2025 European Conference on Computing in Construction

CIB W78 Conference on IT in Construction

Porto, Portugal
July 14-17, 2025

ENHANCING COLLABORATION IN THE PROJECT LIFECYCLE: ADDRESSING BIM-BASED VR CHALLENGES AND BARRIERS

Fujia Lyu[1], Grant Mills[1], and Weiwei Chen[1,2*]

[1] The Bartlett School of Sustainable Construction, University College London, London, WC1E 6BT, UK

[2] Engineering Department, University of Cambridge, Cambridge, CB3 0FA, UK

Abstract

Building Information Modeling (BIM) and Virtual Reality (VR) integration offers significant potential to enhance collaboration throughout the AECO project lifecycle. However, practical implementation faces challenges, including equipment constraints, technical limitations, user experience issues, and policy gaps. This study systematically reviews 36 articles, classifying these barriers and identifying key challenges and future directions in this area. The findings highlight interaction and interoperability as critical challenges, with future research needed in real-time multi-user collaboration, automated BIM-VR data synchronization, and user-friendly systems. Addressing these gaps will maximize the potential of BIM-based VR, fostering effective multidisciplinary collaboration and innovation in the AECO industry.

Introduction

The lifecycle of a building project consists of several phases, including design, planning, construction, operations, and maintenance (Olanrewaju et al., 2022; Eadie et al., 2013; Azhar, 2011). Throughout these phases, complex multidisciplinary collaboration and large-scale data exchange are required (Muthumanickam et al., 2023; Alreshidi et al., 2018; Singh et al., 2011). Building Information Modeling (BIM) has emerged as an important tool in this regard, offering significant benefits in optimizing collaboration, increasing efficiency, and reducing errors (Kelly and Ilozor, 2019; Kassem et al., 2015; Liu et al., 2014; Lu and Korman, 2012). It supports policies and industry standards in many countries (Hamma-adama and Kouider, 2019).

BIM's specialized nature, coupled with the complexity of multidisciplinary collaboration throughout the project lifecycle, has posed a significant challenge to effective engagement (Chen and Laokhongthavorn, 2024; Zaker and Coloma, 2018). This challenge is particularly evident in large and complex projects, such as healthcare and other social infrastructures, where BIM alone does not enable effective visual communication (Okada et al., 2017).

BIM-based VR refers to the integration of Building Information Modeling (BIM) with Virtual Reality (VR) to enable immersive, interactive, and data-driven environments across the entire project lifecycle. Rather than treating BIM and VR as separate tools, BIM-based VR creates a unified platform where stakeholders can engage with building information in real time, improving communication, coordination, and decision-making. As a result, an increasing number of studies have explore the application of BIM-based VR to enhance collaboration through real-time communication and coordination among stakeholders, boosting decision-making and efficiency (Buchanan et al., 2023; Noghabaei et al., 2020; Ahmed, 2018). BIM-VR has the potential to streamline spatial planning and information sharing, potentially facilitating a smoother exchange of ideas (Potseluyko et al., 2022; Getuli et al., 2020; Lin et al., 2018). It also guides processes, optimizes management, and improves safety, ensuring seamless teamwork (Safikhani et al., 2022; Schiavi et al., 2022b; Wu et al., 2020). Collaboration is facilitated by improved communication, reduced misunderstanding, and supported decision-making processes. However, there are practical implementation challenges (Huynh-Dagher et al., 2022; Khan et al., 2021).

Existing studies predominantly focus on isolated aspects, such as technical solutions validation. These include interface design (Dinis et al., 2023) and software development (Schiavi et al., 2022a) etc. There are also unique areas for implementation, such as education (Elgewely et al., 2021), historic buildings (Stanga et al., 2023) and energy (Shahinmoghadam et al., 2021), which have unique complexities and barriers. While many studies acknowledge the gap between theoretical advancements and practical applications, discussions of collaboration-related challenges are often fragmented and treated as secondary to other research objectives. Few studies offer a focused and systematic examination of how these challenges emerge and affect collaborative processes across the AECO lifecycle when implementing BIM-based VR technologies. Therefore, a clear research gap remains in the structured exploration of collaboration-specific issues within this context.

This study aims to systematically review the implementation of BIM-based VR technology, focusing on challenges and barriers during the AECO (Architecture, Engineering, Construction and Operation) collaborative process. It seeks to enhance the understanding of existing problems, facilitate their resolution and maximize the potential of BIM-based VR integration to improve collaboration in the project lifecycle.

