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Review Article

Enabling Digital Transformation in Construction: A Framework for Integrating BIM and VR in Early Design Phases

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Abstract

Integrating Building Information Modeling (BIM) and Virtual Reality (VR) has transformative potential to enhance communication among stakeholders in the early design phases of construction projects. However, architecture, engineering, and construction (AEC) firms still encounter significant challenges, including high initial investment costs, software interoperability limitations, fragmented data workflows, and insufficient workforce training programs.

This study conducts a systematic literature review (SLR) to identify and analyze the most critical barriers to BIM-VR adoption. Based on these insights, this research develops a comprehensive framework to mitigate these challenges and facilitate the practical, scalable integration of BIM-VR in construction projects. The framework outlines key strategies and best practices, ensuring digital innovations are accessible even to firms with limited resources.

This research contributes to advancing digital construction methodologies, improving industry-wide efficiency, and facilitating the seamless adoption of BIM-VR technologies in real-world projects by providing a structured and actionable approach to overcoming BIM-VR implementation barriers. The findings offer significant implications for academia and industry, fostering more cost-effective, collaborative, and technologically advanced construction practices

Keywords: BIM, Virtual Reality, Miscommunication, Early Design Phases, Adoption Challenges, Framework Development

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Highlights

- BIM and VR integration reduces early design miscommunication in construction projects.
- Cost and training barriers limit BIM-VR adoption, especially in smaller AEC firms.
- A framework supports immersive collaboration and real-time design coordination.

1. Introduction

The early design phases of construction projects are critical to ensuring the overall project's success. These stages require high levels of collaboration and communication among diverse stakeholders, particularly architects and structural engineers. However, the complex and interdisciplinary nature of design processes often gives rise to communication breakdowns, resulting in costly rework, project delays, and compromised outcomes (Suleiman, 2022), (Abualdenien et al., 2020). (Kuokka, Daniel R, & Larry T. Harada, 1995).

As the architecture, engineering, and construction (AEC) industry undergoes a digital transformation, innovative technologies like Building Information Modeling (BIM) and Virtual Reality (VR) have emerged as promising tools to streamline communication, improve coordination, and enhance stakeholder engagement (Al Hattab & Hamzeh, 2013). BIM enables the development of data-rich, three-dimensional models that serve as a common reference point across disciplines, while VR offers immersive, real-time visualization that bridges the gap between conceptual intent and structural feasibility (Abouelkhier, Shafiq, Rauf, & Alsheikh, 2024). Integrating BIM and VR technologies offers the potential to shift the paradigm of design collaboration—particularly in early stages where miscommunication is most likely to occur (Paes & Irizarry, 2018). Despite their potential, the widespread integration of BIM and VR remains limited. AEC firms often face significant barriers, such as the high initial costs associated with hardware and software, challenges related to software interoperability, fragmented data workflows, and a lack of training and preparedness among project teams (NBS, 2023) , (Alizadehsalehi, Hadavi, & Huang, 2020) , (Sibenik & Kovacic, 2021). These issues are particularly acute for small- and medium-sized firms that operate with constrained resources, further widening the technology adoption gap across the industry.

Several studies have addressed BIM or VR individually in terms of improving project coordination or communication (Tofigh Hamidavi, Abrishami, & Hosseini, 2020) ,(Vincke & Vergauwen, 2022). However, few studies have explored their combined application, especially in the context of practical, scalable implementation. Additionally, the literature highlights the technical capabilities of these tools while overlooking the organizational and cultural changes required for successful integration. These gaps raise a critical inquiry into the fundamental challenges of implementing BIM-VR technologies during the early design phases of construction projects. This study conducted a systematic literature review (SLR) of publications from 2014 to 2024, aiming to identify the key barriers hindering the integration of BIM and VR in early-stage project collaboration. Based on the insights gained, the paper proposes a structured framework to guide the scalable adoption of these technologies in real-world projects. The findings contribute to the evolving knowledge of digital transformation in construction, offering actionable strategies to improve design communication and foster more collaborative, cost-effective practices.

