the year 2021 to 2022, the advent of new technologies epitomised by DT inundated the BIM with ImTs. In light of the rise of smart cities and the digital transformation to the construction sector, BIM applications have garnered substantial interest in emerging technologies, including GIS, UAV, Industry Foundation Classes

(IFC), blockchain, deep learning, point clouds, and cyber-physical systems. To further elucidate the relationship between years and keywords, the annual hot research keywords to ImTs-driven BIM have been compiled in Table 3.

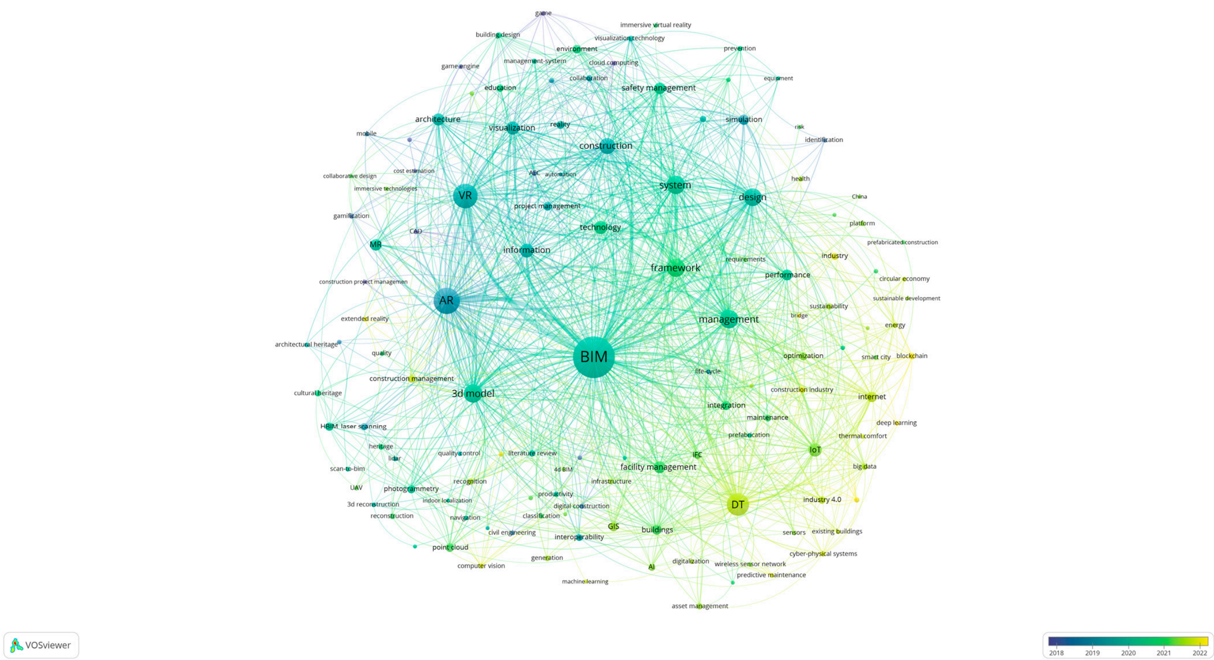

Figure 5. Keywords overlay visualisation of ImTs-driven BIM within the context of metaverse via VOSviewer (generated by the authors).

Table 3. Popular research keywords regarding ImTs-driven BIM within the context of metaverse by overlay visualisation via VOS viewer software (generated by the authors).

Year	Colour *	Keywords
2018		ACE, CAD, AR, digital construction, lean construction, risk management, mobile, laser scanning
2019		VR, information, project management, visualisation, construction, simulation, management-system, quality control, architecture heritage, lifecycle
2020		BIM, 3d model, MR, design, system, framework, safety management, 3d reconstruction
2021		collaborative design, UAV, point cloud, building, 4d BIM, IFC, buildings, GIS, circular economy, industry 4.0, DT, smart city, AI
2022		blockchain, deep learning, construction 4.0, cyber-physical systems

* The colour range in the table is in line with the colour range used in Figure 5.

As indicated in Table 3, the hot research keywords of ImTs-driven BIM within the context of metaverse are summarised in the following five schemes:

- Cutting-edge concept: 4D BIM, smart city, industry 4.0, construction 4.0, and circular economy;
- Advanced technology and tools: digital construction, lean construction, mobile, laser scanning, 3D reconstruction, UAV, point cloud, GIS, blockchain, deep learning, and AI;
- Immersive technology and tools: BIM, CAD, AR, VR, MR, 3D model, information, visualisation, DT, and cyber-physical systems;
- Project management: risk management, project management, construction, simulation, quality control, architecture heritage, and safety management;
- Activity for building the lifecycle: ACE, construction, simulation, lifecycle, system, framework, collaborative design, and buildings.

3.2. Results of Micro-Qualitative Analysis Regarding ImTs-Driven BIM in the Context of the Metaverse

In order to analyse the specific role of ImTs-driven BIM applications in the context of the metaverse, this study selected 88 closely related articles from the 758 publications for the macro analysis on BIM, ImTs, and the metaverse for further micro-qualitative analysis. The selection of strong relevant articles was based on three criteria: (1) the article involves research content on BIM and ImTs including VR, AR, MR, and DT; (2) the main content of the article is proposed based on the context of the metaverse or can be used to construct a BIM-based building metaverse; and (3) the themes of the articles can be mapped to the various stages of a building lifecycle for analysis. The articles have been mapped to the various stages of a building lifecycle, including design, construction, operations and maintenance, renovation and demolition, and full lifecycle.