Methodology

In this study, a Systematic Literature Review (SLR) approach will used to define the research question in conjunction with Kitchenham and Charters SLR (Kitchenham and Charters, 2007) framework. In addition, a PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) process is applied to ensure transparency, consistency, and methodological rigor throughout the literature selection and screening stages (Page et al., 2021).

Following the Kitchenham framework, several sub-research questions as explored:

- SRQ1: How are collaboration challenges in BIM-based VR implementation categorized, and which category is most frequently reported in existing studies?
- SRQ2: During which project activities do these challenges arise, and which stakeholders are most directly affected?
- SRQ3: What future research directions have been proposed to address collaboration challenges in BIM-based VR implementation?

Eligibility Criteria

Inclusion criteria:

- The paper investigated the use of BIM-based VR technology in AECO, specifically in building projects.
- Studies published in ten years, from 2014-2024.
- The paper being analyzed is a research paper or proceeding/conference.

Exclusion criteria:

- The paper is not using English.
- Same paper from different database.
- Not Open-Access.
- Not focused on BIM-based VR.

Search Strategy

The bibliographic search focused on 5 scientific databases: Web of Science, IEEEXplore, SCOPUS, ScienceDirect, Springer. To enhance the efficiency of literature retrieval, three primary keywords were identified and expanded using proximity-based Boolean operators to construct comprehensive search queries: ("BIM" OR "Building Information Modeling") AND ("VR" OR "Virtual Reality" OR "Immersive technologies" OR "Immersive Environment") AND ("Collaboration" OR "Collaborative" OR "Multi*" OR "Co-" OR "Communication" OR "Coordination" OR "Stakeholder engagement").

The search terms were chosen based on a review of literature that identifies key aspects of collaboration in the AEC&FM industry. Terms like "coordination", "stakeholder engagement", "multi-user" frequently appear in studies exploring teamwork and collaboration in BIM and VR contexts (Johansson and Roupé, 2024; Khorchi and Boton, 2024; Astaneh Asl and Dossick, 2022; Davila Delgado et al., 2020).

The first stage of the search strategy was to retrieve data from the database by entering keywords and covering as many of the eligibility criteria as possible using the database's advanced search tools. After collecting data from multiple repositories, studies unrelated to the built environment and duplicates were excluded. Then, search keywords such as education, historic buildings, smart cities, etc., in the title and abstract. Articles not focused on buildings' AECO process were excluded. Finally, by reading the abstracts as well as the full text, articles that could not be accessed in full, as well as those that did not focus on BIM and VR technologies, were eliminated. The specific screening process can be found in Figure 1 PRISMA 2020 flow diagram.

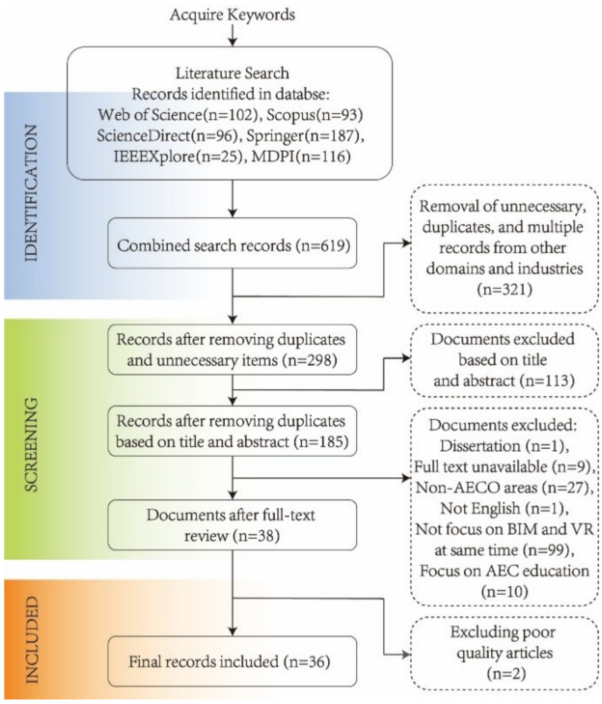

Figure 1: PRISMA search flow

Result Analysis

Initially, 619 articles were searched using the previously mentioned and established Boolean expression (Web of Science (n=102), Scopus (n=93), ScienceDirect (n=96), Springer (n=187), IEEEXplore (n=25), MDPI (n=116)) Removal of duplicate articles and completely irrelevant articles reduced the search results to 298 articles. Subsequently, 185 articles were screened based on titles and abstracts and re-screened based on inclusion and exclusion criteria. Of these, 149 articles were excluded, and 36 were finally precision and synthesized.