2. Literature Review

Effective communication in architecture, engineering, and construction (AEC) environments is widely recognized as a determinant of project success (Suleiman, 2022), (Kuokka et al., 1995). Early-stage miscommunication between architects and structural engineers frequently stems from discipline-specific languages, divergent design priorities, and the absence of real-time coordination tools (Tofigh Hamidavi et al., 2020). These issues are magnified in traditional workflows that rely heavily on 2D drawings, emails, and software systems, leading to fragmented data exchange and decision-making delays (Muhammad Afzal, Li, Ayyub, Shoaib, & Bilal, 2023), (Hurol, 2014).

BIM has been used as a potential solution, enabling centralized data environments where interdisciplinary teams can collaboratively communicate with digital building models throughout the project lifecycle (McCrum, 2017), (Corneliusen, Deleuran, Kirkegaard, & Beatini, 2022). Likewise, VR introduces immersive visualizations that allow stakeholders—including non-technical users—to interact with design elements and spatial arrangements in ways impossible through conventional representations (Muneeb Afzal, Shafiq, & Al Jassmi, 2021). Numerous studies have emphasized the potential of BIM and VR to improve accuracy, reduce rework, and foster stakeholder collaboration (Al Hattab & Hamzeh, 2013). However, real-world implementation is hindered by several recurring challenges. Researchers identify software interoperability, inconsistent standards, and limited user training as systemic issues preventing the effective integration of BIM-VR into mainstream practice (Astaneh Asl & Dossick, 2022), (Ma & Ma, 2017). For example, Lai and Deng, (Lai & Deng, 2018) illustrate how incompatible data formats across BIM platforms contribute to information loss and manual rework during data transfer. Similarly, Solnosky (Solnosky, 2016) argues that digital adoption often fails not due to technological shortcomings but because of organizational resistance and a lack of clearly defined communication protocols. Smaller firms struggle with financial constraints and lack access to skilled personnel, making it difficult to adopt and sustain new technologies (Du, Zou, Shi, & Zhao, 2018), (Sibenik & Kovacic, 2021).

While studies provide a solid foundation on the individual capabilities of BIM and VR, few studies focus on their combined application as a unified communication strategy. Even fewer offer frameworks that address the practical constraints faced by resource-limited firms. Existing research is also heavily concentrated in technologically advanced regions, leaving a significant knowledge gap regarding BIM-VR adoption in developing economies or among small-to-medium enterprises (SMEs) (Alizadehsalehi et al., 2020), (Du, Shi, Zou, & Zhao, 2018). Furthermore, there is limited exploration of how real-time collaboration tools, such as multi-user virtual environments, can be operationalized within the BIM-VR ecosystem to enhance feedback loops and stakeholder decision-making (Hong, El Antably, & Kalay, 2019) , (Du, Zou, et al., 2018).

3. Methodology

A systematic literature review (SLR) approach was conducted in the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework ('PRISMA 2020 statement', 2020), to investigate the barriers to BIM-VR integration in the early design stages of construction projects. The SLR methodology was chosen for its capacity to synthesize existing knowledge across diverse contexts, helping to identify consistent patterns, emerging trends, and unresolved challenges. Given the study's objective of proposing a framework for adoption, a structured and replicable review process offered a robust foundation to build on prior academic and industry findings.

A strategic search was conducted across three significant databases: Scopus, Web of Science (WoS), and Google Scholar to explore relevant literature comprehensively. The search strategy incorporated a combination of keywords, including "architectural design," "structural engineering," "BIM," "virtual reality," "early design," "collaboration," and "miscommunication." These terms were selected to capture the interdisciplinary intersection of communication workflows and technological integration in the AEC sector. The search was limited to English-language journal articles and conference proceedings published between 2014 and 2024, focusing on peer-reviewed studies that addressed BIM and VR implementation in design collaboration. An initial pool of 862 studies was identified, which was then narrowed to 58 relevant articles through a structured screening and exclusion process.