3.2.1. Design Stage

As shown in Table 4, a total of 14 articles are screened in the design stage. Most studies use mixed research methods [89,105–113], followed by modeling [47,114], literature review [115], and case study [116]. Despite a lack of professional knowledge of architectural design review, students acted behaviour patterns similar to professional experts and achieved similar design review results in simulated tasks for barrier-free design review and evaluation of tiny houses in VR and MR environments during the design stage [105], which indicates that the key to the application of ImTs in the design stage lies in the ability of VR and MR to bridge the experience gap and reduce communication barriers among different roles in collaborative design [105].

In general, at the design stage, the main application areas of ImTs-driven BIM can be categorised into three types: teaching and collaboration, user experience design, and technical implementation.

1. Teaching and collaboration [47,105–107,114,115]: In the field of AEC, AR technology can help students establish a connection between the virtual and real worlds. Diao and Shih suggest that the roles and knowledge of teachers, engineers, and designers to strengthen the collaboration between architectural design teaching and practice in AEC should be integrated, creating a superior learning environment with diverse teaching methods [115]. Regarding collaborative design and decision making, studies have proposed various solutions. Conducting constructability analysis meetings through VR-based immersive collaborative 4D simulation can be used for better collaborative design outcomes, linking the 3D model of the facility with the schedule of construction activities [106]. In addition, a database-supported VR/BIM-based Communication and Simulation (DVBCS) system has been developed to engage stakeholders in the design process via a semi-immersive VR environment [107]. Furthermore, it has been demonstrated to improve communication efficiency between design teams and medical stakeholders, and it simplifies the design and decision-making processes through practical application at a cancer centre [107]. However, the key to achieving collaborative design lies in achieving real-time synchronisation of BIM models [47,114]. Therefore, a BIM/VR real-time synchronisation (BVRS) system has been implemented to demonstrate its usability and efficiency in various experimental scenarios [47,114].
2. User experience design [108–111]: A common characteristic of BIM applications for user experience design is the requirement of the construction in a VR world within the BIM system, enabling users to interact directly with the building and environment with the DT environment, which allows for a more comprehensive design evaluation and feedback on the overall user experience design, serving as the basis for design iteration. For instance, an accurate 3D model of the Dublin Docklands area in Ireland has been created to make urban design and planning more transparent and inclusive, enabling public participation in the process of development of the city through interaction and feedback on changes in urban planning [108].

3. Technical implementation [89,112,113,116]: More emerging technologies have been offered for selection to achieve the production of DT models during the design stage, which provide more innovative and practical solutions for integrating VR/AR interfaces in collaborative design. For example, the use of point cloud technology to achieve rapid modeling by fitting precise 3D shapes with point clusters enriches the modeling resources in the design stage and adds possibilities and vitality to the design [89,116]. Additionally, simplifying the process of integrating BIM data into immersive VR and AR environments provides a streamlined openBIM system to achieve low-latency and concurrent operations, and facilitates smooth collaborative design and communication among stakeholders [112].

Table 4. ImTs-driven BIM in the design stage (generated by the authors).

Category	Source	Year	Research Method	Research Topic
Teaching and collaboration in the design stage	Wu et al. [105]	2019	Experiments and questionnaire	Design assessment in VR and MR environments
	Diao and Shih [115]	2019	Literature review	Trends and research issues of AR studies in engineering education
	Boton [106]	2018	Modeling and case study	Supporting constructability analysis meetings using VR and BIM
	Lin et al. [107]	2018	Modeling and case study	Healthcare design using BIM, VR, and game engine
	Du et al. [47]	2018	Modeling	Collaborative decision making using BIM and VR
	Du et al. [114]	2017	Modeling	Collaborative decision making using BIM and VR
User experience design	White et al. [108]	2021	Modeling and experiments	A DT smart city for citizen feedback
	Cha et al. [109]	2019	Experiments and questionnaire	Spatial perception in immersive virtual environments
	Motamedi et al. [110]	2017	Modeling and case study	Signage visibility analysis and optimisation system using BIM and VR
	Shen et al. [111]	2013	Modeling and case study	The user pre-occupancy evaluation method using VR
Technical realisation in the design phase	Lu and Brilakis [89]	2019	Modeling and experiments	DT of existing reinforced concrete bridges
	Pour Rahimian et al. [112]	2019	Modeling and experiments	Virtual showroom using OpenBIM-Tango
	Barazzetti et al. [116]	2015	Case study	Wider user community using HBIM and AR
	Meža et al. [113]	2014	Modeling and testing	Component-based engineering of a mobile BIM system using AR

3.2.2. Construction Stage

As indicated in Table 5, a total of 28 articles have been screened in the construction stage, which is the stage with the most harvest across all the stages. A diverse range of research methods have been utilised such as mixed methods [58,95,117–131], modeling [102,132–135], and literature review [59,136–138], which suggests that the construction stage is a crucial application stage for ImTs to drive BIM, with a rich variety of studies in terms of both quantity and type. Moreover, the topics of current studies indicate that the majority of studies before year 2019 include AR, followed by MR and DT after year 2019. Furthermore, the main application areas of ImTs-driven BIM in the construction stage can be categorised into four directions, which include construction management, construction tool, safety management, and perception of construction.