Statistical Analysis

Scientometric analysis was used to identify journal sources that published research on BIM-based VR for collaboration during the AECO process.

The 36 articles were analyzed based on their publication years (Figure 2). There is a significant growth trend in the number of publications during this decade, with major studies peaking in 2022. Although there is a decline in the number of publications between 2023 and 2024, this may indicate a stabilization in the field, where research focus has shifted from quantity to depth, emphasizing the quality and practical application of BIM and VR integration. The articles were published across 20 journals, the most frequent being Automation in Construction and Buildings, accounting for 13.8% of the total publications. Table 1 provides mathematical statistics of citation indicators to assess the quality of the selected literature.

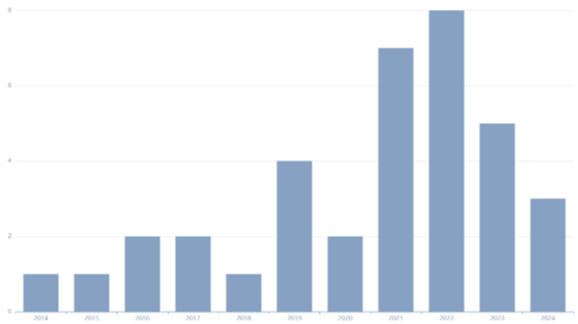

Figure 2: Number of publications 2014-2024

Table 1: Citation metrics of selected articles

Statistic	Value
Mean	48.8
Median	27
Standard Deviation	52.7
Minimum	3
Maximum	199
Count	34

For all the literature screened and analyzed, the average citation count was 49, with a median of 27. This suggests that the selected papers are relatively highly cited and have considerable relevance or impact in the field of study.

In order to summarize the barriers and challenges found in the literature, the articles were first classified according to the question "*Do they present and address specific challenges and barriers during collaborative*?". 16 articles explicitly respond to problems and propose solutions, while 20 articles do not provide clear explanations. The results will be analyzed in detail in the following two subsections.

Collaborative Challenges in Non-Solution-Focused Articles

This group of articles focuses primarily on theory and practice and includes technical surveys, case studies, theoretical discussions, and literature reviews. Most of these articles describe existing collaboration challenges in the discussion section, but do not propose concrete solutions to address these challenges. Drawing from the comprehensive discussions in these articles, this section categorizes the implementation challenges into a general framework for analysis.

The challenges associated with the implementation of BIM-based VR in collaborative processes can be broadly categorized into 4 categories: 1) equipment constraints, 2) technical limitations, 3) user experience and interface concerns, and 4) policy and standardization gaps. The summarized classifications are collected and explained in Table 2.

Challenges and barriers in BIM-based VR applications span multiple domains, with equipment constraints being one of the factors. The performance and functionality of hardware often limit the capacity to handle complex models, and accessibility issues arise due to the high cost and scarcity of advanced devices (Safikhani et al., 2022; Khan et al., 2021). Additionally, technical constraints, such as the integration of BIM-based VR with advanced technologies, pose difficulties in managing large and complex datasets (Schiavi et al., 2022b; Davidson et al., 2020). Interaction and interoperability issues between various software platforms and devices further hinder seamless collaboration (Khan et al., 2021). From a user-centric perspective, problems with user experience and interface, including VR-included discomfort, limited immersion, and unintuitive designs, negatively impact adoption (Khan et al., 2021). Policies and standards also play a role, as the lack of comprehensive guidelines for system compatibility and data workflows creates additional obstacles (Schiavi et al., 2022b).