Data extraction focused on collecting detailed information from each eligible study. These data were manually cross-checked and organized into thematic categories for comparative analysis. Thematic coding enabled the grouping of studies into key clusters, such as data exchange and interoperability, BIM-VR integration frameworks, communication impacts on project outcomes, and organizational barriers to technology adoption.

This analysis approach strengthened the study's internal validity by triangulating data sources and integrating insights across a broad spectrum of research. While the study did not involve human participants and therefore did not require ethical approval, academic integrity was strictly maintained. All sources were cited correctly, and systematic protocols were followed to ensure transparency and reproducibility. Nevertheless, some methodological limitations are acknowledged. Including English-language publications may have excluded relevant studies from non-English speaking regions, potentially narrowing the geographic diversity of insights. Additionally, access restrictions for some full-text documents may have limited the scope of reviewable content. Subjective judgment during abstract and full-text screening—despite being performed independently by multiple reviewers—may also introduce minor bias. Future research could incorporate multilingual databases and include empirical case studies to address these limitations and validate the findings and framework proposed in this review, as seen in Figure 1.

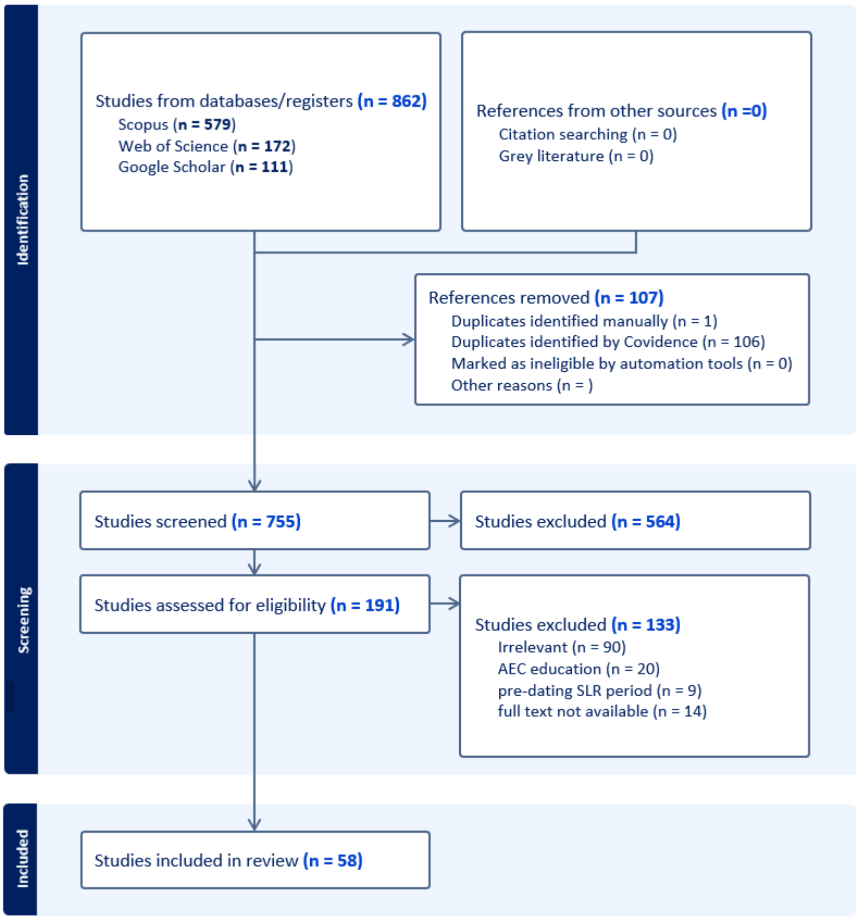

Figure 1. PRISMA Flow Diagram of the Systematic Literature Review Process

4. Results

The core findings of the systematic literature review are organized around key thematic areas derived from the synthesis of 58 studies: communication patterns in early design collaboration, primary sources of miscommunication, the impact of these breakdowns on project performance, and the role of BIM and VR technologies as mitigating tools.

