www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

A SYSTEMATIC REVIEW OF CRITERIA INFLUENCING THE INTEGRATION OF BIM AND IMMERSIVE TECHNOLOGY IN BUILDING PROJECTS

SUBMITTED: May 2024
REVISED: February 2025
PUBLISHED: March 2025
EDITOR: Robert Amor
DOI: 10.36680/j.itcon.2025.011

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SUMMARY: *Integrating Building Information Modeling (BIM) and Immersive Technologies (ImT) provides several benefits, such as the inclusion of clients in the design process, thereby improving construction management practices. BIM's propensity for digital data management, coupled with ImT's enhanced communication and coordination capabilities, addresses inherent issues like fragmentation and collaboration challenges in construction projects. While prior studies have primarily examined BIM and ImT individually, limited research has explored the synergistic integration of these two technologies and the potential benefits they can offer when combined in the context of architecture, engineering, and construction (AEC) industry. This paper reviews strategies and prospects for integrating BIM and ImT in the existing construction management literature, aiming to identify and categorize key socio-technical criteria that support the successful integration of BIM and ImT. A Systematic Literature Review (SLR) was accordingly employed, following PRISMA guidelines, analyzing 56 academic journals from Scopus and the ASCE Library databases on BIM and ImT integration in building projects from 2013 to May 2023. The results reveal various attributes of BIM and ImT integration, including the use of BIM-related software like Autodesk Revit, ImT hardware like Oculus Rift and HTC Vive, game engines like Unity3D, data standards like FBX, and collaborative platforms like Autodesk BIM 360 and Trimble Connect. Essential technical criteria were identified from these aspects: emphasizing software system integration and hardware optimization for seamless data exchange, alongside non-technical criteria focusing on user engagement, learning, and effective stakeholder collaboration. The study also highlights significant gaps, such as the need for standardized methodologies, more detailed technical discussions, and user-centric strategies, pinpointing areas for further exploration to refine BIM and ImT integration practices while providing valuable insights into the adoption and efficacy of digital transformation strategies in the AEC sector.*

KEYWORDS: *Building Information Modeling, Immersive Technology, Systematic Literature Review, Influential Criteria, Building Projects.*

REFERENCE: *Bao Pham Van, Peter Wong & Behzad Abbasnejad (2025). A systematic review of criteria influencing the integration of BIM and Immersive Technology in building projects. Journal of Information Technology in Construction (ITcon), Vol. 30, pg. 243-297, DOI: 10.36680/j.itcon.2025.011*

1. INTRODUCTION

The architecture, engineering, and construction (AEC) industry is a cornerstone of global economic activity, substantially contributing to GDP and employment (Deloitte, 2020). For example, in Australia, the Australian Bureau of Statistics further underscores the sector's economic impact, noting its significant role in Australia's economic growth (ABS, 2022). Despite its critical importance, the sector grapples with challenges such as disruptions from COVID-19 and supply chain shortages, which necessitate the adoption of technology to sustain growth (World Construction Network, 2022). Technological innovation, therefore, becomes imperative to enhance operational efficiency and drive financial success, as highlighted by several studies (Leviäkangas et al., 2017; Fulford, 2019; Nangia et al., 2019).

Despite its status as one of the largest global industries, the AEC sector faces significant hurdles in embracing technology and digital practices, which lead to decreased productivity and increased costs (AMGC, 2018; Martin and Perry, 2019; Wang et al., 2020). These challenges stem from a scarcity of digital skills, entrenched traditional industry structures, and resistance to change (Deloitte Access Economics, 2022; London and Pablo, 2017; Oesterreich and Teuteberg, 2016). Emerging technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), ImT, and BIM, offer viable solutions that revolutionize project planning, execution, and decision-making, thereby enhancing efficiency, safety, and sustainability (Bartodziej, 2017; Oztemel and Gursev, 2020; Gebhardt et al., 2022; Maqbool et al., 2023). Integrating Industry 4.0 technologies, including AI, has been shown to significantly boost productivity and address critical issues such as project management efficiency and worker safety (Riaz et al., 2017; Louis and Dunston, 2018). At the core of the digital revolution in the AEC industry is BIM, a complete digital platform that generates intricate building models and enables uninterrupted information exchange throughout the project lifecycle. Through BIM as an integration hub, other advanced technologies such as Virtual Reality (VR) and Augmented Reality (AR) can be effectively deployed to enable users to experience these digital models in immersive and realistic ways, thereby enhancing project visualization and decision-making processes.

It is seen that the integration of BIM and ImT is particularly transformative, enhancing project management practices by enabling realistic experiences of models through VR and AR, thus increasing productivity and improving operational efficiencies (Deloitte Access Economics, 2022). This integration marks a shift towards a more collaborative and effective construction industry. BIM plays a pivotal role by digitally managing building design and project data throughout a building's lifecycle (Succar, 2009), with global adoption rates reaching up to 75% in various countries (Vilutiene et al., 2019; NBS Enterprises Ltd., 2020). Additionally, the rapid development of ImT offers innovative solutions that enhance communication, worker training, and project coordination (Abbas et al., 2019; Wang et al., 2018). The synergistic benefits of combining BIM and ImT have been demonstrated to improve workspace planning, structural system utility, and maintenance staff benefits (Getuli et al., 2020; Protchenko et al., 2018; Naticchia et al., 2018), contributing significantly to industry advancement. The emerging growth trajectory of AR/VR technology further indicates its promising future utilization in construction projects (Noghabaei et al., 2020).

In the existing literature on the integration of BIM and ImT, several gaps and problems have been identified. The literature reviews conducted over the past decade have shown advancements in BIM and ImT but have been criticized for being partial, fragmented, and failing to address certain issues comprehensively. Studies tend to have narrow perspectives, focusing solely on BIM or ImTs, indicating a lack of holistic analysis (Khan et al., 2021). While some scholars have proposed integration proposals, there is limited research on how this integration will occur and the role of both humans and non-humans and the transformation of the landscape, lies in collaborating with these tools instead of solely relying on them, especially given the recent advancements in AI (Khudhair et al., 2021). The literature emphasizes the importance of BIM as the core of digital transformation in the construction industry and highlights the significant benefits of integrating ImT with BIM, enhancing collaboration processes and communication platforms (Afzal et al., 2021; Liu et al., 2024). However, the studies mostly concentrate on the “WHAT” aspects of BIM and ImT, such as listing supporting factors or proposing research directions, while giving less emphasis to the “HOW” aspects of deployment, indicating a gap in practical integration strategies (Afolabi et al., 2022). Furthermore, challenges related to technical problems, data integration, standards, and social obstacles like resistance to change and coordination issues have been identified as barriers to the effective implementation of integrated BIM-ImT solutions in the construction industry, highlighting the need for more comprehensive research on socio-technical aspects and data integration standards (Özturk, 2021; Shahinmoghadam et al., 2021; Chen et al., 2021).

This research investigates how existing approaches have been applied to enhancing the adoption of BIM and ImT in construction and project management practices. It specifically examines the promotion of BIM-immersive integrated technology within building projects and explores the socio-technical criteria for successful integration. The primary aim is to identify and categorize crucial socio-technical criteria that support effective BIM and ImT integration, thereby advancing construction and project management practices. These criteria are essential as they enable effective collaboration among human and technological agents, which is crucial for maximizing the advantages of BIM and ImT integration. For example, BIM implementation requires co-designing protocols like BIM Execution Plans (BEPs) to align institutional norms with technical standards, ensuring cohesive team coordination in global projects (Anderson and Ramalingam, 2021). In addition, socio-technical frameworks, as highlighted by Oesterreich and Teuteberg (2019), help mitigate adoption barriers by addressing fragmented data interoperability (technical) and resistance to workflow changes (social). This results in reduced rework through the contractual enforcement of collaborative practices. Plus, according to Abdelmegid et al. (2024), by jointly optimizing tools like immersive VR and stakeholder engagement processes, socio-technical systems can maximize value creation in BIM-ImT integration while avoiding automation pitfalls, which have been observed in failed pilot projects. Therefore, the paper will address the following research questions: *RQ1. How can current and proposed future approaches promote the integration of BIM-ImT in construction and project management within building projects? RQ2. What socio-technical criteria are essential for the successful integration of these technologies?* Through this analytical approach, the research seeks to deepen understanding of how integration can enhance project outcomes and drive innovation within the industry. The subsequent parts of this paper are organized as follows: Section 2 elaborates on the literature review regarding BIM and ImT in construction and project management. Section 3 outlines the research methodology, detailing the SLR process. The results from this review are then presented in Section 4. Section 5 presents a detailed discussion of these findings. The paper concludes with Section 6, which summarizes the study's key conclusions and implications and suggests avenues for future research.

2. LITERATURE REVIEW

2.1 Building Information Modeling (BIM)

Over the past two decades, BIM has been gaining momentum in the AEC industry, helping to shift traditional design paradigms toward more dynamic and integrated workflows. However, there is no universally accepted definition of BIM. According to Borkowski (2023), BIM can be viewed from two perspectives: a broad perspective, which encompasses not only digital technologies but also hardware, tangible and intangible resources, and knowledge, emphasizing interdisciplinary collaboration; and a narrow perspective, which focuses on BIM as a semantic database that supports decision-making and project management. This dual understanding reflects the evolution of BIM from a technology-driven tool to a comprehensive methodology. Building upon this foundation, BIM extends beyond conventional 3D modeling to establish a centralized platform for data management and seamless collaboration among stakeholders, enabling informed decision-making and resource optimization across the planning, design, construction, and operational phases of a project (Jiao and Cao, 2023). Over the past two decades, BIM has significantly transformed the AEC industry by shifting from traditional design paradigms to more dynamic and integrated workflows. By enhancing project visualization, enabling early conflict detection, and facilitating real-time progress tracking, BIM has proven essential in improving project planning and execution. Its adoption has minimized errors, reduced rework, and achieved substantial cost and time efficiency through fostering collaboration among architects, engineers, and contractors (Lindblad and Guerrero, 2020).

Recent advancements in digital technologies have further extended BIM's capabilities, particularly through its integration with AI, machine learning (ML), and the IoT. These innovations enable predictive analytics, real-time data sharing, and automated decision-making, underscoring BIM's critical role in driving digital transformation in the AEC industry (Wang, 2024). More notably, the synergy between BIM and VR or AR, has emerged as a revolutionary step forward. These technologies enable stakeholders to interact with highly detailed and realistic simulations of building designs, enhancing spatial understanding and improving collaboration during the design and construction processes (Omrany et al., 2023). As such, the combination of BIM and ImT has opened new avenues for improving project outcomes, fostering innovation, and reshaping the future of the built environment (Abouelkhier et al., 2024).

2.2 Immersive Technologies (ImT)

ImT refers to a suite of advanced digital tools and techniques that enable users to engage with virtual environments through realistic and interactive experiences. From an academic standpoint, ImT is characterized by its ability to merge physical and virtual realities, fostering improved visualization, interaction, and collaboration in various fields, including construction, healthcare, and education (Balasubramanian, 2024; Babalola et al., 2023). These technologies often encompass Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), collectively referred to as Extended Reality (XR). XR represents a comprehensive spectrum of immersive environments, ranging from fully virtual spaces to hybrid physical-virtual settings tailored to specific applications (Khan et al., 2021; Turan and Karabey, 2023). However, ImT extends beyond XR by including a broader array of tools and techniques that enhance multisensory experiences. For example, ImT incorporates systems like haptic feedback, immersive audio, and 360-degree projection systems, which are not strictly part of XR but significantly contribute to deeper engagement and interaction. This distinction highlights the focus of ImT on creating holistic and integrated experiences that combine visual, auditory, and tactile immersion. By adopting the term "ImT", this paper aims to emphasize the inclusion of such advanced technologies that go beyond XR, aligning with the growing diversity of applications in the AEC industry.

VR is a technology employed to develop computerized environments, wherein users feel immersed in the virtual world, isolated from the physical environment. This is achieved through devices such as head-mounted displays (HMDs) or multi-screen setups, enabling users to experience a sense of presence in a virtual environment (Delgado et al., 2020; Shafiq and Afzal, 2020). For instance, VR can simulate tasks in specific working environments, such as experiencing elevated heights, to improve training outcomes with heightened realism (Chander et al., 2021). AR, in contrast, overlays digital information onto the real-world environment to enhance users' contextual awareness of their surroundings (Delgado et al., 2020). Unlike VR, which fully immerses users in a computer-generated environment, AR represents a fusion of real-world scenarios and computer-generated elements to augment reality (Dargan et al., 2023; Parmar, 2023). This approach allows users to interact with digital and physical elements simultaneously, improving task efficiency and awareness in dynamic contexts. MR builds upon AR by allowing digital objects and the real world to coexist and interact in real-time, creating an environment where users can engage with virtual objects within the physical space (Hasanzadeh et al., 2020). This interaction enriches the user experience by enabling dynamic manipulation of digital content, fostering seamless integration between the virtual and real worlds.

The role of ImT in construction projects is particularly significant as it enhances decision-making, stakeholder engagement, and safety through its ability to simulate construction processes, environments, and potential risks in a virtual space (Afzal et al., 2021; Afolabi et al., 2022). These technologies also integrate with complementary systems like BIM, enabling real-time data sharing and analysis within a unified digital ecosystem (Liu et al., 2024; Wijerathna et al., 2024). For example, VR applications integrated with BIM have been widely adopted for health and safety training, allowing workers to experience potential hazards in a safe, controlled environment (Mahammad, 2023). This integration also facilitates the simulation of real-life accidents, such as scaffolding failures, providing preventive training and improving risk awareness among workers (M. Tehrani and Alwisy, 2023). Specifically, BIM and ImT integration supports evacuation modeling in emergencies by combining BIM models with platforms like Unity, offering occupants a training environment to familiarize themselves with facilities and emergency procedures. These applications not only enhance safety and risk management but also improve stakeholder engagement by providing interactive visualizations and intuitive understanding of complex scenarios. Beyond safety applications, the integration of ImT and BIM spans the entire project lifecycle, from design exploration and construction planning to monitoring and facility management. These technologies collectively provide a holistic approach for improving operational efficiencies and delivering better project outcomes (Swallow and Zulu, 2025). By enhancing collaboration, streamlining workflows, and fostering innovation, the integration of ImT and BIM represents a transformative advancement in the AEC industry.

2.3 An overview of the process for integrating BIM and ImT

The integration of BIM and ImT in construction management offers various benefits, including enhanced information transparency, optimized decision-making processes, and a reduction of 30-50% in design error risks (Khan et al., 2021; Babalola et al., 2023). Specifically, BIM provides accurate 3D data about the project, while ImT enables the visual simulation of complex construction scenarios, creating a safe training environment for workers (Khan et al., 2023). Unlike a rigid approach, the process varies significantly based on the intended application, such as design review, stakeholder collaboration, or construction monitoring (Safikhani et al., 2022; Balin et al., 2023). Therefore, an effective integration framework must align with specific socio-technical requirements, including visualization techniques, interoperability, and user experience (UX) design.

From an academic perspective, the integration of BIM and ImT involves three core domains: data management, visualization, and interaction which provide a flexible structure to accommodate various project objectives (Sadhu et al., 2023; Liu et al., 2024). At the heart of BIM and ImT integration is the need to manage and exchange data effectively. This includes integrating geometric and non-geometric data such as timelines, costs, and materials to enrich virtual environments and support decision-making. For instance, collaborative data platforms enable real-time updates, ensuring that all stakeholders have access to consistent and accurate information throughout the project lifecycle (Dalui et al., 2021). Visualization is also a critical component of BIM and ImT integration, enabling stakeholders to explore and analyze project data intuitively. Advanced visualization techniques, such as real-time rendering and dynamic simulations, provide immersive experiences that are particularly valuable for design reviews and safety training. For example, VR environments allow users to conduct virtual walkthroughs of BIM models, identify design conflicts, and assess project feasibility under simulated conditions (Panya et al., 2023). Besides, a key challenge in integrating BIM with ImT is ensuring that users can interact effectively with digital models. Applying UX design principles ensures that immersive environments are accessible, intuitive, and tailored to the needs of diverse stakeholders, including architects, engineers, and contractors (Stanney et al., 2024). This is especially important in applications like AR-based construction monitoring, where ease of use and real-time feedback are essential.

The process of integration is further influenced by the technological and organizational context of the project. For example, VR for design review may not require extensive interoperability or real-time updates, focusing instead on creating highly detailed and visually accurate models (Safikhani et al., 2022). In contrast, AR for construction monitoring demands seamless integration with real-world data and robust hardware capabilities to overlay digital information on physical environments (Pan and Isnaeni, 2024). Ultimately, the integration framework must remain flexible to address the unique challenges and opportunities of each application. This flexibility ensures that the integration process aligns with the influential criteria identified in this study, supporting effective collaboration and advancing construction and project management practices.

3. RESEARCH METHODOLOGY

This research employs a Systematic Literature Review (SLR) to analyze prevailing and emergent strategies for BIM and ImT incorporation within construction management. The investigative approach involves a rigorous SLR, comprehensively exploring integrative methodologies with a specific focus on delineating the technical and non-technical criteria that impact the integration of BIM and ImT in building projects. To achieve this, the methodology incorporates a screening process for literature selection to ensure the literature review is exhaustive and systematic. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Page et al., 2021) was applied for the screening procedure (see Figure 1).