Researchers have identified several future directions to address challenges in BIM-based VR applications. Enhancing VR hardware is crucial to support longer usage durations and ensure compatibility with conventional computers, enabling more effective onsite activities such as construction monitoring and operations. On the technical side, optimizing data visualization and transfer processes will streamline model adaptation, while incorporating complex VR validation scenarios will better reflect real-world implementation challenges. Additionally, integrating advanced digital technologies such as 5G and IoT can enhance accuracy and efficiency in BIM-based VR workflows. From a user experience perspective, improving the realism of virtual environments will enhance immersion, while addressing disorientation issues in large-scale scenarios will help users navigate more effectively. Furthermore, expanding control elements will enhance interaction, leading to more efficient communication and collaboration. Finally, establishing standardized workflows and integrating systems will facilitate seamless coordination among multiple users, ultimately maximizing the potential of BIM-based VR technology.

Table 2: Category of Challenges and Barriers in Collaborative Process

Classifications	Category Description
Equipment constraints	
Equipment capabilities	Performance or functionality of hardware
Accessibility and availability	Challenges in obtaining or deploying necessary equipment
Technical constraints	
Advanced technology integration	Combining BIM-based VR with cutting-edge technologies
Data processing and transmission	Managing large and complex datasets
Interaction, interactivity and interoperability	Technology-induced challenges between users and systems, software platforms and devices
User experience and interface	
User experience	Factors affecting user satisfaction
User interface	Design issues that hinder intuitive operation or accessibility
Policies and standards	Regulatory, industry, or organizational guidelines that create constraints

Solutions to Collaborative Challenges: Analysis and Future Directions

This group of articles focused on technical development and validation, such as conception, framework, protocol, model, or hardware development. These studies identify specific issues affecting collaboration, propose targeted solutions, and outline future research directions based on their proposed solutions. Therefore, this section focuses on the problems, their corresponding solutions and the problems that still exist. Compared to the previous section, this section's discussion of the challenges and future directions is more detailed and grounded due to the availability of prior research and is more focused, providing a clearer framework for further exploration.

From the literature (Table 3), technical issues are most explored. Specifically, in relation to interaction (e.g. user interface, tools), interoperability (e.g. BIM-to-VR conversion, data transfer, metadata), and interactivity (e.g. multi-user), see for example Johansson and Roupé, (2024). A lack of solution orientation has meant that systems, frameworks, and platforms are often hypothesized with limited testing. As such, limitations remain and further testing is often needed. Vincke et al., (2019) for example, it explores the variety and complexity of data formats and packages and embeds datasets in open API platforms, such as those provided by game engines. However, data sets are only partially implemented using a proof-of-concept for embedding multiple data types in a virtual environment.

One of the most mentioned issues is interoperability. The bidirectional interaction of BIM and VR data has been a research topic throughout the past decade. Some research progress has been made by building new frameworks and systems and with the help of OPEN-BIM to address the data transfer problem, timeliness, etc. (Wang and Tung, 2023; Khairadeen Ali et al., 2021; Pour Rahimian et al., 2019; Kieferle and Woessner, 2015). However, limitations in breadth, data uses, and the limited scope of data transfer at a large scale persist, such as data loss and user operation problems. Recent research on interoperability includes three key studies, among which the work by (Rostamiasl and Jrade, 2024) stands out for its development of a semi-automated model. This model allows users to modify the VR environment, with any changes automatically reflected in the 3D BIM model of the proposed houses. However, not all design components can be converted into Revit, which restricts seamless integration, and the automation process is one-directional. While modifications made in VR are automatically updated in the BIM model, changes in the BIM model still require manual updates. To address this, a fully automated, bidirectional connection between Revit and game engines enables real-time synchronization of changes in both environments and enhances the efficiency and usability of BIM-VR workflows.

Khorchi and Boton (2024) proposed an OPEN-BIM-based approach to support 4D collaboration in VR, featuring a module for inputting collaboration data, such as comments and screenshots, using the BCF format. However, their study identified several limitations, including discomfort during VR use, a lack of tutorials for new users, difficulty testing different scenarios, an underdeveloped user interface, and reliance on speech-to-text functionality. The authors recommend future research to implement modifiable fields linked to an XML file with read/write capabilities and improve 3D rendering quality, including lighting and textures, to enhance realism and usability.

Johansson and Roupé (2024) introduced a multi-user VR system for visualizing large, complex BIMs. It features functionalities like efficient IFC import, property-driven filtering, and precise distance measuring. It was tested across eight real-world construction projects to demonstrate its practicality. Despite promising results, there were limitations in participant selection and hardware technology. The authors suggest that untethered, standalone VR devices could simplify integration into daily construction use by removing the need for a PC, and strategies and algorithms for efficient large-model rendering could enhance usability.