1. Construction management [95,102,117–120,132–134]: The key to construction management lies in utilising integration methods of BIM, IoT, and DT and integrating BIM and AR to provide managers with continuously updated and enriched data on functions of facility and performance characteristics [95,102,117,134]. As such, there are a variety of perspectives on how to achieve better construction management. Since BIM itself lacks the ability to manipulate data to evaluate and predict the real-time status of resources and processes in the construction system, adding a data mining component to the DT system to integrate with BIM and IoT enables informed and objective decision making in situation assessment, prediction, and improvement rather than relying on subjective judgments that may be biased and uncertain [117]. The integration of machine learning and image processing methods with immersive and interactive VR-BIM interfaces also helps with addressing the problems [132]. In addition, using AR to visualise real-time physical environment with each construction activity in the actual environment enables construction managers to make clear and accurate decisions [102]. Furthermore, integration of AR and BIM systems provides efficient quality management, reduces the workload of site managers, and establishes defect management processes to prevent the reoccurrence of construction defects [119,120].
2. Construction tool [121–126,135,139]: Construction tools are typically applications that use AR or MR technology in integration with BIM systems to enhance human spatial cognition abilities, which assist users in completing a range of construction tasks by associating 3D models with the actual working environment and flexibly displaying relevant workflows and user interfaces, such as assisting with pipe spool assembly [124,139], welding [135], electrical construction [121], the modular construction of freeform surfaces using brick-like elements [122], and aiding information retrieval during the construction process [123]. In addition, a system called KanBIM has been developed to assist construction workers in making more accurate on-site decisions, by which the workers have increased confidence in their work status and guidelines to work according to lean construction principles [126]. Furthermore, employing AR technology to integrate BIM systems with mobile devices and public/private information, AR and Multiscreen System (AR-MS) benefits information retrieval and prediction of potential issues at construction sites while improving the accuracy and efficiency of on-site decisions [125].
3. Safety management [58,59,127–129,136,140]: Due to the high accident and fatality rates in the construction industry, on-site safety management has been a hot topic in both research and practice in recent years [59]. The main reason is that, in practice, the dynamic and complex construction process could lead to on-site risks and safety plans being overlooked, which results in various safety accidents [136]. Currently, under the guidance of concepts such as DT and ImTs, the emergence of advanced sensing, IoT, and visualisation technologies provides possibilities for improving the health and safety of workplaces, of which applications are divided into three approaches: (1) Incorporating safety management measures directly into workers' work environment is a promising approach to improving on-site safety and health. For example, an application has been developed to transform the view of a MR head-mounted display into a collaborative environment that enables workers to see and interact with, to improve the accuracy and efficiency of risk communication in construction workplaces [127]. In addition, an integration of IoT, BIM, Apriori algorithm, and complex network security risk analysis methods has been implemented to achieve real-time perception and virtual–real interaction of multi-source information during the hoisting process, ensuring effective safety management and decision making [128]. (2) Additionally, conflicts between workspace and path that construction planners are unaware of have been revealed, which are used for facilitating BIM and VR to improve the configuration of the workspace in construction project site planning and

safety procedures defined in project safety plans [129]. (3) The visualisation for a safety management system that is developed using BIM, VR, and AR technologies allows workers to experience safety management processes through case scenarios on the construction site, and enables designers, engineers, and construction workers to visually assess site conditions for identifying potential hazards before the start of construction, eliminating or minimising on-site harm [58,140].

4. Perception of construction [130,131,137,138]: A concept called "digital skin" suggests that in the future ubiquitous construction site, digital skin could be composed of IoT-based sensors, actuators, and display systems, which provide various feedback and assistance to on-site tasks by integrating the obtained information [138]. Additionally, an interactive building anatomy modeling (IBAM) system has been developed based on VR and BIM technologies to provide students with a concrete learning experience in construction, which potentially improves building and construction education [131].

Table 5. ImTs-driven BIM in the construction stage (generated by the authors).

Category	Source	Year	Research Method	Research Topic
Construction management	Pan and Zhang [117]	2021	Modeling and case study	Smart construction project management using BIM and DT
	Pour Rahimian [132]	2020	Modeling	BIM construction monitoring system combining VR and machine learning
	Ratajczak et al. [133]	2019	Modeling	Location-based management system using BIM and AR
	Li et al. [95]	2018	Modeling, testing, and case study	IoT-enabled BIM platform in prefabricated construction
	Meža [118]	2015	Modeling, testing, and interview	AR in civil engineering
	Kwon et al. [119]	2014	Modeling and experiments	Construction defect management using BIM, image-matching and AR
	Wang et al. [134]	2014	Modeling	Construction process controlling for integrating BIM with AR
	Wang et al. [102]	2013	Modeling	Framework for integrating BIM with AR
	Park et al. [120]	2013	Modeling and testing	Construction defect management using BIM and AR
Construction aid tool	Kwiatek et al. [139]	2019	Experiments	Impact of AR and spatial cognition on assembly in construction
	Tavares et al. [135]	2019	Modeling	Collaborative welding system using BIM and AR
	Chalhoub and Ayer [121]	2018	Experiments and questionnaire	Electrical construction design communication using MR
	Fazel and Izadi [122]	2018	Modeling and case study	Constructing free-form modular surfaces using AR
	Chu et al. [123]	2018	Modeling, experiments, and questionnaire	Enhancing efficiency through the integration of BIM and AR systems
	Hou et al. [124]	2015	Experiments and questionnaire	Piping assembly training using BIM and AR
	Lin et al. [125]	2015	Modeling, testing, and questionnaire	A multiscreen environment for construction discussion using AR
	Gurevich and Sacks [126]	2014	Experiments and questionnaire	KanBIM system on subcontractors' task selections in interior works