The first theme highlights that fragmented communication and coordination characterize early-stage collaboration between architects and structural engineers. Over 70% of the reviewed studies (n=41) reported issues such as uncoordinated design updates, delayed feedback, and misaligned expectations among stakeholders (Safikhani, Keller, Schweiger, & Pirker, 2022), (T Hamidavi, Abrishami, Ponterosso, Begg, & Nanos, 2020).(Lin, et al., 2018). These issues were often exacerbated by reliance on sequential workflows and traditional communication tools, such as 2D drawings and non-integrated software platforms. Despite advancements in digital tools, many project teams continued to rely on isolated design methods that hinder real-time exchange, resulting in frequent misunderstandings and missed opportunities for early design optimization (Hong et al., 2019; Sateei, Roupé, & Johansson, 2022).

The second theme identifies the most common sources of miscommunication. These were categorized into three overlapping domains: technological, organizational, and human factors. Technological issues included the lack of interoperability between BIM and structural analysis platforms, data loss during file exchange, and absence of real-time synchronization—all of which were cited in 38 of the studies (Papadopoulos, Sotelino, Martha, Nascimento, & Faria, 2017), (Sibenik & Kovacic, 2021), (Park, Lee, Almasi, & Song, 2020; Rahimian, Seyedzadeh, Oliver, Rodriguez, & Dawood, 2020). Organizational barriers were reported in 25 studies and primarily included role ambiguity, fragmented responsibilities, and resistance to digital adoption, which prevented the efficient use of available collaboration tools (Alizadehsalehi et al., 2020), (Du, Zou, et al., 2018), (Ren et al., 2024). Human-related communication challenges appeared in 19 studies and involved limited digital literacy, cultural or linguistic differences, and the difficulty non-technical stakeholders faced in interpreting 2D documentation (Lin et al., 2018), (Ali, Hegazi, Shanawany, & Othman, 2024), (Zhang & An, 2023).

The third thematic finding relates to the consequences of miscommunication on project performance. Studies consistently demonstrated that unresolved communication issues during early design phases led to measurable adverse outcomes across construction projects. Rework and design revisions were the most frequently reported consequences, highlighted in 34 studies (59%), often resulting from overlooked design changes or misunderstood intent (Du, Zou, et al., 2018), (Yu, Gu, Lee, & Khan, 2022). Twenty-six studies (45%) pointed to delays caused by misaligned schedules and poor coordination, while 21 studies (36%) reported financial losses due to redundant efforts, contractual disputes, or escalated material and labor costs (Wen & Gheisari, 2020), (Du, Shi, et al., 2018). Quality concerns were identified in 18 studies (31%), where lack of synchronization between structural and architectural models led to code violations, unsafe detailing, or performance defects (Hao, Zhang, & Zhao, 2021), (Jia, Liu, Zhang, Song, & Zhang, 2022). These findings underscore a compounding effect, where early miscommunication triggers downstream inefficiencies, conflicts, and budget overruns.

The final theme focuses on the strategies identified in the literature for mitigating these challenges through BIM and VR technologies. Forty-four of the reviewed studies (76%) reported on either successful case studies or conceptual proposals involving BIM, VR, or their integration. The most common approach involved combining BIM's data-rich modeling environment with VR's immersive design interface. This integrated workflow, mentioned in 31 studies, allowed stakeholders to visualize spatial conflicts and interact with design elements in real time, thereby reducing ambiguity and increasing participation [59], (Lin et al., 2018). Real-time data synchronization in cloud-based BIM platforms was cited in 24 studies as an effective method for ensuring that all project participants had access to the latest updates, minimizing errors due to outdated information (Boechat & Corrêa, 2021), (Du, Zou, et al., 2018). Automation workflows that connected BIM models with AI-based feedback systems were highlighted in 11 studies as innovative approaches to detect conflicts and streamline coordination proactively (Park et al., 2020), (Rahimian et al., 2020). Additionally, 14 studies emphasized the utility of multi-user virtual environments (MUVEs), which enabled real-time interaction between geographically dispersed teams using shared virtual platforms (Hong et al., 2019), (Alizadehsalehi et al., 2020).