Table 3: Summary of challenges and solutions

Challenges and Barriers	Solution Provided	Publications
Equipment constraints		
Equipment capabilities		
1. Shared virtual environment introduces challenges regarding limited human locomotion and interaction, due to physical constraints of normal room spaces.	YES	(Keung et al., 2021)
Technical constraints		
Data processing and transmission		
1. Different data format and multiple software packages	YES	(Vincke et al., 2019)
2. Data synchronization issues between the BIM model and the virtual environment	YES	(Khairadeen Ali et al., 2021)
3. Data cannot be automatically interacted with in both directions	YES	(Kieferle and Woessner, 2015)
Interaction, interactivity and interoperability		
1. Current software do not allow model revision and update parameters to be imported into BIM (for cost estimate)	YES	(Wang and Tung, 2023)
2. Multi-disciplinary collaboration and complex visualization for collaboration	YES	(Dossick et al., 2015)
3. No possibility for users to do fully interactive, collaborative 4D definition sessions	YES	(Tallgren et al., 2021)
4. Lack of automation interaction, lack of direct engagement with users and their specific needs	YES	(Rostamiasl and Jrade, 2024)
5. Lack of bidirectional link between BIM tools and VR environments specifically in 4D process; limitation of interoperability between VR and other non-immersive collaboration solutions	YES	(Khorchi and Boton, 2024)
6. Current BIM-VR not been quite advanced in supporting interoperability and collaboration, immediacy and latency problem	YES	(Pour Rahimian et al., 2019)
7. Need to have a collaborative virtual environment share a group of geographically remote stakeholders can interact and communicate effectively in real-time	YES	(Prabhakaran et al., 2022)
8. Efficient integration, such as rendering performance and interoperability issues	YES	(Johansson and Roupé, 2024)
User experience and interface		
User experience		
1. Reorientation is required when walking in large virtual spaces due to the limited nature of real space	YES	(Kunz et al., 2016)
User interface		
1. Current BIM+VR solutions are powerful but overly complex, lacking user-friendly tools for quickly adjusting construction properties	YES	(Podkosova et al., 2022)
2. Users with no prior advanced training and the necessary hardware are limited in what they can view and achieve with current package	YES	(Potseluyko et al., 2022)
Policies and standards	YES	
1. Lack a prescriptive and structured process to drive the effective use of this technology in collaborative meeting and decision-making process	YES	(Mastrolembo Ventura et al., 2020)

These articles have not explicitly discussed or addressed issues related to "accessibility and availability" and "advanced technology integration" in all the aforementioned categories.

Discussion

The following discussion revisits the sub-research questions, interpreting the findings within their context.

Classification of Collaboration Barriers and Challenges

The barriers and challenges of collaboration in BIM-based VR can generally be categorized into four broad areas: equipment constraints, technical constraints, user experience and interface, and policies and standards. Over the past decade, research in this field has been evenly divided between two focuses: theoretical and practical explorations that clarify current collaborative challenges and future research directions, and solution-driven studies addressing specific issues in collaborative processes. Notably, the latter group of studies tends to better reflect the practical priorities and future trends in BIM-based VR collaboration research. The review highlights that the most frequently mentioned challenge category is 'Interaction, Interactivity, and Interoperability', falling under technical constraints. Recent studies within this category primarily focus on multi-user remote collaboration and improving interoperability between BIM and VR platforms. Additionally, 'Data Processing and Transmission', another technical constraint, emerges as the second most frequently discussed issue. This includes challenges such as synchronizing data between BIM and VR and achieving automatic bidirectional linking. These data-related challenges are closely tied to the broader issues of interaction and interoperability, emphasizing their interconnected nature.

Identification of Activities and Key Stakeholders

According to (Schiavi et al., 2022b), VR/AR application can be categorized as Operation Onsite, Safety and Risks Prevention, Construction Management, Maintenance, Quality Control, Design Review, Cost Measurement, Simulation, Logistics, Sustainable Design Processes. Among all solution-oriented articles, the most described activity was design review, followed by construction management. The reason why these two collaborative activities appear most, is because they both involve multiple stakeholders with diverse expertise and perspectives. Design review requires input from architects, engineers, contractors, and clients to ensure the design meets functional, aesthetic, and regulatory requirements, creating complex communication and decision-making dynamics. Similarly, construction management involves coordination across teams for scheduling, resource allocation, and risk management, making collaboration essential to avoid delays, cost overruns, and inefficiencies. Therefore, the people mentioned above are also the most affected stakeholders in the collaborative challenge when implementing BIM-based VR technology.