Table 5. *Cont.*

Category	Source	Year	Research Method	Research Topic
Safety management	Dai et al. [127]	2021	Experiments and questionnaire	MR-enhanced safety communication on construction sites
	Liu et al. [128]	2021	Modeling and case study	Prefabricated building hoisting security management using DT
	Hou et al. [136]	2021	Literature review	DT applications in construction workforce safety
	Getuli et al. [129]	2020	Modeling and case study	Construction workspace planning using BIM and VR
	Guo et al. [59]	2017	Literature review	Construction safety management using visualisation technology
	Azhar [140]	2017	Case study	Visualisation technologies in safety planning and management
	Park and Kim [58]	2013	Modeling and case study	Construction safety management and visualisation system
Perception of construction	Lee and Lee [130]	2021	Modeling and case study	DT for supply chain coordination in modular construction
	Boje et al. [137]	2020	Literature review	Directions for future research in DT
	Edirisinghe [138]	2019	Literature review	Digital skin of the construction site
	Park et al. [131]	2016	Modeling, case study, experiments, and questionnaire	Experiential building construction education

3.2.3. Operations and Maintenance Stage

As indicated in Table 6, a total of 22 articles related to the operations and maintenance stage is listed. Most studies employ mixed research methods [28,49,141–156], followed by modeling [157–159] and literature review [78]. Regarding the research topics, applications in ImTs-driven BIM during the operations and maintenance stage can be categorised into four areas: asset and facility management, operations and maintenance of heritage buildings, environmental monitoring management systems, and operation and maintenance of security systems.

1. Asset and facility management [49,78,141–145,157]: Decision making in building assets and facilities requires the analysis and integration of different types of information and knowledge, such as maintenance records, work orders, causes of failures, and chain reactions. For asset and equipment management companies, a robust data system is becoming increasingly important for managing asset and facility data and recording ongoing facility changes [78]. The DT is the preferred choice for many studies on asset and facility management. For instance, a semi-automatic geometric DT method based on images and CAD drawings has been developed to support efficient and convenient modeling of existing buildings during the operation and maintenance stage [141]. Meanwhile, an intelligent asset management framework has been proposed to integrate AI, machine learning, and data analysis capabilities and incorporate the DT concept to create dynamic digital models and optimise usage processes [157]. In addition, a business dependency network has been integrated with DT to visualise the structure of multiple causal relationships, which is used to organise the functions, changes, and benefits that need to be considered before adoption [142]. Other studies collaborate with VR, AR, and other ImTs to improve user experience. In a MR framework for facility management, field workers use AR applications to collaborate with on-site office managers in immersive augmented virtual reality programs [143]. Additionally, a shared immersive experience for stakeholders using a

VR environment has been created to effectively communicate with detail in facility management [49]. To improve information retrieval, AR and automatic positioning have been integrated to provide visual auxiliary information for managers to manage facilities [144]. Furthermore, an environmental analysis has been visualised through mobile AR technology and associated information with objects at specific locations in an augmented display format [145].

2. Operations and maintenance of heritage building [146–148,158,159]: DT strengthens the connection between digital models and physical heritage assets, providing stakeholders involved in the heritage management decision-making process with more required and satisfied information [158]. There are three practices [146,148,158] that can be referred to the semantically rich HBIM models as digital 3D replicas with real-time operational data provided by on-site sensors through the IoT infrastructure. Additionally, a strategy of using advanced visualisation technologies based on AR and VR has been adopted as effective methods for preserving and accessing information [148]. Meanwhile, a VR for context-aware risk management of architectural heritage has been utilised [146]. To provide a better interactive experience, users have been allowed to fully immerse themselves in the scene and interact with it by using handheld devices for AR and VR [159]. Interestingly, while current DT-based solutions typically demand considerable budgets and time for creating 3D models, a practical alternative that leverages spherical panoramas to develop virtual tour environments has been presented for the researchers to obtain positive feedback upon testing this approach in a case study [147].
3. Environmental monitoring and management system [28,149–153]: Applications in environmental monitoring and management systems are similar to those in abovementioned asset and facility management, focusing on more specific niche areas, which include real-time comfort monitoring in buildings [149,152,153], visual inspections of structures [150], anomaly monitoring of building assets [28], and monitoring and management of parking environments [151], offering specialised application scenarios.
4. Operation and maintenance of security systems [154–156]: During the operation and maintenance process of buildings, security systems are an essential component. A study on the operation and maintenance of security systems has emerged year 2020 when a study utilised a system based on BIM and VR gamified scenarios to conduct pilot tests on simulated fire scenarios, aiming to achieve fire safety during the operation and maintenance [154]. BIM has been used to construct fire safety equipment (FSE) units, which enables FSE inspectors to quickly access and compile relevant information to generate a cloud database for equipment inspection and maintenance, thus achieving FSE inspection and maintenance and overcoming the limitations of paper documents for these tasks [155]. In addition, a DT-based indoor safety management system framework has been proposed to leverage IoT, BIM, Internet, and support vector machines (SVM) to enhance the intelligent level of building indoor safety management, in which the trained SVM model is used to process data within the DT management system to automatically obtain the type and level of hazards [156].