The databases selected for this study, Scopus and the American Society of Civil Engineers (ASCE) Library, were chosen for their relevance and comprehensiveness in covering literature within the fields of construction and engineering. Scopus, as one of the largest interdisciplinary databases, provides access to a wide range of peer-reviewed articles across multiple domains (Baas et al., 2020). Oraee et al. (2017) justified their selection of Scopus over other bibliometric sources such as Web of Science, EBSCOhost, and ProQuest, citing its broader coverage of journals relevant to construction project management (PM) and construction IT. Moreover, it continuously updates the most recent publications, particularly in the field of BIM, which is a relatively new and rapidly growing area of literature (Oraee et al., 2017). Notably, Utami et al. (2022) also mentioned the use of Scopus as a data source for bibliometric analysis related to AR in technical education, highlighting its invaluable role in tracking publication trends and identifying key contributors. Supporting this view, Copper (2024) emphasized Scopus as a general database for architecture, construction, and engineering, with a broader scope than other databases. Additionally, this study also identifies ASCE Library as a reliable subject-specific database for civil engineering. Cho and Wang (2021) highlighted that topics related to the application of new technologies in the built environment, including BIM and ImT, are commonly featured in ASCE journals, aligning well with the objectives of research on the built environment and project management. Furthermore, in the study by Pradhananga et al. (2021) on identifying challenges in adopting robotics in the U.S. construction industry, ASCE journals were selected because of their high quality, strong impact factors, and their status as the most commonly used resources for literature reviews within the civil and construction engineering discipline. It can be observed that, alongside Scopus, ASCE Library specializes in civil engineering research and applications, making it an essential source for studies on BIM and ImT. Therefore, the combination of these databases ensures an exhaustive and systematic coverage of relevant literature.

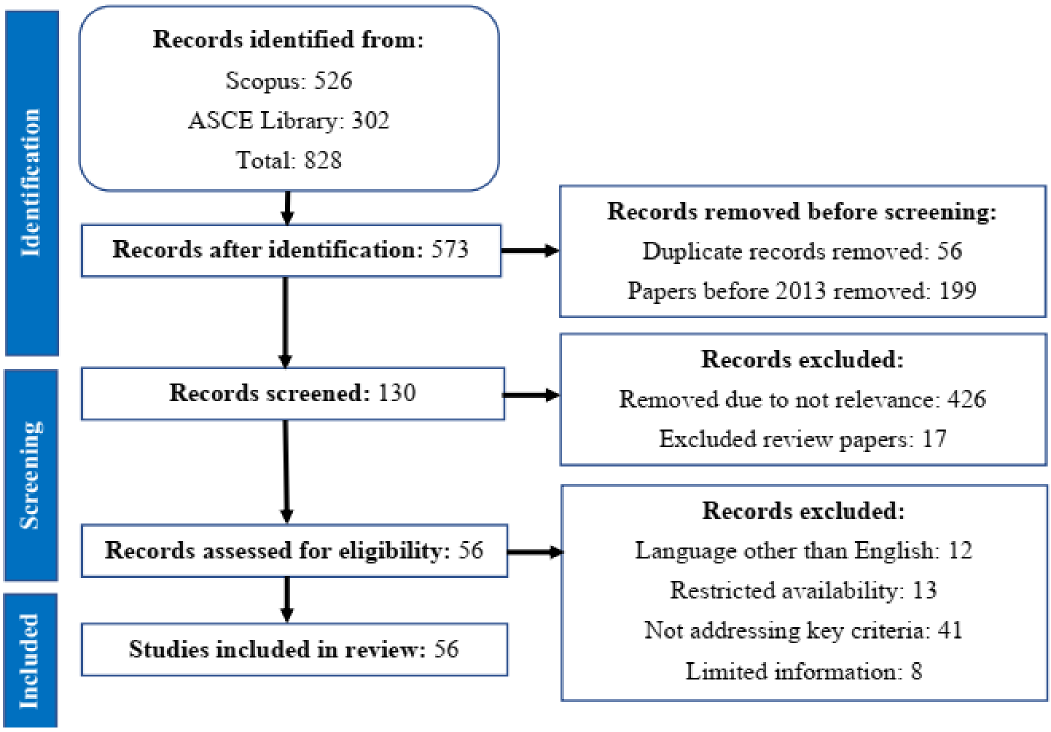


Figure 1: The PRISMA flow diagram of systematic records selection.

First, the search in Scopus is set to ‘Article title, Abstract, Keywords’ and the advanced search field for the ASCE Library. The search terms considered across all databases were (“Criteria” OR “Factor” OR “Barrier” OR “Challenge” OR “Limitation”) AND (“Building Information Modeling” OR “BIM”) AND (“Immersive Technology” OR “Virtual Reality” OR “VR” OR “Augmented Reality” OR “AR” OR “Mixed Reality” OR “MR”) AND “Construction”. Initially, a total of 487 documents were identified from two databases: Scopus (526 records) and the ASCE Library (302 records), including articles in journals and conferences with these search terms in May 2023. Following the identification phase, the records were subjected to deduplication and relevance screening, removing 56 duplicate records and 199 published before 2013. This process yielded 573 records. In the screening phase, out of these 573 records, 130 were screened more closely, which led to the assessment of 56 records for eligibility based on the review criteria. The reasons for exclusion during the screening phase included irrelevance (426 records excluded) and the nature of the content being review papers (17 records excluded). In the final phase, records were excluded based on predefined criteria to ensure the relevance and quality of the chosen studies. Specifically, 12 records were excluded due to language barriers as they were not in English, while 13 records were excluded due to restricted availability, which prevented access to their full content. Furthermore, 41 records were excluded as they did not address the technical and non-technical criteria central to this study. Papers focusing on educational settings, industrial applications, or experimental environments were also excluded, as the analysis is specifically centered on integrating BIM and ImT in construction management research. Additionally, 8 records were excluded as they provided only limited information, such as abstracts, making them unsuitable for in-depth analysis. The culmination of this selection process resulted in 56 studies being included in the final review. These exclusion criteria were meticulously designed to ensure consistency and alignment with the scope of the study, maintaining coherence throughout the analysis. It is worth noting that some papers may cover research activities conducted in multiple locations or countries, but the criteria remained consistent to preserve the integrity of the review process.

This study employs a mixed-methods approach to analyze and synthesize the existing body of literature on the integration of BIM and ImT in construction management. Desktop research forms the foundation of this approach, supported by the use of specialized software tools to ensure a rigorous and systematic analysis. Qualitative data analysis is first conducted using NVivo, which facilitates the coding of literature to identify recurring themes and subthemes central to the study. NVivo is particularly instrumental in organizing and managing complex qualitative datasets (Woolf and Silver, 2017), allowing researchers to uncover patterns, relationships, and insights within the selected body of literature. This capability is especially critical when analyzing large volumes of materials on the integration of BIM and ImT in construction management. According to Manzoor et al. (2021), NVivo is employed in research to analyze qualitative data due to its ability to code and classify complex datasets, such as interviews or text-based information, aiming to construct a research framework for mitigating construction accidents in high-rise building projects via BIM and emerging digital technologies. Their study further highlights that this tool supports thematic analysis, which is particularly useful for understanding how digital technologies like BIM and ImT are applied to enhance safety and project management in construction. To complement the qualitative analysis, bibliometric methods are then employed using VOSviewer, which aids in mapping and visualizing networks of terms and concepts central to the field (Kirby, 2023). As demonstrated in the studies by Khan et al. (2021) and Liu et al. (2024), VOSviewer has been used to analyze keyword networks to identify key research themes, conceptual relationships, and trends within the domain of BIM and ImT in the construction industry. This tool facilitates the visualization of data from scientific publications, illustrating the connections between keywords, clarifying significant thematic clusters, and guiding the development of research directions. By providing a quantitative perspective on the research landscape, VOSviewer enables a comprehensive understanding of the field and helps identify gaps in the existing knowledge concerning the integration of BIM and ImT. Next, EndNote and Microsoft Excel are also selected in this research for their complementary strengths and widespread use in the field. EndNote is employed to systematically manage citations and references throughout the research process, ensuring that all sources are properly documented and organized. As a robust reference management system, EndNote allows researchers to efficiently handle and cite an extensive range of sources, which is particularly critical in construction studies that often draw from multidisciplinary references (Zhong et al., 2019; Wandia and Ralwala, 2024). Microsoft Excel, on the other hand, provides powerful data analysis and visualization capabilities, which are especially valuable for construction-related research (Rayabharapu et al., 2024; Elesawy et al., 2024). Its versatility in managing quantitative data, creating charts, and performing statistical analyses makes it an indispensable tool for researchers in the construction industry. The integration of EndNote for reference management and Excel for data analysis creates a synergistic approach that enhances the clarity and precision of presenting the influential criteria. Overall, the thematic and bibliometric insights derived from the combination of these tools provide a robust foundation for understanding the criteria influencing the integration of BIM and ImT in building projects, ultimately contributing to a more structured and informed discussion within the field.

4. RESEARCH FINDINGS AND RESULTS

4.1 Bibliometric analysis

The annual number of selected papers for this review demonstrates a generally stable trend over the years, with a slight variation in some periods (see Figure 2). This finding indicates that BIM and ImT-related topics are attracting more AEC researchers' attention. The temporary decrease in the number of papers in 2019 and 2020 can be attributed to the global pandemic and the challenges of conducting immersive technology studies during lockdowns. Despite these disruptions, the quantity of screened papers for 2021 and the subsequent peak in 2022 still indicate ongoing interest in BIM and ImT integration, showing resilience in research activities even under extraordinary circumstances.

The selected studies in this review are sourced from a wide range of journals, totaling 56 distinct publications. Table 1 presents those journals that have contributed one or more papers to our research corpus. “Automation in Construction” emerges as the most prolific contributor within this domain, furnishing 10 papers that account for a significant percentage of the journal contributions. Following close behind is the "Journal of Construction Engineering and Management" with 9 publications, underscoring its relevance to the field. The "Journal of Building Engineering", "Advanced Engineering Informatics", "Building and Environment", and the "International Journal of Engineering Education" each add 3 to 4 papers to the compilation, reflecting their sustained interest in the subject matter. The other 24 scholarly venues are peer-reviewed conference proceedings.

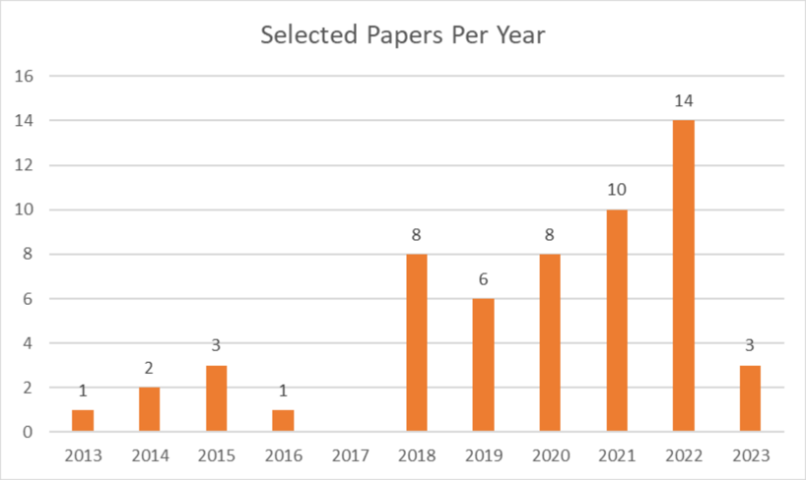


Figure 2: The number of relevant papers per year gathered from Scopus and ASCE libraries for review.

Table 1: Paper distribution by journal.

Journal Name	**Number of papers**
Automation in Construction	10
Journal of Construction Engineering and Management	9
Journal of Building Engineering	4
Advanced Engineering Informatics	3
Building and Environment	3
International Journal of Engineering Education	3
Journal of Computing in Civil Engineering	2
ECAM	2
Computer Applications in Engineering Education	2
Computing in Civil Engineering	2
Construction Innovation	2
Construction Research Congress	2
International Journal of Construction Education and Research	2
International Journal of Occupational Safety and Ergonomics	2
Journal of Architectural Engineering	2
Journal of Information Technology in Construction	2
Journal of Intelligent & Robotic Systems	2
KSCE Journal of Civil Engineering	1
Safety Science	1

In our bibliometric analysis, the co-occurrence network (see Figure 3) was constructed using a dataset of 56 selected papers. Keywords were extracted systematically from the titles and abstracts of these papers through VOSviewer's text mining functionality. The search process was guided by specific terms such as "Building Information Modeling" or "BIM," "Immersive Technology," "Virtual Reality" or "VR," "Augmented Reality" or

"AR," "Mixed Reality" or "MR," "Project Management" and "Construction Industry," ensuring that only domain-specific keywords relevant to BIM and ImT integration in construction were included. To enhance the focus and clarity of the network, generic terms and stop words, such as "study," "analysis," and "research," were excluded. In addition, a minimum occurrence threshold of three was applied to filter out infrequent keywords that did not contribute substantially to the thematic clusters. The co-occurrence network was generated using the full counting method, which accounted for all instances of keyword pairings, and the visualization was produced with a resolution-based modularity clustering algorithm. The spatial distribution of nodes within the network was optimized using the Fruchterman-Reingold layout, ensuring clear and interpretable relationships among keywords. This methodological approach ensures that the visualization accurately reflects the recurring themes and interdisciplinary connections in BIM and ImT research, supporting the validity of our findings.

As illustrated in Figure 3, the visualization comprises six main clusters, embodying the diverse interplay between key topics within the field. The map unveils a substantial cluster around "Building Information Modelling", interconnected with "Virtual Reality", "Augmented Reality", "Project Management", and "Construction Industry", highlighting the multifaceted nature of BIM applications. "Virtual Reality" serves as another prominent node, closely associated with "Education Computing", reflecting its rising importance in experiential learning and design within the AEC sectors. This network, derived from the keyword occurrences in the analyzed literature, extends into nuanced domains, revealing a synergy between "Artificial Intelligence", "Information Theory", and "Design and Construction". Such connections underscore the growing emphasis on intelligent design processes and data-driven decision-making in construction projects.

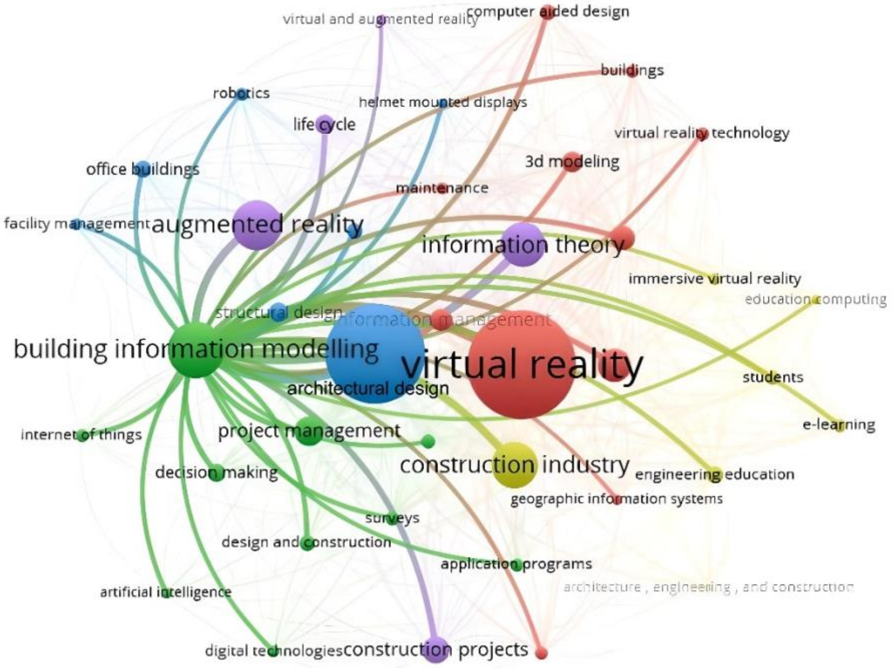


Figure 3: The co-occurrence network for the keywords of systematic records.

Furthermore, the visualization emphasizes the interdisciplinary trajectory of BIM and ImT research, offering vital knowledge into evolving trends and connections within the field. At the core of the graph, "VR" acts as the dominant node, signifying its central role in driving innovation in construction workflows. Its strong connectivity to "BIM" highlights their synergistic potential, with BIM providing a robust digital foundation for data-rich 3D environments, while VR enhances visualization, immersive user interaction, and collaborative capabilities. This connection is reinforced by significant links to applications such as "project management", "structural design", and "facility management", reflecting the wide-ranging impact of immersive technologies across the lifecycle of construction projects. Plus, the prominence of "decision-making", "digital technologies", and "architectural design" underscores how VR and AR enhance precision and stakeholder engagement in the planning and design phases. The connections to "engineering education", "students", and "e-learning" further reveal the growing role of immersive technologies in addressing the skills gap, suggesting their value for training future professionals in using BIM-enabled tools. Peripheral nodes, such as “IoT” and “AI”, signal opportunities for deeper integration of immersive environments with data-driven technologies, enabling real-time updates, predictive modeling, and advanced analytics within BIM platforms. The visualization’s underlying structure, composed of 30 nodes and numerous links, points to an intellectually rich and evolving field. The proximity of nodes within the network correlates with the thematic alignment of the research, while the thickness of the links suggests the strength of these associations. This bibliometric map does not merely chart a static view of BIM-ImT research; it signals an ongoing dialogue among disciplines, a confluence of technology and practice, and an academic sphere responsive to the advances in digital construction technology. The data-driven insights from this analysis are intended to scaffold the future trajectory of BIM research, ensuring that it is aligned with the industry’s shift towards digitalization and sustainability.

4.2 Recent research on the integration of BIM and ImT in building projects

This section will examine key features to explore the context of how the integration of BIM with ImT unfolds in building projects, using findings from previous publications.