Recommendations for Future Research Directions

The future development of BIM-based VR systems should concentrate on overcoming several key challenges that have been highlighted in previous research. These challenges include improving interaction, enhancing interactivity, ensuring interoperability, and optimizing data processing and transmission. To effectively tackle these issues, future research should emphasize advancing multi-user remote collaboration, which would allow stakeholders located in different regions to engage and collaborate seamlessly within a shared virtual environment. Achieving this goal will require the creation of more robust and low-latency systems that enable users to interact with BIM models in real-time without interruptions or delays. Furthermore, integrating these systems with affordable VR devices capable of handling larger, complex BIM models is essential for wider adoption as VR technology becomes more prevalent. Another critical area for development is the establishment of automated bi-directional links between BIM software such as Revit and platforms like game engines. Advancing these integrations will streamline workflows, improve efficiency, and enhance interoperability between various software tools, ultimately enabling smoother collaboration and project execution across the construction and design sectors.

Conclusions

This study provides a comprehensive systematic review of BIM-based VR integration within the AECO industry, especially in building area, and focusing on the challenges and barriers in collaborative processes. The research identifies key issues categorized into four domains: equipment constraints, technical limitations, user experience and interface concerns, and policy and standardization gaps. Among these, the challenges associated with interaction, interactivity, and interoperability are most frequently highlighted, reflecting their critical role in successful collaboration. Additionally, the review highlights a gap in automated, bidirectional BIM-based VR interoperability and remote multi-user interaction, emphasizing the need for future research to address these deficiencies.

While this review offers valuable insights, it is not without limitations. First, the use of only open access literature may have introduced selection bias by excluding potentially relevant paywalled studies, limiting the comprehensiveness of the review. Second, this study is based solely on secondary data and does not incorporate empirical validation through interviews, case studies, or surveys, which could strengthen the practical applicability of the findings. Future work could address these limitations by including subscription-based studies and validating findings through empirical research such as case studies or interviews. By systematically addressing these challenges, the AECO industry can unlock the full potential of BIM-based VR, fostering more effective collaboration and driving innovation in project design, construction, and operations. The study contributes to the ongoing discourse by offering a structured analysis of existing barriers and providing actionable recommendations for overcoming them.

Acknowledgments

This study was supported by the EU-funded INHERIT project (Project ID: 101123326): Next Generation Solutions for Sustainable, Inclusive, Resource-efficient and Resilient Cultural Heritage.

References

Ahmed S (2018) A Review on Using Opportunities of Augmented Reality and Virtual Reality in Construction Project Management. Organization, technology & management in construction : an international journal 10(1). DeGruyter i Građevinski fakultet Sveučilišta u Zagrebu: 1839–1852.

Alreshidi E, Mourshed M and Rezgui Y (2018) Requirements for cloud-based BIM governance solutions to facilitate team collaboration in construction projects. Requirements Engineering 23(1): 1–31.

Astaneh Asl B and Dossick CS (2022) Immersive VR versus BIM for AEC team collaboration in remote 3D coordination processes. Buildings 12(10). 10. Multidisciplinary Digital Publishing Institute: 1548.

Azhar S (2011) Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. Leadership and Management in Engineering 11(3). American Society of Civil Engineers: 241–252.

Buchanan E, Loporcaro G and Lukosch S (2023) On the Effectiveness of Using Virtual Reality to View BIM Metadata in Architectural Design Reviews for Healthcare. Multimodal Technologies and Interaction 7(6). 6. Multidisciplinary Digital Publishing Institute: 60.

Chen J and Laokhongthavorn L (2024) Application of BIM and virtual reality of system integration design and development in medical building projects: A case study in China. Engineering and Technology Horizons 41(3). 3: 410301–410301.

Davidson J, Fowler J, Pantazis C, et al. (2020) Integration of VR with BIM to facilitate real-time creation of bill of quantities during the design phase: A proof of concept study. Frontiers of Engineering Management 7(3): 396–403.

Davila Delgado JM, Oyedele L, Demian P, et al. (2020) A research agenda for augmented and virtual reality in architecture, engineering and construction. Advanced Engineering Informatics 45: 101122.