Table 6. ImTs-driven BIM in the operation and maintenance stage (generated by the authors).

Category	Source	Year	Research Method	Research Topic
Asset and facility management	Lu et al. [141]	2020	Modeling and case study	DT based on images and CAD drawings
	Lu et al. [157]	2020	Modeling	Smart asset management from BIM towards DT
	Love and Matthews [142]	2019	Modeling and case study	Engineering and asset management using digital technology
	El Ammari and Hammad [143]	2019	Modeling, case study, testing, and questionnaire	Facilities management using BIM and MR
	Baek et al. [144]	2019	Modeling, case study, and interview	Facility management using AR and image-based indoor localisation
	Wong et al. [78]	2018	Literature review	Facilities management and digital technology
	Shi et al. [49]	2016	Modeling and case study	Multiuser shared virtual environment for facility management
	Williams et al. [145]	2015	Modeling and case study	Efficient BIM translation to mobile AR applications
Operations and maintenance of the Heritage Building	Jouan and Hallot [158]	2020	Modeling	Research framework for architectural heritage using DT
	Lee et al. [146]	2019	Modeling, experiments, and interview	Risk management for architectural heritage using HBIM and VR
	Napolitano et al. [147]	2018	Modeling and case study	Conservation of cultural heritage sites
	Osello et al. [148]	2018	Case study and testing	Preserve architectural heritage using HBIM and virtual tools
	Albourae et al. [159]	2017	Modeling	Architectural heritage visualisation using HBIM and AR
Environmental monitoring and management system	Shahinmoghadam et al. [149]	2021	Modeling and case study	VR tool for real-time thermal comfort assessment using BIM and IoT
	Liu et al. [150]	2021	Modeling and experiments	Drone-based building inspection using BIM and AR
	Lu et al. [28]	2020	Modeling and case study	Built asset monitoring using DT
	Lin and Cheung [151]	2020	Modeling, case Study, and testing	WSN/BIM-based system for parking garages in smart cities
	Xie et al. [152]	2020	Modeling and case study	Visualised inspection system using DT and AR
	Zaballos et al. [153]	2020	Modeling and case study	DT-based smart campus for sustainable comfort monitoring
Operation and maintenance of security system	Chen et al. [154]	2021	Modeling, experiments, and questionnaire	BIM, IoT, and AR/VR technologies in fire safety and upskilling
	Chen et al. [155]	2020	Modeling, case study, experiments, and questionnaire	Inspection and maintenance of fire safety equipment using BIM and AR
	Liu et al. [156]	2020	Modeling and case study	Framework for an indoor safety management system using DT

3.2.4. Renovation and Demolition Stage

In the renovation and demolition stage, a total of six articles have been selected with leading research methods such as mixed methods [160–164] and modeling [165], as shown in Table 7. In terms of the number of articles, the renovation and demolition stage is significantly less than the other stages. Therefore, the applications in this stage are relatively simple, consisting of two types: renovation of building and demolition of building.

1. Renovation of building [160–163]: In the renovation work of buildings, studies focus on achieving effective communication among stakeholders while enhancing designers' perception and understanding of the on-site environment. The BIM4EEB rapid toolkit has been used to develop a DT-based BIM management system that connects to various stakeholders in the AEC domain and provides an interactive multifunctional toolkit [160]. Similarly, a hybrid representation tool has been provided for digital mock-ups to manage cultural heritage buildings [163]. In addition, an MR technology platform has been used to involve interested stakeholders in the evaluation of renovation design projects, thereby enhancing the renovation decision-making process and improving quality of the projects [161]. Furthermore, the use of BIM and MR technologies integrated with a background elimination method has been explored for collaborative design in the renovation process [162].
2. Demolition of building [164,165]: A conceptual framework for "smart" building demolition has been created to help maximise the utilisation of demolished waste through intelligent BIM, which not only achieves building demolition through three steps: scanning and measuring, building dismantling, and waste transportation, but it also allows the simulation of the demolition process by enabling DT-based BIM to detect possible defects before starting the demolition [164]. Additionally, a semantic-based building demolition model has been proposed to achieve the goal of "zero waste", which uses historical information, structural information, and material information of the building to develop optimised demolition plans and assess their environmental impact through rapid modeling and VR/AR technologies [165].

Table 7. ImTs-driven BIM in the renovation and demolition stage (generated by the authors).