4.2.1 Application areas

It is apparent that the incorporation of BIM and ImT within construction processes has garnered considerable interest from scholars, particularly in areas like safety training (20 studies), collaborative decision-making (13 studies), cost estimation and design modification (10 studies), remote communication (9 studies) and human-robot interaction (4 studies). Notably, construction safety training and education has seen significant scholarly attention, with researchers such as Le et al. (2015) and Shringi et al. (2023) investigating diverse methodologies and technological enhancements to bolster construction site safety. Conversely, the bulk of the research corpus explores how the integration of BIM and immersive technologies can resolve challenges associated with design modifications and decision-making processes in construction. Key contributors to this body of research include Panya et al. (2023), Du et al. (2018), and Marzouk and Zaher (2015). The considerable focus on these themes can be attributed to the critical importance of safety and efficiency within the construction sector, alongside the anticipated benefits of employing sophisticated technologies to enhance these facets.

4.2.2 Research methods

Recent studies on the integration of BIM and ImT in construction projects have adopted diverse research methodologies, primarily encompassing conceptual models, case studies, and experimental setups. While these approaches offer significant insights, they often focus on isolated technical aspects, lacking comprehensive strategies for holistic integration. To begin with, conceptual models dominate the research landscape, providing theoretical frameworks for BIM and ImT integration. However, many models prioritize specific applications such as visualization or progress monitoring while overlooking critical socio-technical dimensions necessary for widespread adoption. For instance, Du et al. (2018) proposed an ontology-based approach to enhance information interoperability between BIM and AR/VR. Although this method effectively addressed data transfer issues, its semi-automatic nature required further development for full automation. This mixed-methods approach, combining qualitative ontology development with quantitative polygon reduction techniques, provided a comprehensive framework but failed to address practical challenges such as user acceptance and interdisciplinary collaboration. Similarly, Wang et al. (2020) developed a conceptual framework for real-time BIM-VR synchronization. Their qualitative approach, focusing on analyzing concepts and relationships, facilitated an in-depth exploration of information latency issues. However, the study’s focus on technical aspects overlooked the organizational changes required for effective implementation, emphasizing the need for a more integrated approach that considers both technical and organizational factors. Moving forward, case studies provide valuable practical insights into the application of BIM and ImT integration. However, many of these studies are limited in scope and fail to address broader implementation challenges. Zaher et al. (2018) utilized a qualitative case study approach to explore the benefits of using handheld mobile devices for construction project tracking. While this method offered practical insights, it relied heavily on pre-existing BIM models and schedules, potentially neglecting the challenges of creating and maintaining these resources in dynamic construction environments. This highlights the need for further research into the processes of generating and updating BIM models in real-world scenarios. Similarly, Ratajczak et al. (2019) employed a mixed-methods approach, combining qualitative descriptions of their AR4C application with quantitative analysis of key performance indicators. While this methodology demonstrated the potential of integrating BIM with AR for performance monitoring, it was limited by its prototype nature, lacking full system integration and large-scale testing across construction phases. These limitations underscore the need for long-term trials to fully evaluate the effectiveness of BIM-AR integration solutions. In addition, experimental studies create controlled environments for testing BIM and ImT integration but often struggle to replicate the complexity of real-world construction scenarios. For example, Getuli et al. (2022) adopted a mixed-methods approach that combined qualitative object identification with quantitative validation through collaborative VR sessions to develop a BIM-based site object library for VR safety training. Although this approach highlighted the potential of VR for safety training, it was constrained by a small sample size and lacked comparisons with traditional training methods. Similarly, Li et al. (2018) employed an experimental procedure with statistical analysis to examine the use of immersive technologies in construction site safety education. While this allowed precise measurement of learning outcomes, the focus on entry-level employees and single-user scenarios overlooked the collaborative nature of actual construction sites. These findings emphasize the need for more complex, multi-user VR simulations to accurately reflect collaborative work environments.

Moreover, when analyzing thematic applications, studies on AR, such as those by Park et al. (2013) and Kwon et al. (2014), primarily employed mixed-methods approaches combining qualitative analysis of current practices with quantitative evaluation of proposed systems. These methods demonstrated the potential of AR for specific tasks like defect management but were often constrained by small-scale implementations and technical challenges in marker recognition and real-time tracking. This calls for further research into markerless tracking techniques and large-scale AR solutions to address these limitations. Similarly, VR-focused studies, including those by Kamari et al. (2020) and Shahinmoghadam et al. (2021), integrated qualitative user feedback with quantitative performance metrics. While these approaches effectively showcased VR's potential for tasks like cost assessment and thermal comfort monitoring, they frequently struggled to resolve issues related to user acceptance and long-term adoption. Addressing these human and organizational factors is essential for the broader application of VR technologies in construction. In another context, research methodologies also varied across different project lifecycle stages. Pre-construction studies, such as Wang et al. (2022), often adopted mixed-methods approaches to evaluate virtual trial assembly processes. Meanwhile, construction-phase studies, like those by Chen et al. (2021), frequently utilized experimental setups to test real-time monitoring systems. Post-construction research, exemplified by El Ammari and Hammad (2019), employed case studies to investigate facility management applications. This diversity in research approaches highlights the necessity of adopting integrated methodologies to study the application of BIM and ImT throughout the entire project lifecycle. In summary, while current research has significantly advanced understanding of BIM and ImT integration, methodological limitations persist. Many studies focus on isolated technical aspects without addressing the complex interplay of human, organizational, and technological factors. Socio-technical challenges, including system interoperability, user acceptance of new technologies, and effective interdisciplinary collaboration, remain critical obstacles. This entails developing integrated frameworks that account for both technical and social-related criteria and conducting longitudinal studies to evaluate the long-term impact of BIM-ImT integration strategies.

4.2.3 BIM-related software

During the integration of BIM and ImT, software tools serve as critical methodological enablers, allowing researchers to experiment with and refine innovative approaches to digital transformation in construction. However, the selection and use of BIM-related software are not solely based on commercial availability but must also consider their ability to meet the specific requirements of each project phase and research methodology. In the domain of modeling and design, software such as Autodesk Revit and Google SketchUp represent two distinct approaches. Revit, with its ability to create complex BIM models and integrate with virtual reality technologies, has opened new opportunities for exploring and evaluating design solutions in immersive environments (Kamari et al., 2020). It is still considered the most widely adopted BIM platform across AEC industries due to its comprehensive collaboration tools and industry-standard status (Hussain, 2023). Additionally, SketchUp, with its simplicity and flexibility, is better suited for the initial conceptualization phase and small-scale projects (Olbina and Glick, 2022). This contrast highlights a critical gap in the current BIM software ecosystem: the lack of intermediary tools that seamlessly bridge the transition from conceptual sketching to detailed model development while maintaining ease of use and the ability to handle complex information. In the context of simulation and analysis, tools like 3ds Max and Fuzor have significantly enhanced the capabilities for visualizing and simulating construction processes. O'Grady et al. (2021) demonstrated that these tools facilitate detailed analysis of "what-if" scenarios in virtual environments, providing robust support for decision-making and risk management. However, data loss during the transfer between BIM and ImT platforms, particularly concerning non-geometric attributes, remains a significant challenge. This issue not only affects data consistency but also undermines the efficiency of BIM-ImT integration in complex projects. From the perspective of visualization and collaboration, ArchiCAD and Unity (though not a dedicated BIM tool) have expanded the boundaries of interaction and collaboration in virtual environments. Research by Meža et al. (2014) and Latini et al. (2023) demonstrated the potential of these tools to enhance collaborative experiences and design evaluation in virtual meetings. However, maintaining consistency between original BIM models and ImT environments remains a substantial challenge, particularly when design changes occur. This underscores the urgent need for more effective automation and synchronization solutions between BIM and ImT platforms.

An overall evaluation of the current software's support for BIM-ImT integration reveals that despite significant advancements, critical gaps remain. Issues such as data compatibility, balancing model complexity with immersive application performance, and ensuring seamless workflows across project phases have yet to be fully addressed. These limitations not only impact technical efficiency but also hinder the broader adoption of BIM-ImT in construction practices. Regarding the relationship between software functionalities and research methodologies, current tools have opened new opportunities for experimental design and addressing social challenges in BIM-ImT research. For example, Revit's parametric modeling capabilities allow researchers to design experiments that evaluate the impact of design changes in real-time within immersive environments (Shringi et al., 2023). Similarly, Unity facilitates in-depth research on user interaction and interdisciplinary collaboration in virtual environments (Adami et al., 2022). However, significant gaps remain in supporting comprehensive research methodologies for BIM-ImT, particularly in assessing the long-term impacts of these solutions on project performance and social outcomes. While BIM-related software has laid a critical foundation for the development of BIM-ImT research and applications, there remains considerable scope for improvement and expansion of their capabilities. Addressing these gaps will require not only technical innovation but also a multidisciplinary approach that integrates social or organizational, and technical factors to advance the holistic development of this field.

4.2.4 The use of ImT hardware

The integration of ImT with BIM in construction projects has significantly transformed the approach to design, construction, and management of buildings. An analysis of previous studies reveals that the utilization of ImT hardware can be categorized into three main groups, including visualization devices, interaction devices, and mobile devices. Each category offers distinct advantages and presents specific challenges in the process of integration with BIM. In terms of visualization devices, various types of head-mounted displays (HMDs) have been employed, including Oculus Rift, HTC Vive, and Microsoft HoloLens. Alizadehsalehi et al. (2020) utilized Oculus Rift and HTC Vive to convert BIM models into VR environments, enabling users to experience models at full scale and interact with building components. This approach significantly enhanced the ability to understand and evaluate designs compared to traditional 2D drawings. However, the implementation of these devices necessitated hardware upgrades to meet complex graphics processing requirements and posed challenges related to file size limitations when uploading to cloud platforms. Concurrently, Microsoft HoloLens was employed to transform BIM models into MR environments, allowing digital models to be superimposed onto the physical world. Also, Rahimian et al. (2020) combined both Oculus Rift and HoloLens in an automated construction progress monitoring system, integrating BIM, machine learning, and VR/AR. This approach enabled users to visually interact with 3D models in virtual environments, improving the ability to detect discrepancies between design models and actual construction. Nevertheless, this integration required the development of complex algorithms to combine data from original BIM models and real-world images into VR/AR environments, presenting technical challenges and implementation time constraints. Regarding interaction devices, handheld controllers accompanying HMDs have been utilized to create more natural interaction experiences in virtual environments. For instance, Dias Barkokebas and Li (2021) employed the HTC VIVE system, comprising two handheld controllers, one VR headset, and two base stations, to create a VR environment for assessing ergonomic risks in industrialized construction tasks. This approach allowed for accurate simulation of real-world tasks in virtual environments, enabling proactive ergonomic risk assessment from the initial design stage. However, the study also highlighted the need for improvements in VR's ability to accurately simulate hand movements and complex interactions, indicating a persistent gap between virtual and real-world interactions that requires further technological advancements in motion sensing and processing. In the field of mobility, the use of tablets and smartphones to deploy AR applications on construction sites has been widely discussed in various studies. A good example is that Ratajczak et al. (2019) developed the AR4C (Augmented Reality for Construction) application using a Lenovo Phab 2 Pro smartphone with Google Tango AR technology. This application allowed for the display of 3D BIM models in the real environment on-site, facilitating location-based task management and construction progress monitoring. However, the use of mobile devices also presented challenges related to the performance of processing complex 3D graphics and the accuracy of AR positioning in dynamic construction environments.

While ImT devices offer numerous benefits in visualizing and interacting with BIM models, integrating them into existing workflows is not without challenges. Many studies have indicated a steep learning curve for users when familiarizing themselves with new interfaces and interaction modes (Liu et al., 2024). For example, Olbina and Glick (2022) observed that students required time to acclimate to VR/AR technology, particularly AR, as it was their first exposure to the technology. This underscores the need for training and technical support when implementing ImT solutions in real construction projects. Furthermore, the integration of ImT with existing BIM processes poses challenges related to compatibility and workflow. Du et al. (2017), in developing a real-time BIM-VR data synchronization system (BVRS), encountered system performance issues when BIM models contained numerous interdependent objects. This highlights the need for careful consideration of how BIM data is organized and optimized to ensure performance when used in ImT environments. From a technical standpoint, compatibility issues between different software platforms and hardware devices present a significant challenge. Alizadehsalehi et al. (2020) had to utilize multiple intermediate software such as Fuzor, Microsoft 3D Viewer, HoloLive, and HoloView to convert BIM models into formats compatible with various ImT devices. This process is not only time-consuming but can also lead to information loss or discrepancies during the conversion process. In conclusion, the use of ImT hardware in integration with BIM offers numerous benefits in terms of visualization, interaction, and mobilization of construction information. However, to effectively harness the potential of these technologies, significant investment is required in user training, workflow optimization, and development of seamless integration solutions between BIM and ImT. It is necessary to focus on addressing these social-technical challenges while exploring new applications of ImT throughout the entire lifecycle of construction projects, from the design phase to operation and maintenance of buildings.

4.2.5 Integration of BIM with ImT through game engines

The integration of BIM with ImT in construction management increasingly relies on game engines, which provide immersive and interactive environments to enhance visualization, collaboration, and decision-making. Unity and Unreal Engine have emerged as dominant platforms in recent years due to their adaptability, open-source tools, and ability to support real-time rendering for complex construction scenarios. These advancements underline the transformative potential of game engines in addressing contemporary challenges within the AEC sector. Potseluyko et al. (2022) highlighted the capabilities of Unreal Engine in BIM manipulation, leveraging its real-time rendering and cross-platform compatibility to facilitate efficient workflows and enhanced stakeholder collaboration. Similarly, Han et al. (2021) utilized Unity 3D alongside Autodesk 3ds Max and Visual Studio C# to create a VR platform, demonstrating the fusion of BIM and ImT technologies to support design iteration and real-time project visualization. Early studies, such as Marzouk et al. (2015) and Kwon et al. (2014), explored the initial applications of Unity 3D and ARToolKit for specific tasks like defect management and site coordination. While these studies laid important groundwork, they were constrained by the hardware and software limitations of their time, as well as a narrower focus on isolated use cases. For example, Marzouk et al. (2015) emphasized defect management but did not extend their framework to other lifecycle stages or cross-disciplinary collaboration. By contrast, recent studies, such as Wang et al. (2022), demonstrate a broader focus by employing Dynamo in Autodesk Revit for parametric design, addressing contemporary challenges like system scalability and data interoperability.

The evolution of game engines highlights significant progress in their application to BIM-ImT integration. Earlier implementations were often limited by the technological constraints of their time, offering task-specific solutions with restricted ability. Recent advancements, however, focus on modularity, cross-disciplinary collaboration, and enhanced user interaction design. These developments reflect the growing importance of game engines as flexible and adaptable tools for integrating BIM with ImT across diverse construction scenarios. Therefore, the development of methodological frameworks that align with recent technological advancements is critical for advancing the integration of game engines into BIM-ImT workflows. Rather than emphasizing specific tools or platforms, it is important to explore how game engines can be systematically integrated into this process to address socio-technical challenges, including stakeholder engagement, data interoperability, and lifecycle management.

By focusing on these broader aspects, the use of game engines in BIM-ImT integration can significantly contribute to the ongoing digital transformation of the construction industry.

4.2.6 Data standards

Data standards play a crucial role in facilitating seamless data exchange and integration between BIM and ImT systems. Standards such as IFC (Industry Foundation Classes) have been widely adopted to enable the consistent representation and transfer of building information across platforms. For example, IFC provides a standardized structure for exchanging BIM data, ensuring compatibility between different software solutions (Meža et al., 2014). To implement these standards in practice, data formats like FBX (Filmbox) are often used to convert and transfer BIM models for specific applications. FBX, widely recognized as a format for 3D data exchange, is extensively applied in immersive environments to integrate BIM models with VR and AR applications (Balali et al., 2020). This highlights the complementary roles of standards and formats, where standards like IFC define the structure and semantics of data, and formats like FBX provide the means to transfer and visualize it effectively. Likewise, formats such as XML and CSV play a critical role in BIM workflows. These formats act as mediums to structure and transfer data based on predefined standards. One notable example is ifcXML, an XML representation of the IFC standard, which facilitates the exchange of structured BIM data within interoperable workflows (Han and Leite, 2022). Additionally, CSV files are commonly employed to export tabular BIM data for integration into other tools, though their effectiveness depends on adherence to established standards (Kamari et al., 2020). Recent research also illustrates the importance of consistent naming conventions and data organization when implementing standards like IFC. Delgado et al. (2020) highlighted the need for strict adherence to naming conventions to ensure accurate data retrieval and visualization in VR and AR contexts. By providing a unified framework for data exchange, these standards and formats collectively enable the effective integration of BIM and ImT technologies, bridging gaps in interoperability and supporting the digital transformation of the construction industry.

4.2.7 Collaboration and communication platforms

In the process of integrating BIM and ImT into construction projects, collaboration and communication platforms play an important role in connecting stakeholders, managing data, and creating efficient working environments. Analyzing previous studies reveals that these platforms focus on three main aspects such as data management, immersive features, and communication protocols. Each of these aspects has its own distinct contributions to improving workflows, along with certain limitations.