Dinis FM, Rodrigues R and Martins JP da SP (2023) Development and validation of natural user interfaces for semantic enrichment of BIM models using open formats. Construction Innovation 24(1). Emerald Publishing Limited: 196–220.

Dossick CS, Anderson A, Azari R, et al. (2015) Messy Talk in Virtual Teams: Achieving Knowledge Synthesis through Shared Visualizations. Journal of Management in Engineering 31(1). American Society of Civil Engineers: A4014003.

Eadie R, Browne M, Odeyinka H, et al. (2013) BIM implementation throughout the UK construction project lifecycle: An analysis. Automation in Construction 36: 145–151.

Elgewely MH, Nadim W, ElKassed A, et al. (2021) Immersive construction detailing education: Building information modeling (BIM)–based virtual reality (VR). Open House International 46(3). Emerald Publishing Limited: 359–375.

Getuli V, Capone P and Bruttini A (2020) Planning, management and administration of HS contents with BIM and VR in construction: An implementation protocol. Engineering, Construction and Architectural Management 28(2): 603–623.

Hamma-adama M and Kouider T (2019) Comparative analysis of BIM adoption efforts by developed countries as precedent for new adopter countries. Current Journal of Applied Science and Technology 36(2). Science Domain International.

Huynh-Dagher S, Lamé G, Duong T-A, et al. (2022) Design research in healthcare: a systematic literature review of key design journals. Journal of Engineering Design 33(8–9). Taylor & Francis: 522–544.

Johansson M and Roupé M (2024) Real-world applications of BIM and immersive VR in construction. Automation in Construction 158: 105233.

Kassem M, Kelly G, Dawood N, et al. (2015) BIM in facilities management applications: a case study of a large university complex. Built Environment Project and Asset Management Peter E.D. Love JM and SL (ed.) 5(3). Emerald Group Publishing Limited: 261–277.

Kelly D and Ilozor B (2019) A Quantitative Study of the Relationship between Project Performance and BIM Use on Commercial Construction Projects in the USA. International Journal of Construction Education and Research 15(1). Routledge: 3–18.

Keung CCW, Kim JI and Ong QM (2021) Developing a BIM-based MUVR treadmill system for architectural design review and collaboration. Applied Sciences 11(15). 15. Multidisciplinary Digital Publishing Institute: 6881.

Khairadeen Ali A, Lee OJ, Lee D, et al. (2021) Remote indoor construction progress monitoring using extended reality. Sustainability 13(4). 4. Multidisciplinary Digital Publishing Institute: 2290.

Khan A, Sepasgozar S, Liu T, et al. (2021) Integration of BIM and immersive technologies for AEC: A scientometric-SWOT analysis and critical content review. Buildings 11(3). 3. Multidisciplinary Digital Publishing Institute: 126.

Khorchi A and Boton C (2024) An OpenBIM-based 4D approach to support coordination meetings in virtual reality environments. Journal of Building Engineering 85: 108647.

Kieferle J and Woessner U (2015) BIM Interactive - About combining BIM and Virtual Reality - A Bidirectional Interaction Method for BIM Models in Different Environments. In: eCAADe 2015 : Real time - Extending the reach of computation, Vienna, Austria, 2015, pp. 69–75. Available at: http://papers.cumincad.org/cgi-bin/works/paper/ecaade2015_329 (accessed 21 January 2025).

Kitchenham B and Charters SM (2007) Guidelines for Performing Systematic Literature Reviews in Software Engineering.

Kunz A, Zank M, Fjeld M, et al. (2016) Real Walking in Virtual Environments for Factory Planning and Evaluation. Procedia CIRP 44. 6th CIRP Conference on Assembly Technologies and Systems (CATS): 257–262.

Lin Y-C, Chen Y-P, Yien H-W, et al. (2018) Integrated BIM, game engine and VR technologies for healthcare design: A case study in cancer hospital. Advanced Engineering Informatics 36: 130–145.

Liu ZS, Wu XF and Xu RL (2014) Applied Research of BIM Technology on Prestressed Steel Structures in Xuzhou Stadium. Applied Mechanics and Materials 444–445. Trans Tech Publications Ltd: 971–975.

Lu N and Korman T (2012) Implementation of Building Information Modeling (BIM) in Modular Construction: Benefits and Challenges. American Society of Civil Engineers: 1136–1145.