Despite these promising strategies, many studies also acknowledged challenges in practical adoption. High initial costs, technical complexity, and the lack of training infrastructures were frequently cited as barriers to implementation—especially among small and medium-sized firms with limited resources (Astaneh Asl & Dossick, 2022), (Ibraheem & Mahjoob, 2022),(Ren et al., 2024). These findings affirm the need for scalable, adaptable frameworks that integrate technology effectively and address organizational readiness and user capability.

5. Discussion

The findings of this systematic review highlight the persistent challenges that miscommunication poses during the early design phases of construction projects, as well as the growing potential for digital tools—particularly BIM and VR—to serve as enablers of interdisciplinary collaboration. The recurrence of fragmented data exchange, software incompatibility, and unclear communication channels reinforces the observation that traditional workflows dominate many AEC practices, even in digitally capable firms. This underscores a critical gap between technology availability and practical implementation, which this study aims to address through its proposed framework.

Notably, integrating BIM and VR is not merely a technical solution but a transformative shift in how design intent is communicated and understood. BIM's structured, data-driven approach to model coordination offers clarity, while VR introduces spatial immersion, allowing stakeholders to engage more intuitively with design concepts. When applied in tandem, these technologies can dissolve many of the barriers caused by discipline-specific knowledge silos and static documentation. However, the review revealed that such integration remains uneven across regions and organization types, with smaller firms particularly disadvantaged due to cost, training, and infrastructure constraints.

Identifying organizational and human barriers—such as lack of role clarity, resistance to change, and poor stakeholder alignment—emphasizes that technological adoption must accompany cultural and managerial shifts. Strategies that include phased implementation, structured training, and multi-user collaboration environments effectively minimized resistance and increased the usability of BIM-VR systems. Moreover, several studies suggested that real-time data access and automated coordination tools significantly reduce the risk of design conflicts, thus improving project timelines and outcomes. Finally, this study's findings demonstrate that current research treats BIM and VR in isolation or within case-specific applications. The lack of generalizable, scalable frameworks leaves a gap in guiding industry-wide adoption. This paper contributes to filling that gap by synthesizing existing strategies into an actionable, practical model that can be adapted by digitally mature organizations and those just beginning their transition toward integrated design technologies.

6. Conclusions

This study examined how BIM and VR can be leveraged to address miscommunication challenges between architects and structural engineers during the early design phases of construction projects. Through a systematic literature review of 58 peer-reviewed publications spanning 2014 to 2024, the research identified the principal sources of communication breakdown—ranging from software incompatibilities and fragmented data exchanges to organizational inefficiencies and limited stakeholder understanding of spatial intent.

The review also highlighted the significant impact of these communication issues on project performance, particularly regarding rework, cost overruns, quality degradation, and schedule delays. However, it found that BIM and VR—when strategically integrated—offer promising solutions. These tools have been shown to enhance visual clarity, support real-time collaboration, and reduce the cognitive and technical barriers that often impede effective interdisciplinary communication.

Despite their benefits, the adoption of BIM and VR remains inconsistent, especially among firms with limited digital infrastructure or expertise. This reinforces the need for structured, scalable implementation frameworks that extend beyond technical integration and address cultural, educational, and organizational readiness.

The study contributes to academic and practical discourse by proposing a conceptual foundation for such a framework that emphasizes interoperability, real-time feedback, and immersive collaboration. For future work, empirical validation of this framework across diverse geographic and organizational settings is recommended. Additionally, further exploration into the role of extended reality (XR) technologies, AI-driven feedback systems, and cost-effective deployment strategies for SMEs will be crucial for expanding the accessibility and impact of digital construction methodologies. By advancing this integrated perspective, the study encourages a more collaborative, efficient, and technologically adaptive construction industry where digital communication tools do more than support design.

Data Availability Statement

The data supporting the findings of this study are derived from publicly available academic literature accessed through Scopus, Web of Science, and Google Scholar. As this research is based on a systematic literature review, no new datasets were generated or analyzed. All references are cited within the manuscript.

Conflicts of Interest

The authors declare no conflict of interest. No external funding was received for this research. The authors carried out the design, data collection, analysis, writing, and publication decisions without any influence from third-party organizations..

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