In terms of data management, platforms such as BIM 360, CloudDB, and Google Fusion Tables have introduced breakthroughs in centralizing and sharing project information. BIM 360, as applied in the NASA-Mars habitat project by Alizadehsalehi et al. (2020), demonstrated its capability as a cloud-based storage platform that enables all stakeholders to access BIM models in real time. This not only provides a single source of truth for the project, improving collaboration but also supports experimental designs where multiple stakeholders can simultaneously interact with updated BIM data, fostering cooperative decision-making in complex projects. However, the limitation in file size when uploading AR models to the cloud remains a technical challenge that needs to be addressed to optimize the platform’s performance. Similarly, CloudDB, studied by Alirezaei et al. (2022), has achieved significant progress in facilitating real-time data sharing between office teams and on-site personnel. By integrating CloudDB with mobile AR applications, the platform has contributed to bridging socio-technical gaps, allowing stakeholders to dynamically identify and resolve risks. The use of CloudDB for managing risk data through color-coded AR visualizations over BIM models has introduced a proactive approach to risk management. Nevertheless, maintaining stable internet connectivity for real-time updates remains a challenge, particularly in complex construction environments. In addition, Google Fusion Tables, as applied by Marzouk and Zaher (2015), has opened up opportunities for storing and sharing construction progress data integrated with 5D BIM models for cost and schedule analysis. This platform enables project managers to collaborate on real-time updated datasets, enhancing decision-making efficiency. However, its inability to support highly detailed BIM models on mobile devices limits its usability in complex construction projects. This highlights the need for developing data optimization solutions to ensure consistent performance across devices with varying configurations.

Regarding immersive features, platforms such as Second Life (SL), CoVR, and AR4C have achieved notable advancements in enhancing interaction and visualization in virtual or augmented environments. Second Life, studied by Le et al. (2015), demonstrated its capability to create a shared 3D environment where multiple users can interact. This platform supports collaborative learning and decision-making by allowing users to navigate BIM models and simulate construction scenarios in real time. However, its steep learning curve and high hardware requirements have limited accessibility. Despite these challenges, SL offers unique insights into user interaction and social dynamics in collaborative tasks, contributing to experimental designs that explore behavior and workflows in virtual environments. Additionally, CoVR, developed by Du et al. (2018), is a multi-user VR system that integrates BIM data into a cloud-based virtual environment. The platform facilitates real-time voice communication and collaborative interaction among remote stakeholders. While CoVR has improved engagement and coordination, challenges such as model optimization for rendering and software compatibility hinder its ability. Nonetheless, CoVR demonstrates the potential of immersive technologies to overcome geographical barriers and enhance experimental designs through collaborative simulations. This opens up opportunities for further research on how virtual environments can be utilized to simulate and optimize complex construction workflows. Furthermore, AR4C, developed by Ratajczak et al. (2019), integrates BIM with AR and location-based management systems (LBMS). The application enables visualization of construction progress and performance indicators directly on-site using Google Tango technology. Although AR4C has improved real-time monitoring and decision-making, challenges remain in aligning virtual models with physical environments and integrating diverse data sources. These limitations emphasize the need for streamlined workflows and user training to maximize the potential of AR technology in construction. Further research into optimizing AR alignment and data integration could unlock new opportunities for adopting AR in construction project management.

For communication protocols, studies have highlighted the importance of protocols such as HTTP, REST, WebSocket, and WebRTC in facilitating real-time data exchange. Shahinmoghadam et al. (2021) utilized HTTP and the VaRest plug-in to establish REST communication between IoT sensors and VR game engines. This setup enabled real-time monitoring of construction conditions by streaming data directly from cloud modules to immersive environments. While challenges such as low sensor accuracy and the complexity of IoT data integration into VR persist, the system's ability to visualize dynamic conditions in real time has significantly contributed to experimental designs focused on real-time decision-making. Additionally, Bao et al. (2022) emphasized the use of WebRTC and WebSocket to support voice, video, and data communication in WebXR environments. These protocols facilitate seamless interaction among users by maintaining low-latency connections, even in multi-user settings. However, optimizing 3D models for mobile VR rendering remains a limitation. The use of these protocols demonstrates how communication frameworks can support experimental designs by enhancing accessibility and collaboration across devices and platforms. Besides, El Ammari and Hammad (2019) used the RPC protocol for synchronized data streaming between AR and IAV modules, enabling real-time visual collaboration between field workers and office managers. This protocol bridged the gap between physical and digital environments, allowing georeferenced task assignments and defect marking. However, challenges such as optimizing 3D models for mobile devices and overcoming user resistance to adopting new workflows remain unresolved. It is evident that, although these collaboration and communication platforms have introduced notable technical advancements in integrating BIM and ImT, the gaps in comprehensively addressing socio-related challenges must also be emphasized. Consideration of factors such as technology acceptance, user training and skill development, as well as impacts on organizational structures and workflows, is essential to better understand how these platforms can be effectively integrated into construction environments.

4.3 Social-Technical aspects of BIM-ImT Integration in building projects

The integration of BIM and ImT in building projects is influenced by various criteria, which can be broadly categorized into *technical* and *non-technical criteria*. *Technical criteria* encompass factors such as data exchange and synchronization, software compatibility, hardware requirements, visualization capabilities, real-time interaction, and model modification. On the other hand, *non-technical criteria*, which also include what are often referred to as *social-related criteria* in this study, focus on aspects such as user acceptance and engagement, collaboration and communication, training and education, as well as user experience and interaction design. These criteria also address regulatory compliance, privacy, and ethical considerations. While technical criteria are primarily concerned with the practical aspects of technology, non-technical or social-related criteria are more focused on the human and organizational factors that facilitate or hinder the adoption and integration of BIM and ImT. Additionally, the role of AI technologies in improving these integration approaches is emphasized, further supporting the enhancement of both technical and non-technical dimensions. Specific details and in-depth analyses of these criteria will be presented and discussed in the following section, while the corresponding references will be included in Tables 3 and 4 of the Appendix.

5. RESEARCH DISCUSSION

Based on the literature review, several technical and social criteria have been identified as crucial for the effective use of BIM software in integrating with ImT in building projects. The authors carefully chose these criteria to address specific aspects that significantly impact the performance and compatibility of BIM software in immersive environments.

5.1 Technical-related criteria

The integration of BIM with ImT is influenced by a variety of technological parameters that are necessary in ensuring the compatibility, performance, and usability of the integrated system. In the subsequent sections, these technical aspects are examined in depth to reveal their influence on advancing industry practices. By focusing on the interplay between these criteria, the discussion highlights their role in driving the digital transformation of construction processes. Each criterion is analyzed in terms of its contribution to achieving flexible, integrated, and robust solutions, ensuring that BIM-ImT systems meet the demands of increasingly complex and dynamic construction environments.

5.1.1 BIM-related software

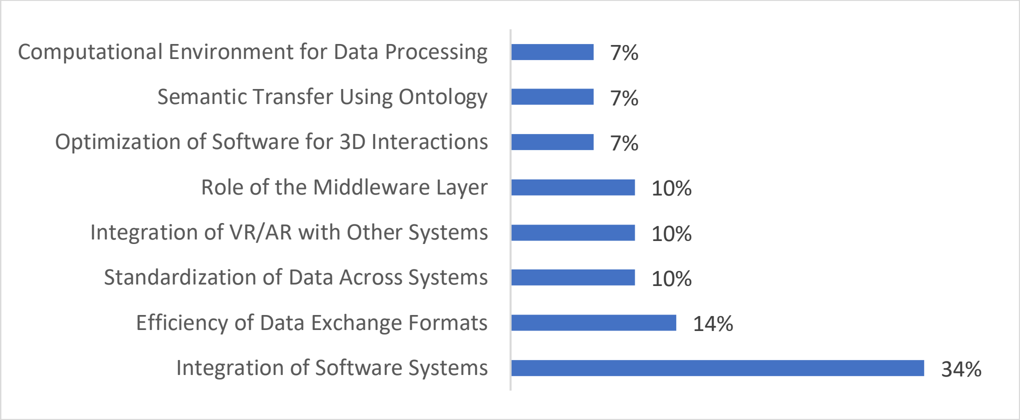


Figure 4: Summary of technical criteria regarding BIM-related software mentioned in reviewed studies.

The integration of BIM-related software in AEC projects is governed by a range of technical criteria that influence both the efficiency and applicability of BIM-ImT workflows. Each criterion reflects specific challenges and opportunities, shaping the overall potential for advancing construction management practices.

First, the *"Integration of Software Systems"* (34%) serves as a critical technical criterion in the integration of BIM and ImT, focusing on compatibility and seamless data exchange between platforms such as Autodesk Revit and ArchiCAD. Alizadehsalehi et al. (2020) and Balali et al. (2020) emphasize that proprietary systems often create data silos, hindering workflows and limiting accessibility. To address this, adopting standardized data exchange formats such as IFC (Industry Foundation Classes) has been highlighted as a key approach to ensuring interoperability. By enabling smooth information flow across project stages, these standards mitigate technical barriers, foster collaboration, and enhance project coordination. Additionally, Balali et al. (2020) propose the development of custom plugins to establish direct connections between BIM software and ImT platforms, allowing real-time data synchronization. Rahimian et al. (2020) further underscore the importance of optimizing performance during the transfer of complex BIM models into immersive environments, recommending the use of dynamic Level of Detail (LOD) techniques to balance model accuracy and display speed. Furthermore, O'Grady et al. (2021) suggest implementing centralized version management systems to track changes in BIM models and update them in corresponding ImT environments. These strategies collectively address the challenges of compatibility and performance, facilitating seamless integration while improving data exchange efficiency in BIM-ImT workflows.

Second, the *"Efficiency of data exchange formats"* (14%) plays a pivotal role in ensuring consistent and accurate information transfer across diverse BIM and ImT platforms. Standardized formats such as FBX and CSV help reduce the need for complex data conversions, minimizing errors and preserving data integrity throughout the project lifecycle (Delgado et al., 2020). This is particularly critical in large-scale projects, where fragmented data exchange can lead to costly delays and inefficiencies. Open formats like IFC are widely adopted to enhance interoperability among different BIM software systems. By providing detailed descriptions of building components – including geometry, materials, and relationships – IFC facilitates the seamless exchange of complex data (BIMcollab, 2024). Additionally, the application of open standards like Information Delivery Specification (IDS) defines clear requirements for data exchange, ensuring BIM model quality is established from the beginning. IDS aids in setting precise parameters for information delivery, thereby reducing inconsistencies during the design and construction phases. To further optimize this process, specialized tools are employed for transforming and harmonizing BIM, CAD, and GIS data, enabling semantic interoperability across systems (Birkenbeul, 2020). These tools not only bridge gaps between disparate platforms but also provide a framework for data refinement, integration, and quality assurance within a unified workflow. Interactive graphical interfaces, as emphasized by Alizadehsalehi et al. (2020), are instrumental in defining essential processing steps, combining tasks such as data harmonization, integration, and validation into a cohesive pipeline. Such graphical interfaces streamline workflows, reduce manual intervention, and enhance the reliability of data exchange processes. Moreover, the use of format-independent tools, highlighted by Rahimian et al. (2020), allows for greater flexibility in combining diverse workflows. These tools support seamless collaboration by enabling smooth integration of BIM data with ImT platforms, irrespective of the specific formats being utilized. This flexibility not only improves the efficiency of data exchange but also ensures information integrity across the project lifecycle, which is especially significant for large-scale construction projects.

Third, the *"Role of the Middleware Layer"* (10%) is essential in bridging the gap between BIM platforms and ImT like VR and AR. Middleware functions as an intermediary, enabling flawless data transformation and synchronization across these systems. Specifically, it facilitates this process through mechanisms such as Application Programming Interfaces (APIs) and Software Development Kits (SDKs), which allow for efficient data retrieval and conversion from BIM to formats compatible with ImT tools (Zaher et al., 2018). For instance, middleware can convert BIM models from formats like IFC into FBX or OBJ, ensuring compatibility with game engines such as Unity or Unreal Engine. In addition, middleware enables real-time synchronization between BIM and ImT by employing protocols like WebSocket (Bao et al., 2022) or REST API (Shahinmoghadam et al., 2021). This functionality ensures that any modifications made to BIM models are immediately reflected in immersive environments and vice versa. Moreover, middleware supports data compression and optimization techniques to improve performance when rendering complex models in ImT environments (O'Grady et al., 2021). Hence, middleware is important in improving the viewing and interaction possibilities of BIM data within ImT applications by tackling issues of compatibility and performance. Effective BIM-ImT integration depends mostly on its capacity to provide real-time changes and smooth data interchange.

Fourth, the "*Integration of VR/AR with Other Systems"* (10%) has become a critical component in enhancing project visualization and stakeholder engagement. These immersive tools facilitate real-time interaction with BIM models, enabling early error detection and informed decision-making, as emphasized by Shayesteh et al. (2023). This integration reflects the increasing demand for dynamic and interactive solutions in construction project management. In practice, integrating VR and AR systems with BIM software involves a complex technical process to ensure data compatibility and synchronization. Delgado et al. (2020) advocate for the use of ontology to establish automated bidirectional communication between BIM models and VR/AR systems. This process typically requires converting BIM data into formats compatible with VR/AR environments, often facilitated by middleware tools such as Unity or Unreal Engine. Le et al. (2015) highlight the importance of employing fiducial markers to accurately position virtual models within physical spaces, ensuring precise alignment and enhancing user interaction. Additionally, O'Grady et al. (2021) propose integrating game design principles with BIM digital twins to create highly interactive VR experiences. This approach involves optimizing BIM models to reduce complexity, maintaining performance efficiency in VR/AR environments while preserving the accuracy of information. However, achieving real-time data synchronization between BIM models and VR/AR environments remains a significant technical challenge. Ensuring consistent information flow across platforms is essential to maintain data accuracy and usability.

Fifth, the "*Standardization of Data Across Systems"* (10%) is a crucial technical criterion for integrating BIM and ImT, particularly in ensuring interoperability and data consistency across diverse software platforms. Achieving effective data standardization involves several key approaches. The adoption of open file formats such as IFC is fundamental to enabling compatibility between different systems, as highlighted by BIMcollab (2024). Nguyen et al. (2022) emphasize the importance of utilizing shared communication protocols like RESTful APIs to facilitate seamless data exchange between BIM and ImT environments. Additionally, creating a unified data dictionary, such as the International Framework for Dictionaries (IFD), ensures semantic consistency during information exchange, as noted by Colabaga Don and Axéll Gholizadeh (2023). Specialized ETL (Extract, Transform, Load) tools, proposed by Yousif et al. (2021), play a vital role in transforming and standardizing data across disparate systems. Moreover, establishing a standardized Common Data Environment (CDE) provides a centralized platform for storing and managing BIM and ImT data, as evidenced by Alizadehsalehi et al. (2020). Shayesteh et al. (2023) further highlight the need for developing automated workflows to maintain data consistency during system transitions. Finally, the adoption of international standards, such as ISO 16739 for BIM data sharing, promotes interoperability and standardization on a global scale (Standards Australia, 2017). By implementing these measures, organizations can enhance data consistency and improve integration between BIM and ImT systems, fostering more effective collaboration and streamlined workflows.

Sixth, the "*Optimization of Software for 3D Interactions"* (7%) is also a crucial technical criterion for improving the usability and performance of 3D BIM models in immersive environments. Optimizing software for 3D interactions involves enhancing graphical rendering efficiency and streamlining data processing. Balali et al. (2020) emphasize the importance of utilizing effective data exchange formats, such as IFC or glTF, to optimize data transfer between BIM software and ImT platforms, ensuring compatibility and reducing latency. Nechyporchuk and Baskova (2021) highlight the role of dynamic LOD techniques, which adjust the complexity of 3D models based on viewing distance, balancing image quality and rendering speed. Furthermore, incorporating interactive tools like gesture recognition and haptic feedback improves the intuitiveness of user interactions within immersive environments. Johansson and Roupé (2024) suggest employing occlusion culling to eliminate hidden objects from rendering pipelines, thereby reducing GPU workload and enhancing frame rates. Advanced techniques for data compression and on-demand streaming also minimize delays, enabling smooth interactions with complex 3D models. These optimizations collectively improve system performance, while also enhancing the accuracy and intuitiveness of 3D interactions, particularly in the design and planning phases of construction projects.

Seventh, the "*Semantic Transfer Using Ontology"* (7%) plays a key role in bridging the semantic gap between BIM and ImT systems, enabling more effective data exchange and intelligent processing in construction workflows. Ontology-based methods ensure a structured and consistent representation of BIM data, facilitating semantic understanding and enhancing interoperability. Chen et al. (2020) highlight how semantic approaches improve data retrieval and management by introducing a systematic process. This involves clearly representing source data records, normalizing identifier references, aggregating equivalent identifiers from multiple sources, and applying forward reasoning rules to generate representations based on shared ontological models (El-Mekawy and Östman, 2010). Furthermore, Yin et al. (2024) demonstrate the use of OWL (Web Ontology Language) to enhance semantic structures, enabling the creation of vocabulary graphs that support complex query generation. These methodologies not only ensure data consistency but also allow intelligent queries across various construction applications, improving efficiency and accuracy in managing BIM-ImT workflows. By implementing such techniques, developers can establish a semantic bridge between BIM and ImT, facilitating more effective data retrieval, enhancing interoperability, and paving the way for deeper integration of these technologies into construction processes.

Lastly, the "*Computational Environment for Data Processing"* (7%) is a critical factor in determining the ability of BIM software to handle the demanding requirements of complex data processing in ImT workflows. A robust computational infrastructure not only supports advanced functionalities, such as AI-driven simulations and real-time rendering, but also enhances the efficiency and effectiveness of modern construction practices (Latini et al., 2023). High-performance computing (HPC) solutions, including dedicated servers and cloud services, play a vital role in augmenting the data processing capabilities of BIM environments, as highlighted by Lucena and Saffaro (2022). For instance, segmenting BIM models into manageable components, employing dynamic LOD techniques, and optimizing rendering algorithms are essential strategies for achieving significant performance improvements. Furthermore, advanced data compression techniques and intelligent caching mechanisms help reduce system loads, ensuring smoother handling of complex BIM models in immersive environments. By implementing these strategies, professionals can establish an optimized computational environment that minimizes delays, supports real-time data interactions, and ultimately enhances decision-making in complex construction projects.