Category	Source	Year	Research Method	Research Topic
Renovation of buildings	Daniotti et al. [160]	2022	Modeling and case study	Interoperable toolkit for efficient renovation in buildings
	Carbonari et al. [161]	2022	Modeling and experiments	On-site assessment of building renovation using MR
	Zhu et al. [162]	2020	Modeling, experiments, and questionnaire	Integrated co-designing using BIM and MR for stock renovation
	Nicolas et al. [163]	2013	Case study and experiments	Digital mockup for heritage buildings renovation using BIM and MR
Demolition of buildings	Kang et al. [164]	2022	Modeling and case study	Building demolition waste management using BIM, DT, and IoT
	Marino et al. [165]	2017	Modeling	Demolition waste becomes resources for reconstruction using VR and AR

3.2.5. Whole Lifecycle Stages

There are a total of 18 articles selected for the whole lifecycle stages, as shown in Table 8, which differs from other stages, with the use of literature reviews [20,166–169] and mixed method [8,18,23,61,170–174] which integrates qualitative and quantitative research to explore research problems and provide deeply comprehensive explanations and solutions. In addition, in whole lifecycle stages, the applications concern the full lifecycle DT model, full lifecycle BIM, and review and exploration.

Table 8. ImTs-driven BIM applications across whole lifecycle stages (generated by the authors).

Category	Source	Year	Research Method	Research Topic
Full-cycle Digital Twin (DT) model	Teisserenc and Sepasgozar [170]	2021	Literature review and modeling	Adoption of blockchain through DT in the Industry 4.0
	Lee et al. [61]	2021	Modeling and case study	Information sharing framework using DT and blockchain
	Yitmen et al. [171]	2021	Modeling and questionnaire	Adapted model for building lifecycle management using DT
	Tagliabue et al. [172]	2021	Case study	Sustainability assessment of an educational building using DT
	Peng et al. [94]	2020	Case study	DT hospital buildings
	Kaewunruen et al. [175]	2020	Case study	DT-aided audit for subway stations
Full-cycle BIM model	Alizadehsalehi et al. [8]	2020	Review and case study	BIM and XR
	Kaewunruen and Lian [27]	2019	Modeling	Sustainability-based lifecycle management using DT
	Wang et al. [173]	2014	Modeling and testing	BIM-based VR for fire emergency evacuation
	Jiang et al. [166]	2021	Literature review	DT and its implementations in the civil engineering sector
	Opoku et al. [20]	2021	Literature review	DT application in the construction industry
	Sepasgozar [167]	2021	Literature review	Smart and sustainable built environment
	Sidani et al. [168]	2021	Literature review	Recent tools and techniques of BIM-based VR
	Zhang et al. [23]	2020	Mixed	Virtual reality applications for the built environment
	Davila Delgado et al. [18]	2020	Mixed	AR and VR in architecture, engineering, and construction
	Davila Delgado et al. [174]	2020	Mixed	Drivers and limitations of AR and VR in architecture
	Cheng et al. [169]	2019	Literature review	MR applications in the AECO industry

1. Full lifecycle DT model [61,94,170–172,175]: The possibilities of the integration of blockchain technology with DT have been explored to increase information trust, security, decentralisation, efficiency, traceability, and transparency throughout the project lifecycle [61,170]. However, the integration of intelligence and cognition with DT may indeed yield a paradigm-shifting potential in technological advancements [94,171]. Consequently, a novel paradigm for DT has been proposed to encompass AI and Machine Learning to tackle unresolved challenges [171]. In addition, a DT software system with real-time visualisation management and AI diagnostic modules has been developed and deployed to allow managers to grasp the detailed status of the entire hospital through visualisation management and receive timely facility diagnostics and operational suggestions [94]. Interestingly, a transition from static sustainability assessments to dynamic methodologies predicated upon DT and bolstered via IoT has been set up to facilitate decision-making processes pertinent to sustainability throughout the entire building lifecycle [172]. Furthermore, a parallel approach has been implemented to amalgamate information from various stages of the project lifecycle into a singular DT model, while intending to foster enhanced asset management and facilitate communication among stakeholders via data visualisation [175].

2. Full lifecycle in BIM [8,27,173]: An extended reality (XR) including VR, AR, and MR has been integrated into a full lifecycle BIM model to allow all the AEC stakeholders to access and analyse data at any stage of the project, thereby empowering experts to discern distinct scenarios across diverse project stages and devise suitable strategies accordingly [8]. Furthermore, the world's first 6D BIM has been established and analysed for a railway turnout system in lifecycle management including 4D construction sequencing information, 5D cost information, and 6D project lifecycle management information, which improves the overall information flow for turnout planning and design, manufacturing pre-assembly and logistics, construction and installation, operation and management, and demolition, leading to better project performance and quality [27]. Intriguingly, a series of games has been amalgamated with BIM to engender a highly adaptive VR environment, targeting the enhancement of fire evacuation planning throughout the building lifecycle [173].
3. Review and Exploration [18,20,23,166–169,174]: The ImTs within the realm of AEC have been explored in reviews [23,168,169], whilst other reviews [20,166,167] focus on current definition and application level of DT in the construction industry. In addition, a series of exploratory workshops and questionnaires has been employed to lay out a research roadmap on AR and VR within the construction domain [18]. Furthermore, eight focus groups consisting of 54 experts and online surveys have been conducted for identifying four types of limiting factors and four types of driving factors to provide valuable insights for stakeholders [174].