Mastrolembo Ventura S, Castronovo F and Ciribini ALC (2020) A design review session protocol for the implementation of immersive virtual reality in usability-focused analysis. Journal of Information Technology in Construction 25: 233–253.

Muthumanickam NK, Brown N, Duarte JP, et al. (2023) Multidisciplinary design optimization in architecture, engineering, and construction: A detailed review and call for collaboration. Structural and Multidisciplinary Optimization 66(11): 239.

Noghabaei M, Heydarian A, Balali V, et al. (2020) Trend Analysis on Adoption of Virtual and Augmented Reality in the Architecture, Engineering, and Construction Industry. Data 5(1). 1. Multidisciplinary Digital Publishing Institute: 26.

Olanrewaju OI, Kineber AF, Chileshe N, et al. (2022) Modelling the relationship between building information modelling (BIM) implementation barriers, usage and awareness on building project lifecycle. Building and Environment 207: 108556.

Page MJ, McKenzie JE, Bossuyt PM, et al. (2021) The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ 372. British Medical Journal Publishing Group: n71.

Podkosova I, Reisinger J, Kaufmann H, et al. (2022) BIMFlexi-VR: A virtual reality framework for early-stage collaboration in flexible industrial building design. Frontiers in Virtual Reality 3. Frontiers.

Potseluyko L, Pour Rahimian F, Dawood N, et al. (2022) Game-like interactive environment using BIM-based virtual reality for the timber frame self-build housing sector. Automation in Construction 142: 104496.

Pour Rahimian F, Chavdarova V, Oliver S, et al. (2019) OpenBIM-tango integrated virtual showroom for offsite manufactured production of self-build housing. Automation in Construction 102: 1–16.

Prabhakaran A, Mahamadu A-M, Mahdjoubi L, et al. (2022) BIM-based immersive collaborative environment for furniture, fixture and equipment design. Automation in Construction 142: 104489.

Rostamiasl V and Jrade A (2024) A cloud-based integration of building information modeling and virtual reality through game engine to facilitate the design of age-in-place homes at the conceptual stage. Journal of Information Technology in Construction 29: 377–399.

Safikhani S, Keller S, Schweiger G, et al. (2022) Immersive virtual reality for extending the potential of building information modeling in architecture, engineering, and construction sector: Systematic review. International Journal of Digital Earth 15(1). Taylor & Francis: 503–526.

Schiavi B, Havard V, Beddiar K, et al. (2022a) A VR training scenario editor for operation in construction based on BIM 4D and domain expert authoring. Smart and Sustainable Built Environment 12(5). Emerald Publishing Limited: 1074–1089.

Schiavi B, Havard V, Beddiar K, et al. (2022b) BIM data flow architecture with AR/VR technologies: Use cases in architecture, engineering and construction. Automation in Construction 134: 104054.

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

Singh V, Gu N and Wang X (2011) A theoretical framework of a BIM-based multi-disciplinary collaboration platform. Automation in Construction 20(2). Building Information Modeling and Changing Construction Practices: 134–144.

Stanga C, Banfi F and Roascio S (2023) Enhancing building archaeology: Drawing, UAV photogrammetry and scan-to-BIM-to-VR process of ancient roman ruins. Drones 7(8). 8. Multidisciplinary Digital Publishing Institute: 521.

Tallgren MV, Roupé M and Johansson M (2021) 4D modelling using virtual collaborative planning and scheduling. Journal of Information Technology in Construction (ITcon) 26(42): 763–782.

Vincke S, de Lima Hernandez R, Bassier M, et al. (2019) Immersive visualisation of construction site point cloud data, meshes and bim models in a vr environment using a gaming engine. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLII-5-W2. Copernicus GmbH: 77–83.

Wang K-C and Tung S-H (2023) Cost estimation model based on building information modeling and virtual reality for customizing presold homes. KSCE Journal of Civil Engineering 27(4): 1397–1411.

Wu B, Chen Y, You Y, et al. (2020) Research on the Application of BIM + VR Technology in the Project. IOP Conference Series: Earth and Environmental Science 531(1). IOP Publishing: 012063.

Zaker R and Coloma E (2018) Virtual reality-integrated workflow in BIM-enabled projects collaboration and design review: A case study. Visualization in Engineering 6(1): 4.