5.1.2 The use of ImT hardware

The integration of ImT hardware into BIM workflows is influenced by several technical criteria, each playing a distinct role in advancing system performance, usability, and industry adoption. Below is an in-depth exploration of these criteria and their implications for construction management.

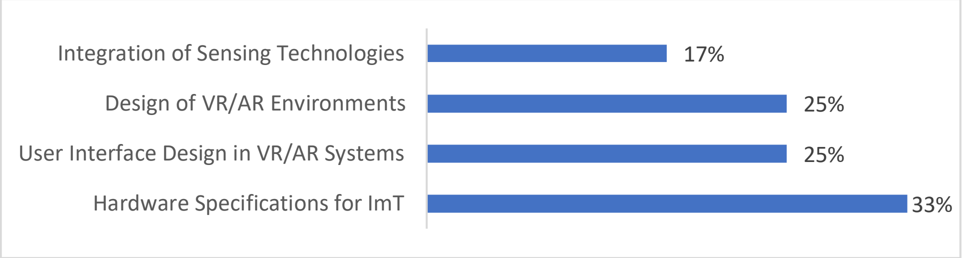


Figure 5: Summary of technical criteria regarding the use of ImT hardware mentioned in reviewed studies.

First, the *"Hardware Specifications for ImT"* (33%) is a critical factor in optimizing the performance of immersive technologies in construction workflows. Advanced hardware such as the Oculus Rift and HTC Vive provide high-quality visual displays and precise motion tracking, enabling construction professionals to interact with virtual environments accurately and intuitively during design reviews and project planning (Lucena and Saffaro, 2022). Key technical features, including high refresh rates above 90Hz and resolutions of at least 2K per eye, are essential for minimizing motion sickness and enhancing the immersive experience, as emphasized by McDonnell (2021). Additionally, motion tracking with six degrees of freedom (6DoF) plays a pivotal role in facilitating natural movement within virtual spaces, with systems like HTC Vive's Lighthouse offering superior accuracy, while Oculus Quest 2 provides portability for on-site applications (Jacobsen et al., 2022). Moreover, powerful graphics processors and a minimum of 16GB of RAM are necessary to handle real-time rendering of complex BIM models, ensuring seamless interactions in virtual environments (Zaker and Coloma, 2018). To further enhance interaction, devices such as haptic gloves provide tactile feedback, significantly improving precision in design and simulation tasks (Shayesteh et al., 2023). However, achieving a balance between hardware performance and portability remains challenging, particularly for on-site applications where mobility is essential (Han et al., 2021). Edge computing offers a potential solution by distributing computational loads between wearable devices and remote servers, thus addressing performance constraints. Despite these advancements, inconsistencies in hardware capabilities across platforms pose challenges for standardizing workflows, leading to fragmented adoption and uneven performance benchmarks. Therefore, standardizing hardware specifications across ImT platforms is vital to ensuring consistent implementation of BIM technologies in construction projects.

Second, the *"User Interface Design in VR/AR Systems"* (25%) is essential for improving the accessibility and usability of immersive technologies, especially for construction teams with diverse technical proficiency. Well-designed user interfaces (UI) facilitate seamless interaction with digital models, enabling stakeholders to make real-time adjustments to project designs and improving the efficiency of construction workflows. For instance, Garbett et al. (2021) demonstrated how intuitive AR interfaces on mobile devices streamlined communication and collaboration among geographically dispersed teams, promoting better decision-making. To achieve this, developers must optimize user experiences by applying 3D spatial design principles, as highlighted by Li et al. (2022), which involve utilizing depth, perspective, and spatial orientation to create interfaces that are visually intuitive and easy to navigate. Furthermore, integrating natural interaction methods such as hand gestures, head movements, and voice commands can make user interactions more intuitive and precise. Yu et al. (2022) showed that motion tracking technology significantly enhanced the accuracy and speed of operations in complex construction tasks. Optimizing performance by minimizing latency is equally important, as delays can lead to user discomfort and fatigue, especially during prolonged sessions. Olbina and Glick (2022) emphasize the need to balance image resolution and frame rates to ensure a smooth and immersive experience. Additionally, incorporating haptic feedback and spatial 3D audio can enhance the sense of presence and interaction, enabling users to engage with virtual environments in a more realistic and meaningful way. By implementing these strategies, developers can design VR/AR interfaces that are not only visually and functionally effective but also tailored to the needs of the construction industry, ultimately improving adoption and workflow efficiency.

Third, the *"Design of VR/AR Environments"* (25%) is crucial in transforming training, stakeholder cooperation, and safety evaluations in construction management via the development of immersive and realistic situations. These environments enable teams to identify design errors and refine safety protocols before physical implementation, significantly reducing risks and inefficiencies (Shayesteh et al., 2023). For instance, tools like Magic Leap One enhance spatial understanding and workflow optimization during the planning stages, providing an invaluable resource for improving project outcomes. Besides, effective VR/AR environments depend on three core factors including 3D modeling, interaction design, and performance optimization. As highlighted by Li et al. (2022), creating precise and detailed 3D models forms the foundation for immersive environments, which often requires specialized software like Autodesk Revit or SketchUp, coupled with laser scanning technologies to replicate real-world settings accurately. Regarding interaction, Yu et al. (2022) emphasize the importance of intuitive user interfaces and natural control mechanisms, such as hand gestures or eye tracking, facilitated by devices like Oculus Touch or HTC Vive controllers, to ensure seamless interaction. To address performance challenges, techniques such as dynamic LOD, recommended by Nechyporchuk and Baskova (2021), adjust the complexity of models based on the observer's distance, while advanced data compression algorithms reduce hardware strain. Furthermore, incorporating spatial 3D audio and haptic feedback, delivered through devices like haptic gloves, elevates the realism and engagement of these environments. However, the greatest challenge lies in balancing visual quality and performance, particularly when managing complex BIM models on mobile or standalone VR headsets with limited processing capabilities. Despite the high costs and technical expertise required, attaining cost-efficient extensibility in the design of VR/AR environments remains a critical step toward widespread industry adoption, especially for small and medium-sized construction enterprises.

Finally, the *"Integration of Sensing Technologies"* (17%) is indispensable for the improvement of real-time monitoring and interactivity in immersive construction environments. Sensing technologies, such as Leap Motion's markerless motion capture systems, perform a significant influence in enabling real-time data collection and analysis, providing stakeholders with actionable insights during design iterations and on-site coordination (Shayesteh et al., 2023). For instance, real-time tracking of user movements in virtual environments allows construction managers to simulate workflows, identify inefficiencies, and refine processes before physical implementation. This integration is technically achieved through the use of IoT sensors, MEMS devices, and wearable technologies, which are connected to BIM and ImT platforms via communication protocols like Bluetooth Low Energy or Wi-Fi Direct (Fawad et al., 2024). The data collected from these sensors, including accelerometers and gyroscopes, is processed using machine learning algorithms on GPUs embedded in ImT devices, enabling real-time gesture recognition and interaction. In addition, Zhang et al. (2020) proposed a distributed system architecture in which sensor data is aggregated through a central gateway using MQTT protocols and synchronized with BIM models via RESTful APIs. This setup facilitates real-time updates of 3D models in immersive environments, ensuring that sensor data accurately reflects current conditions. However, challenges such as latency in motion capture and inaccuracies in complex scenarios can hinder the reliability of these technologies, particularly in large-scale construction projects where precision is critical (Li et al., 2022). Besides, techniques like Kalman filtering and SLAM (Simultaneous Localization and Mapping), as noted by Yarovoi and Cho (2024), are crucial for improving positional accuracy and ensuring reliable tracking of movements in 3D spaces. Plus, optimizing network bandwidth and minimizing data transmission latency are necessary to maintain a smooth and responsive user experience within immersive environments.

5.1.3 Integration of BIM with ImT through game engines

The integration of BIM with ImT through game engines is driven by several technical criteria that significantly influence their effectiveness in construction management workflows. These criteria not only enhance technical performance but also address critical challenges in project planning, visualization, and stakeholder collaboration.

First, the *"Real-Time Visualization Capabilities"* (18%) are a critical aspect of integrating BIM with immersive technologies, leveraging game engines like Unity3D and Unreal Engine to enable dynamic interaction with BIM models. This capability allows construction stakeholders to detect design clashes and errors instantly, facilitating more efficient project reviews and reducing delays caused by miscommunication (Shahinmoghadam et al., 2021). Technically, this process involves converting BIM data into formats compatible with game engines before importing them into platforms like Unity3D or Unreal Engine (Zaman et al., 2024). These engines employ advanced rendering techniques, including ray tracing and global illumination, to produce high-quality visuals while optimizing performance through GPU enhancements and LOD techniques (Pinnacle Infotech, 2023). Moreover, Johansson and Roupé (2024) emphasize the role of custom shaders and occlusion culling in improving rendering efficiency, enabling smooth visualization of complex BIM models without lag. Techniques such as model chunking, proposed by Delgado et al. (2020), further enhance performance by dividing models into smaller sections for gradual loading, reducing startup times and memory usage. Additionally, the integration of APIs for real-time data retrieval ensures that any changes made to BIM models are immediately reflected in the immersive environment, as highlighted by Zaher et al. (2018). These combined advancements create a seamless and responsive visualization experience, allowing users to interact with BIM models effectively in immersive settings while supporting real-time decision-making and collaboration across multidisciplinary teams.

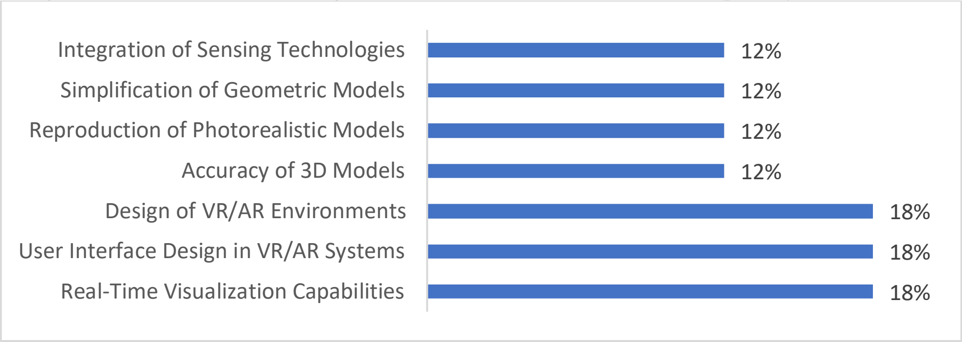


Figure 6: Summary of technical criteria regarding the integration of BIM with ImT through game engines mentioned in reviewed studies

Second, the *"User Interface Design in VR/AR Systems"* (18%) is essential for improving the accessibility and efficacy of BIM-driven VR/AR applications, allowing users with varying technical expertise to interact effectively with intricate models. Intuitive interfaces, as highlighted by Li et al. (2022), streamline user adoption and operational efficiency in construction tasks by reducing the learning curve and facilitating rapid training for workers and engineers, ultimately boosting productivity during the pre-construction and construction phases. To achieve this, developers can apply UI/UX design principles tailored for 3D environments, utilizing the capabilities of game engines such as Unity and Unreal Engine to create interactive 3D widgets. These widgets allow users to directly manipulate BIM components within virtual spaces, providing a hands-on approach to engaging with digital models. Moreover, incorporating natural gestures and voice controls, as suggested by Olbina and Glick (2022), enhances the intuitiveness of the interface, making it easier for users to navigate and interact with highly detailed BIM models. Yu et al. (2022) further emphasize the importance of optimizing rendering performance to maintain stable frame rates, particularly when working with complex BIM datasets. Additionally, integrating analytical and simulation tools directly into VR/AR interfaces, such as the ability to view detailed information about building components by interacting with them in virtual environments, supports better decision-making and problem-solving. These advancements not only make BIM-VR/AR applications more accessible to a broader range of users but also significantly improve efficiency in construction process.

Third, the *"Design of VR/AR Environments"* (18%) is also a key component in integrating BIM with ImT, offering transformative applications in training simulations, safety planning, and stakeholder engagement. The creation of these environments involves complex technical workflows that combine BIM data with the advanced capabilities of game engines. Unreal Engine, with its sophisticated rendering features, enables high-fidelity reproductions of construction sites, providing stakeholders with realistic visualizations that enhance project planning and risk assessment (Panya et al., 2023). This process begins with converting BIM models into formats compatible with game engines, typically through intermediary software like 3ds Max or Blender (Li et al., 2022). Game engines such as Unreal Engine and Unity are then utilized to optimize geometry, apply materials and textures, and configure lighting systems, resulting in highly immersive virtual environments. Moreover, Olbina and Glick (2022) emphasize the importance of incorporating interactive features within these environments, allowing users to navigate, manipulate objects, and access BIM data seamlessly. This often requires advanced programming skills using tools like C# or Blueprint Visual Scripting. However, maintaining performance while ensuring high levels of detail, particularly for large-scale projects, presents a significant challenge. Techniques, in this case, such as LOD and occlusion culling, as proposed by Johansson and Roupé (2024), are essential for optimizing rendering efficiency. Additionally, integrating dynamic BIM data, such as schedule or cost information, into VR/AR environments demands the establishment of sophisticated data synchronization protocols (Yu et al., 2022). Although game engines provide robust tools, developing high-quality VR/AR environments still requires substantial time and resources, limiting their accessibility to high-budget projects. However, with the advancement of specialized plugins, the process is expected to become more efficient in the future, broadening the applicability of VR/AR environments across a wider range of construction projects.

Fourth, the *"Accuracy of 3D Models"* (12%) is an important consideration in the integration of BIM with ImT through game engines, as accurate 3D models are essential to ensure that VR/AR representations align with real-world construction elements. Common evidence from Shahinmoghadam et al. (2021) indicates that improved model accuracy directly impacts material estimation and resource allocation, optimizing overall project costs and timelines. To achieve high accuracy, techniques such as point cloud scanning and photogrammetry are employed to gather detailed real-world data (Yu et al., 2022). Subsequently, tools like Autodesk 3ds Max and Unity 3D are utilized to process and optimize the models, ensuring both accuracy and performance when displayed in virtual environments – an essential factor in minimizing errors during project implementation. Latini et al. (2023) propose the use of LOD algorithms to automatically adjust model complexity based on viewing distance, balancing precision and performance. Meanwhile, O'Grady et al. (2021) emphasize the importance of integrating metadata from BIM into 3D models within game engines, enabling detailed information retrieval about building components. To ensure consistency, automated quality control processes are deployed to compare models in the game engine with the original BIM data (Ma, 2022). Additionally, techniques such as occlusion culling and texture atlasing in game engines optimize performance while maintaining high accuracy of 3D models (Hitech, 2018). These methods not only enhance model precision but also improve user experiences in immersive environments, fulfilling a necessary function in the effective integration of BIM with ImT.

Fifth, the criterion "*Reproduction of Photorealistic Models"* (12%) refers to the ability to create highly detailed and visually engaging models. This capability bridges the gap between technical BIM data and client expectations, ultimately improving project approvals and fostering trust among stakeholders (Garbett et al., 2021). From a technical perspective, producing photorealistic models involves a sophisticated integration of BIM with game engine tools. Zaman et al. (2024) explain that the process begins with exporting BIM data into formats compatible with game engines. Game engines such as Unreal Engine or Unity then process this data using advanced rendering algorithms, including global illumination, ambient occlusion, and ray tracing, to create lifelike visualizations. Li et al. (2022) emphasize the importance of optimizing mesh and texture to ensure real-time performance, particularly on mobile VR devices. Techniques such as LOD and texture atlasing are employed to balance visual quality with rendering efficiency. Additionally, the use of custom shaders and particle systems enhances the realism of elements such as water, fire, and smoke in virtual construction environments. A significant technical challenge lies in maintaining consistency between the original BIM data and the rendered models within immersive environments, which requires automated synchronization processes and rigorous quality control checks. The integration of technologies like photogrammetry and 3D scanning further improves the accuracy of photorealistic models, especially in renovation or heritage preservation projects (Julin, 2021). Overall, reproducing photorealistic models demands a delicate blend of traditional BIM techniques and advanced game engine technologies, resulting in a complex yet highly rewarding process that delivers realistic and interactive visual outputs.

Sixth, the criterion *"Simplification of Geometric Models"* (12%) pertains to the process of streamlining 3D models, which considerably influences data transmission and performance in ImT applications. Simplifying geometric models not only reduces computational demands but also directly influences how BIM data is processed and displayed in ImT environments. Meža et al. (2014) emphasized that simplified models are especially beneficial for extensive projects, where rendering highly detailed models can be resource-intensive. For construction managers, this translates to faster loading times and more efficient hardware utilization, enhancing overall tasks without compromising critical information. Specifically, Khairadeen Ali et al. (2021) applied a simplification method based on the voxel grid search algorithm, which automatically generates region proposals for objects of interest from laser-scanned point clouds without requiring prior object segmentation. This approach significantly reduces the number of vertices and triangles in geometric models while preserving their overall shape. Pepe et al. (2024) further developed this concept by combining geometric feature analysis with parametric object construction in Rhinoceros/Grasshopper software. Using the ShrinkWrap algorithm, they created polygonal meshes that envelop point clusters, allowing for parameter adjustments such as target edge length, deviation, and smoothing iterations. Their results demonstrate that this method can substantially decrease storage requirements while maintaining geometric accuracy. Such optimization is especially critical when integrating BIM with game engine tools, where real-time performance is paramount. By reducing model complexity while retaining essential information, these techniques enable faster data transmission and smoother rendering in ImT environments. This, in turn, fosters interactivity and enriches user experiences in ImT applications for the construction industry.