4. Discussion

4.1. Research Hotspots and Development Trends of ImTs-Driven BIM

In the lifecycle of buildings, the construction of a digital world that can interact bidirectionally with the physical world has triggered an unprecedented revolution in the field of ACE [22]. The results of Section 3.1.2 suggest that AR, VR, and DT have become hot topics in the BIM field, which will be key to building an AEC metaverse. The AEC industry currently is anticipating to transition from a traditional physical-space-focused model to a primarily digitally oriented one, employing metaverse technologies to facilitate the digitisation and intelligent integration of various processes, including architectural design, construction, management, and operation [176].

The results in Table 5 in Section 3.1.3 indicate that the year 2021 is recognised as a groundbreaking year to ImTs-driven BIM, which is mainly reflected in two aspects:

1. Technological focus: from year 2018 to 2020, the technologies in ImTs-driven BIM approaches underwent an iterative process, evolving initially from AR to VR and then to MR. Especially, in year 2021 and 2022, a number of advanced technologies and tools began to emerge in ImTs-driven BIM applications, such as UAV, GIS, AI, blockchain, and deep learning. The integration of these advanced technologies and tools provides more excellent development opportunities for ImTs-driven BIM.
2. Research concepts: from year 2018 to 2020, few cutting-edge concepts appeared, with the focus primarily on specific applications, such as digital construction and project management. From 2021 onward, several advanced concepts began to be widely researched, including 4D BIM, smart cities, Industry 4.0, Construction 4.0, and the circular economy.

Although there are no specific studies exploring the reason for the groundbreaking year 2021, industry trends and policies illustrate its distinctiveness. In year 2021, tech giants such as Meta, Microsoft, and NVIDIA began to lay out plans for the metaverse [177]. Simultaneously, the year 2021 has been marked as the beginning of China's 14th Five-Year Plan, in which China announces strategic objectives such as accelerating the construction of Digital China, smart society, and new urbanisation, offering more policy supports and market opportunities for the construction industry [178].

Since integrating BIM with various ImTs is fundamentally transforming how the buildings will be designed, built, operated, and monitored [8], future research trends will gradually shift towards the convergence of BIM with ImTs, and more advanced technologies and tools, with an increasing emphasis on smart cities and Construction 4.0. Consequently, exploring the building metaverse through new technologies and concepts to create an exciting digital world and to construct a better physical world is a promising endeavour [179].

4.2. Challenges of Immersive Technologies (ImTs)-Driven Building Information Modeling (BIM) Applications

The results of the micro-qualitative analysis in Section 3.2 reveal that modeling, case study, and mixed research method with modeling and case study are the three most-used research methods across building lifecycle stages, which have helped to produce various research findings and applications at each stage of the building lifecycle. However, the vast number of publications generated with relatively independent and dispersed content makes difficulties for systematically understanding the challenges faced by the mainstream of research directions at each stage of the building lifecycle [8,18,23]. Therefore, it is essential to explore the challenges of ImTs-driven BIM applications throughout all the stages of the building lifecycle.

4.2.1. Design Stage

The results of Section 3.2.1 suggest that collaborative work and improved user experience are the two main themes of ImTs-driven BIM applications in the design stage. Using collaborative 4D tools for simulation planning and constructability analysis is a significant application method for collaborative work [106]. However, studies point out that adapting collaborative 4D tools to actual needs of practitioners is a challenge that collaborative work should face directly [180,181]. Consequently, Boton highlights this as a particularly important issue that future studies need to specify interaction methods to feed collaboration results back into 4D models [106]. Similarly, a number of ImTs applications also face various user experience issues. For example, Lin et al. suggest to use a semi-immersive approach to reduce digital motion sickness of users in VR environments [107]. Additionally, Cha et al. focus on spatial perception of participants in different virtual environments for further exploring of the user experience [109]. In studies related to improving user experience, Motamedi et al. [110] and Shen et al. [111] adopted a novel approach for user activity simulation for evaluation at the design stage. This application and practice generate more improvement suggestions, aiming to achieve more efficient iterations of design solutions.

4.2.2. Construction Stage

The results in Section 3.2.2 show that the construction stage is a crucial application stage to ImTs in BIM domain, with a rich variety of studies. Although there are many types of ImTs-driven BIM studies in the construction stage, the challenges revealed by these studies are similar. Firstly, the most prominent challenge lies in the current limitations of the devices, such as the overly narrow field of view, cumbersome wearing experience, and internet connection quality [121,127]. Secondly, many detailed issues need to be addressed in the applications. The retrieval and export of various information from projects that contain large amounts of BIM information consume significant computational power [182], whilst during the model conversion steps, information is prone to be lost [148]. Since safety risk management struggles to keep up with the dynamics information of construction sites, the lack of real-time information exchange leads to difficulty in establishing effective information integration and sharing mechanisms [128]. Additionally, 3D building models and real objects often have alignment errors in practical applications, meaning that the model does not always perfectly overlay the actual building, with deviations ranging from approximately 0.4 to 1 m [133,136]. Therefore, studies still need to be completed to increase efforts in model alignment, including adapting to occlusions, clutter, lighting, and scale changes [183].