Finally, the criterion *"Integration of Sensing Technologies"* (12%) is associated with the effect of integrating sensing technologies for real-time monitoring in immersive environments. Tools like ARToolKit and Vuforia SDK facilitate real-time interaction within ImT environments, enabling construction teams to simulate various scenarios effectively. Kwon et al. (2014) emphasized the significance of these technologies in monitoring on-site activities and conducting safety assessments. By integrating real-time data from sensors, construction managers can make informed decisions that enhance site efficiency and ensure compliance with safety standards. Specifically, Li et al. (2022) demonstrated that this integration is achieved by utilizing game engine APIs to connect and process data from sensors. This data is then transformed into 3D objects within the virtual environment, allowing for the visualization of parameters such as temperature, pressure, and movement. Furthermore, Lucena and Saffaro (2022) highlighted the role of custom plugins in game engines, which optimize sensor data processing by reducing latency and increasing the accuracy of simulated environments. The integration extends beyond visualization, enabling bidirectional interaction. Users can adjust parameters in the virtual environment, and these changes are reflected back in the physical sensor systems. This creates a closed feedback loop, empowering project managers to not only monitor but also remotely intervene in construction activities through the intuitive interface provided by game engines.

5.1.4 Data standards

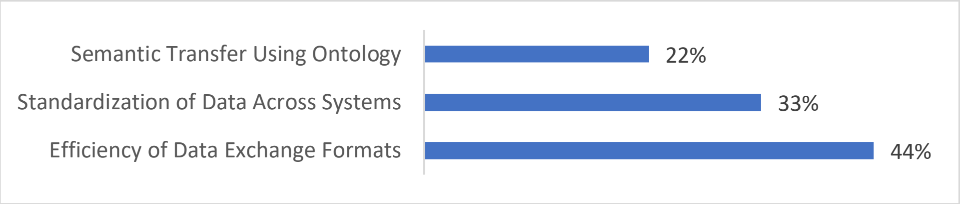


Figure 7: Summary of technical criteria regarding data standards mentioned in reviewed studies.

Data standards form the backbone of interoperability in BIM and ImT integration, enabling seamless collaboration and consistent workflows. Key technical criteria – efficiency of data exchange formats, standardization of data across systems, and semantic transfer using ontology – significantly enhance the ability of different systems to work cohesively, which is essential for the successful adoption of digital technologies in construction projects.

Regarding the criterion "*Efficiency of Data Exchange Formats"* (44%), it is evident that data exchange formats play a crucial role in transferring BIM models to ImT platforms for visualization and interaction. Technically, FBX is considered a key format that enables the accurate and efficient conversion of BIM models to ImT platforms. Unlike data standards, which define rules for organizing information, formats like FBX facilitate practical implementation by preserving the integrity of 3D models during the transfer process. Specifically, FBX maintains the integrity of 3D models by retaining information about geometry, materials, and textures during conversion (Kothawade, 2024). Kamari et al. (2020) also demonstrated FBX's effectiveness in integrating Revit models with game engines such as Unity, enabling real-time visualization and enhancing stakeholder engagement. Additionally, O'Grady et al. (2021) highlighted how FBX optimizes this process through advanced data compression algorithms, reducing file sizes without compromising quality. To handle large datasets, Park et al. (2013) proposed a model segmentation approach, dividing data into manageable parts before conversion. Rahimian et al. (2020) further contributed by introducing data streaming techniques, allowing portions of the model to be loaded and displayed on demand, thereby minimizing latency. However, challenges remain in preserving non-geometric attributes and the relationships between objects during the transfer process. Alizadehsalehi et al. (2020) suggested the use of supplementary metadata files to store this information, ensuring data consistency throughout the conversion process. Optimizing these methods is key to enhancing the efficiency of data exchange between BIM and ImT, supporting increasingly complex digital processes.

Next, the criterion *"Standardization of Data Across Systems"* (33%) warrants significant attention, as data standards like IFC are essential for maintaining interoperability between BIM and ImT platforms. By providing a widely accepted schema for data exchange, IFC ensures the consistent flow of information across diverse software environments. Studies by Du et al. (2018) and Getuli et al. (2020) highlighted how IFC minimizes translation errors, facilitates smoother collaboration, and reduces rework in multidisciplinary projects. Wang et al. (2022) emphasized that adhering to strict file-naming conventions and standardized protocols reinforces this consistency, enabling more streamlined workflows. Furthermore, Potseluyko et al. (2022) argued that adopting the IFC standard extends beyond using an exchange format and requires the establishment of a consistent data structure. Specifically, Matarneh et al. (2022) proposed developing specialized Model View Definitions (MVDs) for ImT, which precisely define the information to be extracted from BIM models for use in immersive environments. Achieving this necessitates close collaboration between BIM and ImT software developers to identify required attributes and relationships. Wang et al. (2021) added to this discussion by proposing the use of middleware - dedicated intermediary software for transforming and synchronizing data between BIM and ImT systems. These middleware solutions not only handle format conversion but also apply semantic rules to ensure information consistency. For instance, a “door” object in BIM must be converted into an interactive entity in a VR environment, complete with attributes such as open/close functionality and corresponding sound effects. To address the lack of semantic depth in IFC for specific ImT applications, researchers have suggested the development of extension schemas for IFC (Teles, 2023). These schemas add attributes and relationships specific to ImT, such as material reflectivity properties to create more realistic effects in VR. Implementing such extension schemas requires consensus within the community and standardization through recognized organizations. On another front, to ensure workflow consistency, Potseluyko et al. (2023) proposed creating standardized workflow templates for BIM-ImT integration. These templates clearly define the steps required, from BIM model preparation and data extraction to conversion into ImT environments and subsequent updates back into BIM. Such workflows not only ensure data consistency but also optimize the efficiency of multidisciplinary teams. However, implementing these standardization solutions requires significant time and resource investment, particularly in the initial stages.

Lastly, the criterion *“Semantic Transfer Using Ontology”* (22%) highlights the significance of ontology-based semantic transfer methods in facilitating the integration of BIM and ImT. This approach not only preserves the meaning and context of data but also establishes a unified framework for exchanging information across diverse platforms. Such methods are particularly beneficial in multidisciplinary projects where accurate data interpretation is essential. Chen et al. (2020) explored ontology-based solutions to enhance semantic data transfer between BIM and ImT platforms, emphasizing their utility in managing complex data structures. However, these solutions remain limited in application due to a lack of detailed methodologies and computational complexity, which present initial barriers to broader adoption in real-world scenarios. To be specific, the process involves constructing specialized ontologies for BIM and ImT and subsequently creating semantic mappings between them. Yin et al. (2024) utilized the Web Ontology Language (OWL) to model concepts and relationships within BIM, while Chen et al. (2020) focused on developing ontologies for objects in ImT environments. The next step entails identifying semantic correspondences between concepts in these two ontologies, typically facilitated by tools such as Protégé or TopBraid Composer (Panzarella et al., 2023). Practical data transfer is achieved by using query languages like SPARQL to extract information from BIM models, followed by applying predefined transformation rules to generate data compatible with ImT ontologies. Besides, Karimi et al. (2021) developed an intermediary system, called the Building Information Robotic System (BIRS), to automate this process and establish a semantic bridge between BIM, GIS, and robotic navigation systems. Nevertheless, several challenges hinder the implementation of this method. First, constructing and maintaining ontologies is inherently complex, especially when continuous updates are required to reflect advancements in BIM and ImT domains. Second, performance issues arise when processing large datasets, necessitating optimization solutions such as graph databases or distributed computing techniques. Third, the lack of standardized ontologies within the construction industry presents a significant barrier. Despite these obstacles, the potential of ontology-based semantic transfer methods is substantial. They not only enhance the accuracy of transferred data but also pave the way for developing more intelligent ImT applications capable of understanding and interacting with BIM models in a more profound manner.

5.1.5 Collaboration and communication platforms

The integration of BIM with ImT relies heavily on the functionality and robustness of collaboration and communication platforms, which influence technical coordination and interdisciplinary processes in construction. Key technical criteria, such as data fragmentation management, utilization of cloud-based services, security and privacy in AR/VR technologies, bandwidth, speed, and latency in data transfer, and incorporation of automation and AI in VR/AR, are integral to optimizing these platforms.

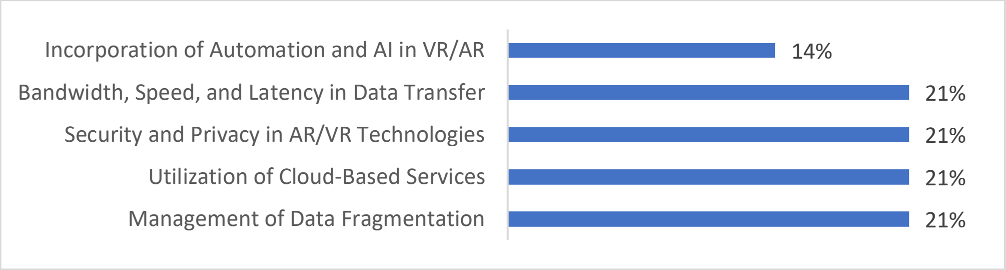


Figure 8: Summary of technical criteria regarding collaboration and communication platforms mentioned in reviewed studies.

First, the criterion *"Management of Data Fragmentation"* (21%) is considered critical, as effective collaboration hinges on maintaining consistent and integrated data across multiple systems and stakeholders. As Panya et al. (2023) highlighted, interoperability challenges between different software tools remain a significant obstacle. Such inconsistencies often lead to the creation of data silos, undermining project efficiency and increasing the likelihood of errors in complex workflows. To address this issue, Bao et al. (2022) proposed a multi-level strategy. At the data level, intermediary file formats like IFC standardize information exchange across diverse BIM and ImT platforms. At the process level, implementing standardized workflows and rigorous version control ensures the integrity and coherence of shared information. Furthermore, Autodesk BIM 360 exemplifies a centralized, cloud-based platform that facilitates real-time collaboration and data synchronization among multidisciplinary teams while serving as a reliable data source. As emphasized by Kamari et al. (2020) and Alizadehsalehi et al. (2020), this platform supports version tracking and access control, effectively addressing data fragmentation and ensuring uninterrupted cooperation across stakeholders. Nevertheless, integrating diverse data sources remains challenging, as noted by Chen et al. (2020). They proposed leveraging ontologies and semantic web technologies to create an intermediary layer that bridges disparate data systems. This approach enables more flexible querying and integration, particularly when dealing with complex BIM models in ImT environments. Additionally, the adoption of standard APIs and open data exchange protocols like RESTful API significantly enhances system interoperability and reduces fragmentation (Zaher et al., 2018). Despite these advancements, managing fragmented datasets continues to pose challenges, necessitating advanced frameworks to ensure unified data consistency and support seamless collaboration across disciplines.

Second, the criterion *"Utilization of Cloud-Based Services"* (21%) plays an important role in enhancing remote accessibility, collaboration, and information exchange in the integration of BIM and ImT. Currently, cloud platforms such as Autodesk 360 and Google Fusion Tables leverage virtualization and distributed technologies to store and process BIM/ImT data across multiple servers, enabling simultaneous access and real-time updates (Bim Americas, 2024). These platforms support geographically dispersed teams in managing BIM and ImT data; however, concerns over data loss, security breaches, and limited standardization on cloud services pose persistent challenges (Alirezaei et al., 2022). Developing robust cloud strategies tailored to the specific needs of construction projects is deemed essential. Specifically, PlanRadar (2023) highlights that cloud services employ microservices architecture to separate functions such as 3D rendering, data analytics, and version management, optimizing performance and capacity. Similarly, Chen et al. (2020) point out that integrating cloud platform APIs into BIM/ImT software enables seamless data synchronization across different applications. To ensure security, cloud solutions implement end-to-end encryption, multi-factor authentication, and role-based access controls, as noted by Tejjy Inc (2024). Delgado et al. (2020) emphasize the importance of establishing standard data-sharing protocols, such as IFC, to ensure interoperability among various cloud platforms. Technically, the use of container technologies like Docker can simplify the deployment and management of BIM/ImT applications on the cloud (Smart Structures, 2023). Additionally, Du et al. (2018) propose adopting machine learning and artificial intelligence to automate tasks such as clash detection and design optimization on cloud platforms. Nonetheless, to fully unlock the potential of cloud services in integrating BIM and ImT, a comprehensive strategy is required. This strategy should include staff training, the development of new workflows, and the establishment of appropriate data management standards.

Third, measures to address security and privacy issues in AR/VR technologies are outlined under the criterion *"Security and Privacy in AR/VR Technologies"* (21%). The integration of ImT technologies into BIM collaboration platforms poses significant concerns related to security and privacy, particularly when handling sensitive project data. To address these challenges, specific technical solutions must be implemented. First, adopting robust end-to-end encryption is crucial to protect data during transmission and storage (Kaspersky, n.d.). Cardoni et al. (2023) recommend utilizing advanced encryption algorithms, such as AES-256, in combination with secure key management to ensure the confidentiality of AR/VR data. Then, implementing multi-factor authentication (MFA) and role-based access control (RBAC) is essential to prevent unauthorized access (Janeiro, 2024). Potseluyko et al. (2022) further emphasize the importance of integrating biometric authentication methods, such as facial or voice recognition, into AR/VR devices to enhance security. Next, conducting regular and comprehensive security assessments is necessary to identify and address potential vulnerabilities (Tripwire, 2024). Shayesteh et al. (2023) also suggest employing automated security analysis tools combined with manual reviews to ensure thorough threat detection. Additionally, adopting strict security policies, such as the principle of least privilege and data segmentation, plays a vital role in limiting the scope of potential breaches (Pranamya, 2024). Without a robust security framework, it is evident that collaboration in AR/VR environments could expose projects to data breaches, undermining trust and operational efficiency.

Fourth, the criterion *"Bandwidth, Speed, and Latency in Data Transfer"* (21%) serves a crucial function, as reliable and efficient data transmission is the technical foundation for real-time visualization and collaboration in BIM-ImT integration. High-speed connectivity minimizes latency and ensures synchronized workflows throughout project execution. Achieving optimal performance requires a focus on three key aspects. In terms of bandwidth, optimization is essential to support the transmission of complex 3D data from BIM models and ImT environments. Ko et al. (2017) employed adaptive data compression techniques that can reduce network traffic by up to 60% while maintaining image quality. Additionally, adopting 5G technology with bandwidths up to 10 Gbps can meet the demands of real-time large-scale data transmission (Thales Group, 2024). Regarding speed, Otta (2024) emphasizes the importance of optimizing transmission protocols. They propose using UDP instead of TCP in certain cases to minimize latency, especially in real-time data transfers within ImT environments. Furthermore, deploying geographically distributed servers can reduce physical distances and improve transfer speeds. For latency, Hou et al. (2019) suggest motion prediction techniques to mitigate the impact of network delays in ImT applications. By forecasting user movements, systems can preload necessary data, reducing response times to under 20ms (PubNub, 2024). Combined with edge computing, as highlighted by Scott (2022), data processing can be moved closer to users, drastically reducing latency. While HTTP communication protocols have been utilized to address these requirements (Shahinmoghadam et al., 2021), limitations persist in analyzing their scalability and performance under complex network conditions. Effective implementation requires intelligent network management techniques such as Quality of Service (QoS) to prioritize critical data streams (Xie et al., 2018). The use of real-time network performance monitoring tools is also crucial for quickly detecting and addressing issues related to bandwidth, speed, and latency. Overall, optimizing bandwidth, speed, and latency demands a holistic approach that integrates advanced data transmission techniques, network management strategies, and distributed processing methods.

Finally, the criterion *"Incorporation of Automation and AI in VR/AR"* (14%) performs a similarly vital function in enhancing responsiveness and productivity within VR/AR environments integrated with BIM. The integration of AI and automation into VR/AR systems offers promising opportunities to optimize repetitive tasks, enhance decision-making processes, and improve data management. This is achieved through several specific technical approaches. First, AI algorithms are embedded into VR/AR platforms to analyze BIM data in real time, enabling design conflict prediction and automated resource allocation (Schiavi et al., 2022). For instance, systems can employ machine learning to recognize patterns in historical project data, providing early warnings about potential issues in design or scheduling. Next, automation is applied to the conversion of BIM models into VR/AR environments, saving time and minimizing human errors (Lee et al., 2019). Automated tools can optimize complex geometries, adjust resolution, and apply appropriate textures to ensure performance in virtual environments. In terms of communication and collaboration, Schiavi et al. (2022) also emphasize that AI-integrated platforms can automatically synthesize and visualize information from multiple BIM data sources, making it easier for stakeholders to grasp project status within VR/AR environments. However, despite its significant potential, this criterion remains underutilized in current research. Practical applications demonstrating measurable impacts on project outcomes are still scarce, indicating the need for further in-depth studies (Rahimian et al., 2020). This may be attributed to the substantial investments required in technology, training, and the shift away from traditional processes to implement these solutions effectively.

5.2 Non-technical/Social-related criteria

The successful integration of BIM with ImT requires not only robust technical foundations but also the consideration of social and organizational factors that drive adoption and effective use. Non-technical criteria, such as user engagement, collaboration dynamics, and adaptability to new systems, play a crucial role in bridging the gap between advanced technologies and their practical application in construction workflows. This section explores the social-related aspects influencing the integration of BIM-ImT systems, highlighting their importance in fostering seamless communication, aligning stakeholder efforts, and enhancing user satisfaction. By examining these criteria, the discussion sheds light on how human-centric approaches contribute to the broader goal of creating resilient, adaptable, and efficient construction processes in an increasingly digitalized industry.

5.2.1 BIM-related software

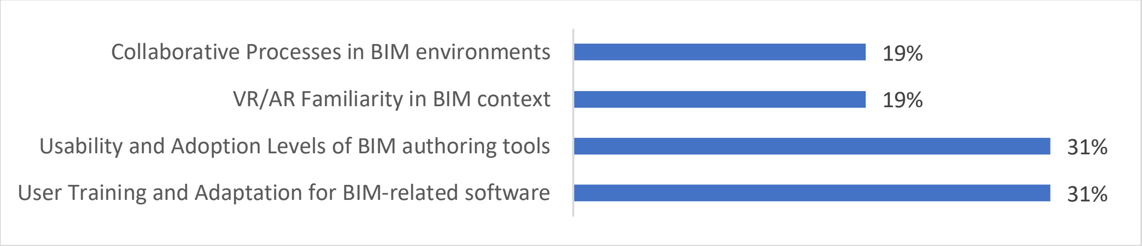


Figure 9: Summary of non-technical criteria regarding BIM-related software mentioned in reviewed studies.

The adoption of BIM-related software in construction workflows is shaped by various non-technical criteria that center on user engagement, adaptability, and collaboration. These criteria – user training and adaptation, usability and adoption levels of BIM authoring tools, VR/AR familiarity in BIM contexts, and collaborative processes within BIM environments – highlight the intersection of human factors and technological efficiency, ensuring that advanced systems are effectively utilized within the construction industry.

First, the criterion *"User Training and Adaptation for BIM-Related Software"* (31%) underscores the system's effectiveness in enabling users to acquire new skills and adapt to BIM-related software. Training users in BIM software plays a pivotal role in the integration of BIM and ImT. According to Kayes et al. (2005), effective training programs should focus on building technical competencies through methods such as experiential learning and team-based training. Specifically, Filzmoser et al. (2016) advocate for conducting hands-on workshops where learners directly interact with BIM software under expert guidance. This approach helps users quickly familiarize themselves with the software's interface and basic functionalities. Similarly, Rahimian et al. (2020) stress that training programs combining comprehensive tutorials, practical workshops, and adaptive learning platforms provide a structured approach to developing technical skills. These systems reduce the learning curve for new users while reinforcing best practices for experienced professionals, ensuring consistent outcomes across diverse teams. Additionally, Sacks et al. (2018) highlight the importance of developing personalized training roadmaps tailored to the skill levels and needs of different user groups. For instance, beginner programs could focus on fundamental skills such as 3D modeling and data management, whereas advanced users might receive training on energy analysis or construction simulation. However, addressing varying levels of technical expertise remains a significant challenge. For example, seasoned professionals may resist new tools that disrupt established workflows, while less experienced users might find BIM's complexity overwhelming. Besides, Kokoç (2019) suggests leveraging online learning platforms to provide flexible and accessible training materials. Tutorials, practical exercises, and online discussion forums enable users to learn at their own pace and exchange experiences with peers, which is particularly valuable given the growing prevalence of remote work. Designing modular and customizable training solutions can help mitigate these issues, empowering all users to confidently engage with BIM tools and facilitating smoother technology integration into project workflows. For long-term effectiveness, Nikolic et al. (2021) emphasize the importance of continuously evaluating and updating training programs. Regular user satisfaction surveys and software performance analyses help identify areas for improvement. Training content can then be adjusted to better meet users' practical needs and emerging technological trends in BIM and ImT. Such enhancements ultimately improve the efficiency of design reviews, data coordination, and communication processes.

Second, the significance of the criterion *"Usability and Adoption Levels of BIM Authoring Tools"* (31%) represents the practicality and actual utilization of BIM authoring tools within operational environments. Usability is a key determinant of whether BIM authoring tools can be effectively adopted within an organization. Tools with intuitive interfaces and simplified workflows enable users to perform tasks such as model editing, data processing, and design coordination more efficiently. However, balancing simplicity with advanced functionality remains a frequent challenge. To address this issue, Park et al. (2022) recommend integrating user-friendly features such as drag-and-drop interfaces and pre-designed templates, allowing new users to quickly become familiar with the software. Tsai et al. (2019) further propose a tiered approach, enabling users to gradually explore more complex functionalities as they master basic tasks, thereby minimizing the steep learning curve. Additionally, Wenger-Trayner (2015) suggests establishing internal communities of practice, where users can share experiences and tackle project-specific challenges, fostering continuous learning and a culture of mutual support for BIM adoption. Meanwhile, Chen et al. (2020) emphasize the importance of seamless integration between BIM authoring tools and ImT software. Open APIs and plugins allow customization of user interfaces and workflows, enabling organizations to tailor BIM tools to their specific needs. By developing software that is scalable in complexity - offering intuitive execution of basic tasks while maintaining access to advanced options for professional users - BIM authoring tools can meet the diverse needs of users. By promoting usability and broader adoption, these systems help accelerate project progress and reduce inefficiencies caused by technical barriers, particularly during time-sensitive project phases.

Third, the criterion *"VR/AR Familiarity in the BIM Context"* (19%) is also considered essential, as integrating VR/AR into BIM workflows requires a complex process of social and organizational adaptation while presenting challenges related to user familiarity with immersive systems. To overcome this barrier, businesses can adopt a multidimensional training strategy and a gradual approach. Low et al. (2023) propose an "experiential learning" method, where users are gradually exposed to VR/AR technology through small pilot projects before applying it to larger initiatives. This approach not only minimizes anxiety but also enhances user confidence. Additionally, establishing a peer-support system, where experienced users mentor newcomers, fosters a positive learning environment and encourages knowledge sharing. Meanwhile, Vittori et al. (2021) emphasize the importance of customizing VR/AR user interfaces to reflect familiar BIM workflows, making it easier for users to transition between tools and reducing disruptions to established processes. Furthermore, integrating VR/AR into regular project meetings not only improves skill development but also demonstrates the practical value of the technology in enhancing communication and decision-making. However, resistance to change and limited access to VR/AR training resources can hinder widespread adoption. To achieve broader acceptance, organizations must cultivate an innovative culture that encourages experimentation and learning from mistakes (Leepila, 2023). Finally, measuring and communicating specific performance metrics related to VR/AR use in BIM, such as enhanced visualization capabilities, improved stakeholder communication, and real-time collaboration, will help demonstrate the technology's value (Ratajczak et al., 2019). This, in turn, fosters long-term acceptance and unlocks the transformative potential of VR/AR technology in BIM environments.

Finally, the criterion *"Collaborative Processes in BIM Environments"* (19%) is emphasized to ensure the flexibility of workflows associated with the integration of BIM and ImT systems. Collaboration forms the foundation of effective BIM integration, requiring seamless workflows that enable teams to share, analyze, and modify project data in real-time. Integrated BIM environments support interdisciplinary collaboration by providing a centralized platform where stakeholders can interact with shared models, facilitating error detection, design adjustments, and coordinated decision-making (Rahimian et al., 2020; Olbina & Glick, 2022). To promote effective collaborative processes within BIM environments when integrated with ImT, organizations need to adopt a multidimensional approach. First, Clerkin and Jones (2013) argue that establishing a clear governance framework is essential, including defining specific roles and responsibilities for each team member, as well as setting up decision-making and conflict-resolution processes. This aligns with Rahimian et al. (2020), who highlight the importance of developing a "common language" among stakeholders to ensure that all participants consistently understand and use BIM and ImT terminology. Then, continuous training and skill development are indispensable. Training programs should focus not only on the technical aspects of BIM and ImT software but also on soft skills such as effective communication and conflict management. Mills et al. (2013) propose utilizing group learning sessions and experience-sharing workshops to foster mutual learning. Although these platforms enhance productivity and minimize delays, they require adjustments to traditional workflows, which can disrupt communication models and team dynamics. The implementation of integrated systems demands a phased approach, ensuring that teams gradually adapt to new tools without jeopardizing ongoing projects (Vince et al., 2024). This also involves fostering a collaborative culture that prioritizes transparency, accountability, and inclusivity in decision-making. Next, continuous evaluation and improvement of collaborative processes are necessary. As discussed by Coates et al. (2002), the use of key performance indicators (KPIs) is critical to measuring the effectiveness of collaboration and identifying areas for improvement in BIM implementation. By adopting these methods, organizations can create an effective collaborative environment, maximizing the benefits of integrating BIM and ImT, improving not only project efficiency but also team satisfaction, leading to more relevant project outcomes and stronger relationships among stakeholders.

5.2.2 The use of ImT hardware:

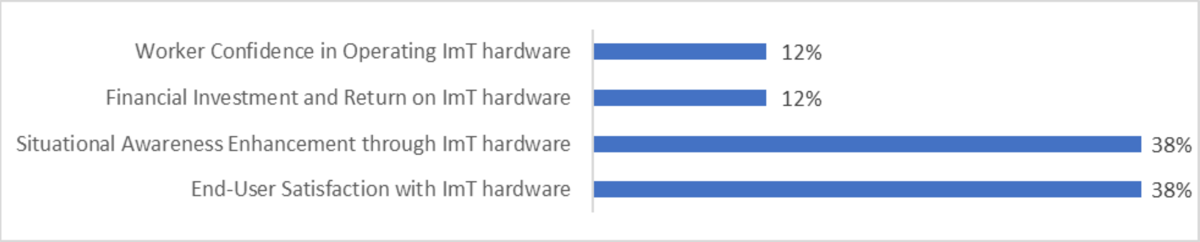


Figure 10: Summary of non-technical criteria regarding the use of ImT hardware mentioned in reviewed studies.

The deployment of ImT hardware in construction workflows is shaped by several non-technical criteria, emphasizing the interaction between technology and its users. These criteria include end-user satisfaction, situational awareness enhancement, financial investment and return, and worker confidence.

First, the criterion *"End-User Satisfaction with ImT Hardware"* (38%) stands out, emphasizing that the satisfaction and fulfillment of end-users after utilizing integrated ImT hardware can reflect its usability, efficiency, and the overall experience of interacting with the hardware. Studies by Balali et al. (2020) and Kamari et al. (2020) highlight that satisfied users are more likely to adopt and consistently use these technologies. Achieving this requires a focus on optimizing the user experience. According to Mulder (2001), organizing in-depth training sessions and providing continuous technical support are key to enhancing satisfaction. Specifically, training programs should be tailored to specific user groups, concentrating on practical scenarios they are likely to encounter. Additionally, Park et al. (2022) suggest adopting a user-centered design approach, where developers consistently collect feedback and adapt interfaces based on users' actual needs. This can be achieved through regular surveys, in-depth interviews, and direct observation of users during operation. Moreover, creating an online user community where individuals can share experiences and support one another is an effective way to enhance satisfaction and encourage long-term adoption of the technology (Sukma and Leelasantitham, 2022). However, the biggest challenge lies in balancing simplicity and ease of use with the ability to meet complex project requirements, which necessitates continuous improvement and regular feedback from users. By addressing diverse user needs and preferences, satisfaction ensures that tools such as head-mounted displays and integrated AR systems seamlessly fit into processes, thereby promoting the sustained adoption and utilization of ImT hardware in BIM integration.

Second, the criterion *"Situational Awareness Enhancement through ImT Hardware"* (38%) is highlighted as critical because enhancing situational awareness through ImT hardware not only provides benefits but also poses several social challenges during BIM integration. Lucena and Saffaro (2022) note that devices such as AR glasses and VR systems enable real-time data visualization, allowing construction teams to assess risks and monitor progress more effectively. Chan et al. (2023) further emphasize that improved situational awareness fosters better safety protocols and collaborative decision-making on-site. However, implementing these tools requires changes to traditional workflows, which can disrupt established processes. To address this issue, businesses can adopt a phased training approach, beginning with simple tasks and gradually increasing complexity. This approach helps users familiarize themselves with new technologies, minimizing workplace disruptions. Additionally, organizing group training sessions and facilitating experience sharing among team members are essential for enhancing ImT hardware usage skills (Sacks et al., 2013). Another critical aspect is the generational gap in technological proficiency among employees. To overcome this challenge, businesses can implement mentorship programs where younger staff assist older colleagues in adopting new technologies (Chaudhuri and Ghosh, 2012). Then, fostering a corporate culture that encourages innovation and continuous learning will create a supportive environment for adopting ImT technology, thereby enhancing situational awareness and optimizing its impact during BIM integration.

Third, *"Financial Investment and Return on ImT Hardware"* (12%) represents a crucial non-technical criterion in the integration of ImT with BIM, particularly concerning the use of hardware for ImT. Understanding this aspect requires evaluating the factors that influence investment decisions and identifying strategies for optimizing return on investment (ROI). Investing in ImT hardware involves more than just the initial acquisition costs; it also encompasses considerations like staff training and equipment maintenance. For example, Vittori et al. (2021) and Mohamed et al. (2024) emphasize the importance of crafting a detailed financial plan that includes cost-benefit analyses to ensure data-driven decisions and predictable long-term benefits. Another key consideration is the need for financial strategies that enhance ROI by addressing the compatibility of ImT hardware with existing BIM systems. Ensuring that investments contribute to both immediate efficiency and long-term performance improvements can reduce risks and enhance productivity. Research suggests that organizations effectively adopting ImT technologies tend to achieve shorter project timelines and better collaboration among stakeholders (Rashmi et al., 2024). However, the disparity in ROI between projects often creates barriers for smaller businesses in accessing ImT technologies. Addressing this issue through supportive financial models - such as external funding or government subsidies - can lower the financial burden and encourage broader adoption of ImT (Bakhtiari, 2021). In sum, effective use of ImT hardware requires not only consideration of costs but also a focus on financial management and strategic investment to ensure sustainable benefits.

Lastly, the criterion *"Worker Confidence in Operating ImT Hardware"* (12%) is also highlighted, underscoring that workers' confidence plays an equally important role in their ability to operate and collaborate using integrated ImT hardware. To enhance this confidence, organizations need to implement specific and effective measures. Initially, establishing structured training programs is essential. According to Alizadehsalehi et al. (2020), training sessions should be designed in progressive levels, starting with fundamental knowledge of ImT and advancing to more complex skills for utilizing BIM-ImT integrated hardware. Next, providing opportunities for workers to gain hands-on experience through practical sessions and simulations of real-world scenarios is crucial. This gradual exposure helps them become more familiar and confident in operating the equipment. Additionally, demonstrating the effectiveness of the technology through concrete examples and statistical evidence of productivity improvements and error reduction is vital to convince workers (Noy and Zhang, 2023). Once workers are accustomed to the technology, they are more likely to use these tools effectively, improving productivity and minimizing errors. However, this process requires substantial time and resources, potentially slowing down the pace of technology adoption. To address this, organizations can simplify hardware interfaces and develop user-friendly instructional materials. Furthermore, creating a robust technical support system that is readily available to answer user queries can significantly boost their confidence (Dario, 2019). Besides, fostering a workplace environment that encourages learning and sharing experiences among colleagues is highly beneficial. Research by Eiris Pereira et al. (2018) suggests that organizing experience-sharing sessions and group discussions on effectively using ImT hardware can significantly enhance workers' confidence. By integrating these measures, organizations can build a skilled and confident workforce capable of leveraging the full potential of BIM-integrated ImT technology. This, in turn, improves job performance and drives organizational growth in the digital era.

5.2.3 Integration of BIM with ImT through game engines

The integration of BIM with ImT through game engines hinges on several social-related criteria that facilitate effective collaboration, decision-making, and data management within construction workflows. These criteria – stakeholder collaboration, evaluation and future directions, collaborative workflow, privacy and security, and impact assessment – address the interaction between users and systems, ensuring the integration meets the demands of diverse project stakeholders.

First, the criterion *"Stakeholder Collaboration in BIM-Game Engine Integration"* (33%) highlights the extent to which the integrated system facilitates joint decision-making among diverse project stakeholders during the integration of BIM and game engines. Collaboration among stakeholders is a key factor in environments involving multiple participants with varying expertise and priorities working toward shared project goals. Integrating BIM with ImT via game engines enhances collaboration by enabling real-time interaction and collective decision-making. Tools like Unity3D and Unreal Engine provide platforms that support various communication methods, ensuring stakeholders across different project phases can access and contribute to shared models (Zaman et al., 2024). To achieve effective collaboration, several specific approaches should be implemented. Initially, establishing a unified workflow through standardized procedures allows stakeholders to interact with BIM models via game engine interfaces. This includes clearly defining roles, responsibilities, and access rights for each party. Next, conducting in-depth training sessions on the use of BIM-game engine integration tools and offering continuous technical support is essential. Additionally, creating an online platform enables stakeholders to easily access, update, and share project information through the game engine's intuitive interface (Assaf et al., 2023). Moreover, organizing interactive virtual meetings utilizing the 3D visualization capabilities of game engines allows stakeholders to explore and discuss BIM models collaboratively in real-time environments (Rostamiasl and Jrade, 2024). Finally, establishing a feedback and improvement mechanism by collecting user input on their experience with the integrated tools can facilitate continuous enhancements to the interface and functionality, better meeting stakeholder needs. However, accommodating varying levels of technological proficiency and expectations requires a system that is both intuitive and robust. Achieving this balance fosters transparency, minimizes communication misunderstandings, and aligns team efforts, ultimately driving project success. As Balali et al. (2020) noted, creating a shared working environment through BIM-game engine integration not only improves communication but also promotes innovation and creativity during the design and construction process. Similarly, Assaad et al. (2021) emphasized that effective stakeholder collaboration through this technology can lead to the early identification of potential issues, thereby mitigating risks and enhancing overall project efficiency.