Aside from technical issues, Chu et al. point out that the implementation of BIM forces on-site workers to increasingly receive amounts of information, which may hinder their decision making and productivity [123]. Hence, how to customise these vast amounts of information at a low cost to accommodate various tasks in construction will be a significant challenge at the construction stage. In addition, current experiments are conducted in controlled environments rather than active real-world on-site job situations [121]. As such, on-site workers may hesitate to abandon traditional construction drawings in favour of new visualisation methods [121].

4.2.3. Operations and Maintenance Stage

The results of Section 3.2.3 (Table 6) indicate that DT is a widely investigated research direction during the operation and maintenance stage. In addition, DT-assisted operation and maintenance management has been proven to be an effective method [141]. For the intelligent asset management that associates DT with BIM, Lu et al. comprehensively summarised the limitations and gaps of current research and standards for developing a smart asset management in the operation and maintenance stage in terms of technology, information, organisation, and standards [157]. However, the results of the micro-qualitative analysis to the operation and maintenance stage in this paper suggest that a number of studies believe that it is currently a significant challenge to monitor each asset in complex building systems as finely as possible within certain budget constraints [28,149,151,154].

Comparing traditional education to building operation and maintenance, Zaballos et al. focused on the comfort of the educational environment in operation and maintenance [153]. Zomorodian et al. believe that the comfort of the educational environment is a critical factor in providing efficiency and promoting social progress in school [184]. However, the current Information and Communication Technology (ICT)-based comfort monitoring and recommendations are one-sided [185], which either have not been adjusted through a large number of internal and external parameters or only focus on qualitative research on local comfort due to a lack of a cost-effective technical paradigm [185].

4.2.4. Renovation and Demolition Stage

The results in Section 3.2.4 reveal that the ImTs-driven BIM applications in the renovation and demolition stage are the least among all the stages. Although Li et al.'s study confirms that eight advanced technologies are currently used in the demolition stage [186], they have not explained why ImTs-driven BIM applications are scarce. Interestingly, the studies carried out by Kang et al. [164] and Marino et al. [165] found that applications dominated by DT, AR, and VR have advanced significantly in the demolition stage. Similarly, ImTs-driven BIM applications have also received effective feedback in the renovation process, which is consistent with some current studies [160–163]. Due to the small number of relevant applications, it is unclear what challenges ImTs-driven BIM applications currently face in the renovation process. However, a number of studies have expressed expectations and trusts in facilitating DT, AR, VR, and MR with BIM during the renovation and demolition stage. For example, Kang et al. believe that simulating the demolition process of a building using DT and BIM technologies can make demolition planning less laborious and without being limited by the knowledge and experience of project managers [164]. Additionally, Carbonari et al. suggest that the integrated application of BIM and MR is expected to lead to a more sustainable design process by reducing the needs for rework in renovation projects and reducing greenhouse gas emissions [161].

5. Conclusions

This paper adopts a mixed research method to quantitatively and qualitatively explore the hotspots, current situation, research trends, and challenges of ImTs-driven BIM in the context of the metaverse. The main contributions of this paper are as follows:

1. In terms of research methodology, this is the first attempt to combine macro-quantitative bibliometric analysis and micro-qualitative analysis methods to explore the research

topic of ImTs-driven BIM. This study obtains 758 related studies in the past decade (year 2013 to 2022) through a series of keywords from the WoSCC database and uses VOSviewer software to conduct keywords co-occurrence analysis and overlay visualisation to visualise the relationship between ImTs and BIM. The macro-quantitative analysis on ImTs-driven BIM applications throughout all the stages of the building lifecycle reveals the themes, content, and characteristics of the applications across the stages.
2. In terms of research technique, based on the bibliometric visualisation tool VOSviewer, this study reveals the hotspots and research trends of ImTs-driven BIM applications from year 2013 to 2022, which contains six clusters, namely VR, IoT, DT, 3D model, design, and AR.
3. In terms of research content, compared with existing research, this study comprehensively analyses the current situation of ImTs-driven BIM applications across lifecycle stages of the building via micro-qualitative analysis and with main research directions for each stage, which is in the context of the metaverse that can be used to construct a BIM-based building metaverse.
4. This study identifies the future research hotspots and development trends of ImTs-driven BIM that tend to be integrated with emerging advanced technology and tools, such as AI, blockchain, and deep learning. Additionally, the current challenges faced by ImTs-driven BIM throughout stages of the building lifecycle are determined, which are multifaceted and have various characteristics and goals in each of the stages.

Hence, this paper provides valuable information and inspiration for researchers, designers, and developers in related fields for better understanding of the development status and future trends of ImTs-driven BIM. However, this study has certain limitations. Although this study has merged a large number of synonymous keywords in the retrieval process, in which manual merging is challenging to cover all synonymous keywords due to the enormous number of retrieved articles, different studies may use different keywords to express the same meaning, which may lead to a slight bias in the keyword data results analysed using VOSviewer. Since the data obtained for the bibliometric analysis have been collected from WoSCC database, other databases may contribute to the topic. Therefore, future research could consider expanding the analysis to other databases, such as IEEE Xplore and Scopus, to provide a more comprehensive understanding of the development trends and latest achievements of ImTs-driven BIM.

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