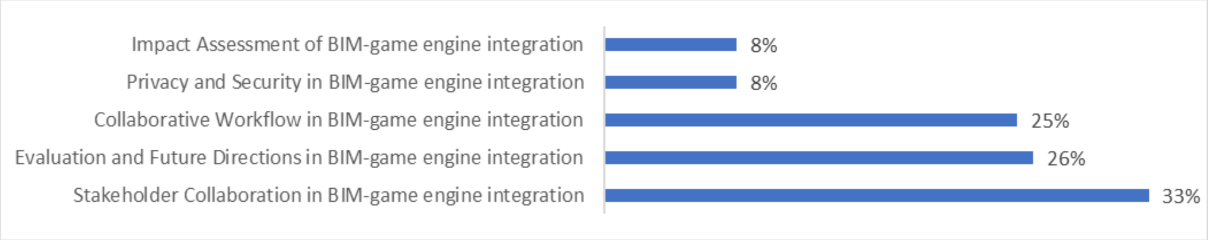


Figure 11: Summary of non-technical criteria regarding the integration of BIM with ImT through game engines mentioned in reviewed studies.

Second, the importance of the criterion *"Evaluation and Future Directions in BIM-Game Engine Integration"* (26%) lies in its ability to support continuous improvement and maintain system relevance through regular assessment and updates during the integration of BIM with game engines. Gomes et al. (2016) proposed an evaluation process that includes gathering user feedback through surveys and interviews, analyzing system usage data to identify performance issues, and organizing focus group discussions with stakeholders to determine development directions. Zaman et al. (2024) further emphasized the significance of establishing a dedicated task force comprising BIM experts, game engineers, and end-users to conduct periodic evaluations. This iterative approach not only ensures that the system remains aligned with industry practices but also facilitates the gradual integration of advanced functionalities over time (Figueres-Munoz and Merschbrock, 2015). However, the major challenge lies in maintaining active participation from stakeholders throughout the long-term evaluation process, particularly since such evaluations require sustained investments in resources and expertise, which may pose difficulties for organizations with limited budgets. To address this issue, Buhammood et al. (2020) recommended implementing a reward and recognition system to encourage active contributions from participants. Additionally, integrating automated analysis tools into the system can alleviate the burden of manual evaluations. Although this proactive approach requires initial investment, it enables early detection of issues, improves system performance, and enhances user satisfaction in the long run. It also ensures that the BIM-game engine integration remains relevant and effective as technology evolves.

Third, the non-technical criterion *"Collaborative Workflow in BIM-Game Engine Integration"* (25%) not only highlights the efficiency and flexibility of workflows created through the integration of BIM and game engine systems but also plays a pivotal role in construction projects. This workflow begins with exporting BIM data into a format compatible with the game engine, followed by the development of an intuitive user interface that enables stakeholders to interact and collaborate on the model. Research by Zaman et al. (2024) has demonstrated that synchronized work environments facilitate real-time data sharing and interaction, allowing multiple stakeholders to simultaneously engage with the models, thereby streamlining decision-making processes and accelerating project timelines. To enhance collaboration, Brady and Davies (2010) emphasized the importance of establishing clear rules and procedures for information sharing and updates, including the definition of specific roles and responsibilities for each team member. This collaborative workflow improves coordination by breaking down barriers and promoting transparency throughout project execution. However, integrating these workflows with existing processes may disrupt established practices, requiring comprehensive change management strategies. Continuous training programs and user support are essential to help users adapt to the new tools and integrated workflows (Olbina and Glick, 2022; Vittori et al., 2021). By addressing these challenges, collaborative workflows can contribute to improved project efficiency and adaptability in the dynamic construction environment.

Fourth, the criterion *"Privacy and Security in BIM-Game Engine Integration"* (8%) plays a critical role in safeguarding user data and ensuring security within the integrated BIM-game engine environment, particularly when sensitive project data is visualized and manipulated in a shared virtual space. Anyanwu et al. (2024) emphasize the necessity of encryption protocols, secure access controls, and continuous monitoring to prevent unauthorized access and maintain data integrity. Protecting these systems is essential to retaining user trust and avoiding costly breaches. However, implementing these measures requires careful consideration of the approach. Turk et al. (2022) propose a role-based access management framework, where varying levels of permissions are assigned to different user groups based on their job functions. This approach minimizes the risk of sensitive information leaks while still enabling necessary data sharing. Additionally, Hijazi et al. (2023) advocate for the use of blockchain technology to create an immutable ledger of all actions performed on BIM data, enhancing transparency and accountability. Nevertheless, deploying these solutions demands significant time and resource investments, as well as close collaboration among stakeholders. Moreover, a balance between security and accessibility is crucial to prevent a decline in user productivity. Training employees on best security practices and raising awareness of potential threats are also vital to fostering a robust security culture. Next, adapting to rapidly evolving cybersecurity threats requires constant updates to security frameworks, which can place additional strain on resources (Balisane et al., 2024). Despite these challenges, robust security protocols are indispensable for building trust and promoting the broader adoption of BIM-game engine integrations.

Lastly, the criterion "*Impact Assessment of BIM-Game Engine Integration"* (8%) is shown for its essential role in measuring the effectiveness and value brought by the integration of BIM and game engines. To conduct impact assessments effectively, organizations need to establish a comprehensive evaluation framework that incorporates both quantitative and qualitative metrics. According to Coates et al. (2002), defining specific KPIs for each project phase is crucial. These KPIs may include time saved during the design process, the number of conflicts detected and resolved early, stakeholder satisfaction levels, and cost reduction rates resulting from minimized errors. Additionally, Harris and Brown (2019) suggest using structured surveys and interviews with stakeholders to gather detailed feedback on user experiences and the perceived value of the integrated system. Moreover, comparing the performance of projects utilizing BIM-game engine integration with similar projects that do not employ this technology can provide valuable insights. However, assessing the impact of specific integrated features may pose challenges due to external variables, such as project complexity and the expertise of the team (Zaman et al., 2024). Despite these challenges, rigorous impact assessments enable organizations to identify best practices and inform the optimization of future integrations. To ensure objectivity, Picciotto (2013) recommends that organizations consider hiring independent evaluation experts. Sharing assessment results transparently with all stakeholders not only promotes technology adoption but also creates opportunities for continuous improvement, ensuring that this technology continues to meet the practical needs of the construction industry.

5.2.4 Data standards:

The integration of data standards within BIM and ImT workflows is underpinned by several critical non-technical criteria that address user experience, adaptability, usability, collaboration, and compliance. These social-related factors are fundamental for creating systems that are accessible, efficient, and aligned with both industry needs and user expectations.

First, the criterion *"User Experience in Data Standardization"* (21%) plays a pivotal role in the integration of BIM and ImT, particularly in the context of data standardization. User experience is a critical factor influencing the adoption and effective utilization of data standards. Intuitive and engaging interfaces enhance user satisfaction and facilitate seamless interaction with complex systems. To improve user experience, Park et al. (2022) recommend employing a user-centered design approach, where BIM software developers conduct user interviews and surveys to understand their needs and work habits. This process helps create user personas representing different user groups, enabling the design of tailored interfaces (Coorevits et al., 2016). Furthermore, O'Grady et al. (2021) and

Al-Shafei (2024) highlight the importance of providing visual guides and integrating support tools, such as chatbots, to help users quickly familiarize themselves with data standardization processes. Clear and predictable interfaces allow users to navigate standardization workflows without confusion, ensuring consistency in task execution. However, the challenge lies in designing systems that balance simplicity with the ability to handle complex data operations, ensuring users are neither overwhelmed nor limited in functionality (Falegnami et al., 2024). In construction workflows, optimized user experiences improve productivity and reduce the likelihood of errors caused by interface complexity. To further enhance user experience, organizations should organize regular training sessions and establish user communities for sharing knowledge and best practices. Then, collecting regular user feedback and continuously refining the interface based on this input will improve the quality of user experience in data standardization processes.

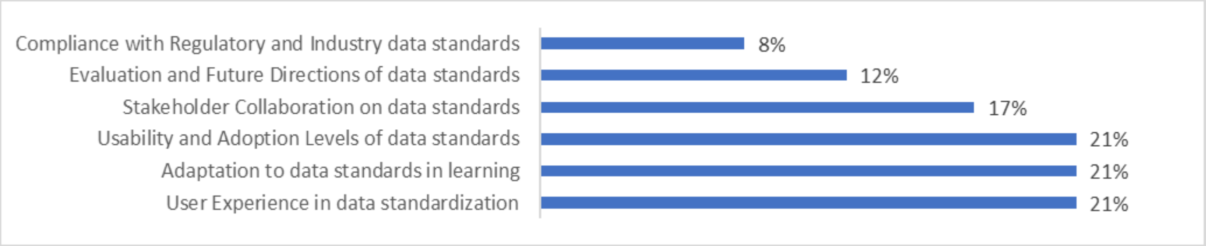


Figure 12: Summary of non-technical criteria regarding data standards mentioned in reviewed studies.

Second, the criterion *"Adaptation to Data Standards in Learning"* (21%) emphasizes the importance of supporting users in adapting to new data standards during the learning and application of BIM integrated with ImT. This adaptation is critical in equipping users with the necessary skills to navigate an ever-evolving technological environment. Chen et al. (2020) and Han and Leite (2022) highlight the significance of step-by-step learning systems that minimize barriers for users with diverse technical backgrounds. Achieving this requires a multidimensional approach. Specifically, developing tiered training programs, ranging from basic to advanced levels, enables users to gradually familiarize themselves with complex standards such as IFC and COBie (buildingSMART, 2020). The learning path could begin with short courses on foundational concepts, followed by practical workshops and culminating in experimental projects. Moreover, integrating visualization tools and 3D simulations into the learning process, such as using standardized sample BIM models compliant with IFC, helps users visualize and understand the practical application of data standards (Xu et al., 2016). Standardized data frameworks provide a consistent foundation, reducing the learning curve and facilitating knowledge transfer between teams. However, to accommodate varying levels of expertise, flexible training programs and user-centered system designs remain essential (Park et al., 2022). In construction management, such adaptive systems enhance team readiness to adopt new workflows, leading to smoother project execution and improved collaboration. Ultimately, establishing online learning communities, as suggested by Sukma and Leelasantitham (2022), along with evaluation mechanisms and certification systems, not only motivates learners but also ensures training quality. This creates a solid foundation for the effective implementation of BIM integrated with ImT in practice.

Third, the criterion *"Usability and Adoption Levels of Data Standards"* (21%) also holds substantial influence, reflecting the practicality and extent of data standard usage in operational environments. To enhance usability and adoption levels, the focus must be on effective implementation strategies. According to Jiang et al. (2019) and Arayici et al. (2018), organizing intensive training programs and practical workshops helps users familiarize themselves with data standards, thereby improving their adoption in daily workflows. The usability of data standards is a determining factor in their integration into everyday operations. User-friendly and practical systems enable smoother workflows, allowing teams to leverage standardized frameworks for decision-making and data exchange. However, balancing advanced functionality with simplicity remains a critical challenge. The system must be robust enough to meet industry demands while remaining accessible to users with varying levels of expertise. In construction projects, this balance ensures consistent use of standardized frameworks, minimizing delays caused by miscommunication or poor data management (Shehzad et al., 2021). Additionally, Jalaei et al. (2015) recommend developing decision-support systems that integrate data standards, enabling users to easily access and apply them during the design and construction phases. Developing plugins and add-ons compatible with popular BIM software is another effective way to enhance the usability of data standards. Furthermore, establishing communities of practice and forums for experience sharing among professionals creates an environment for learning and exchanging knowledge about applying standards in real-world projects. This collaborative approach fosters innovation and consistent adoption, ultimately maximizing the benefits of data standards in the industry.

Fourth, a significant contribution is made by the criterion *"Stakeholder Collaboration on Data Standards"* (17%), which emphasizes the degree to which the integrated system facilitates joint decision-making among diverse project participants regarding data standards. Effective collaboration is a key factor for the successful implementation of data standards, allowing stakeholders from various disciplines to contribute their expertise and perspectives. Consistent and accurate data standards provide a common language for decision-making, enhancing coordination among multidisciplinary teams (Bawden and Robinson, 2016). To foster this collaboration, it is essential to establish a centralized platform for data sharing and management, enabling all stakeholders to access and update information in real time. According to Alizadehsalehi et al. (2020), tools such as the Common Data Environment (CDE) can effectively facilitate this process. In addition, regular meetings and workshops should be organized to discuss and reach consensus on data standards, ensuring that all parties understand and adhere to the agreed-upon protocols. Soliman and Ojalainen (2023) highlight the importance of creating a clear process for resolving conflicts related to data standards. Consequently, establishing a system for continuous feedback and improvement will help stakeholders refine collaboration processes and enhance the adoption of data standards. However, the diverse needs of stakeholders and the complexity of projects may hinder the development of universally applicable tools. Hence, it is evident that promoting collaboration through standardized data in construction processes contributes to improved project efficiency, reduced conflicts, and enhanced overall effectiveness.

Fifth, *"Evaluation and Future Directions of Data Standards"* (12%) is also included, stressing not only the system's capacity for supporting ongoing improvements and maintaining relevance through regular assessments and updates of data standards but also the methodologies for implementing this process. Zhu (2024) proposes a systematic approach to evaluating and updating data standards, which includes establishing multidisciplinary expert committees, organizing regular workshops, and conducting end-user surveys. This approach ensures both comprehensiveness and the creation of a continuous feedback mechanism from stakeholders. Liu et al. (2023) further recommend leveraging big data analytics tools to monitor standard usage trends and identify areas for improvement. Continuous evaluation of data standards ensures their relevance and effectiveness as technology evolves. Regular updates allow systems to adapt to new technological advancements and meet industry demands.

However, the biggest challenge lies in balancing the stability of existing standards with the integration of emerging technologies like ImT into BIM. Addressing this issue requires close collaboration between standardization organizations, technology developers, and end-users. For instance, creating "sandbox" environments for testing new standards in a controlled setting before widespread implementation is an effective approach (Podkosova et al., 2022). In parallel, developing long-term roadmaps for standard evolution that consider anticipated technological trends can help the industry better prepare for future changes. Additionally, implementing training programs and raising awareness of the importance of evaluating and updating data standards will foster a culture of continuous improvement within the construction industry. This accordingly ensures that systems remain competitive and effective over time.

Finally, but no less significant, is the criterion *"Compliance with Regulatory and Industry Data Standards"* (8%), which refers to the level of alignment of the integrated system with current regulatory and industry-specific standards. Achieving compliance necessitates a comprehensive and flexible approach during the integration of BIM and ImT. To ensure effective compliance, organizations must undertake several specific steps. First and foremost, establishing a comprehensive data governance framework is essential, incorporating stringent quality control and data validation procedures (Kosasih, 2024). Moreover, training programs and awareness initiatives should be implemented to educate employees about the importance of adhering to standards such as IFC, COBie, or gbXML (Collier, 2023). Additionally, Lucena and Saffaro (2022) emphasize the integration of automated compliance-checking tools into workflows to identify non-conformities at an early stage. In parallel, Bao et al. (2022) highlight the importance of establishing effective communication channels with regulatory bodies and standard-setting organizations to stay updated on regulatory changes. Furthermore, the adoption of open standards like ISO 19650 and the use of cloud-based platforms can facilitate collaboration and real-time data sharing, streamlining compliance processes (Bjørn et al., 2022). Lastly, applying a risk-based approach to prioritize key compliance areas can help optimize resources and focus on the most critical aspects of adherence (Farhadi, 2024).

Although the slow adaptation of regulations to technological advancements may hinder the integration of innovations, compliance remains fundamental to building trust and ensuring systems align with industry expectations. Ultimately, it minimizes risks associated with non-standardized practices, securing the foundation for sustainable and reliable integration.

5.2.5 Collaboration and communication platforms:

Collaboration and communication platforms are fundamental to ensuring seamless integration of BIM and ImT technologies in construction workflows. Key social-related criteria include user engagement, collaboration effectiveness, user training and acceptance, accessibility, participant recruitment, cognitive load, and task management. These criteria reflect the importance of fostering a user-centric approach, enhancing collaborative processes, and improving system adoption for all stakeholders.

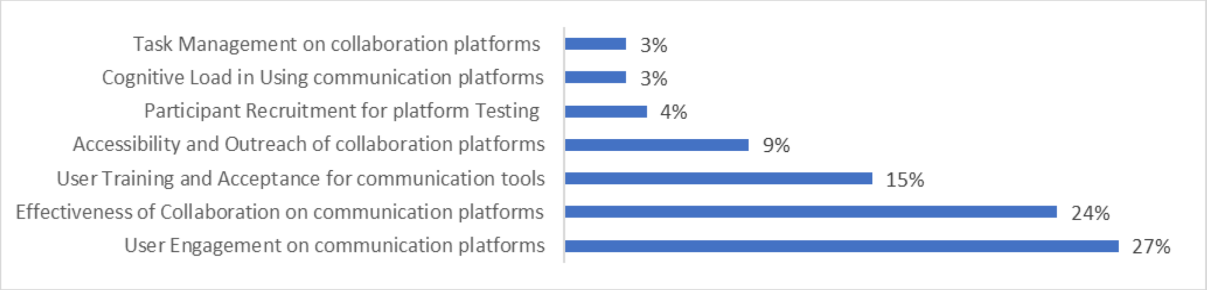


Figure 13: Summary of non-technical criteria regarding collaboration and communication platforms mentioned in reviewed studies.

First, the criterion *"User Engagement on Communication Platforms"* (27%) emphasizes the level of active involvement and enthusiasm users demonstrate when interacting with communication platforms. Active user participation is a crucial factor for the success of collaborative platforms, as it fosters sustainable usage, deeper insights, and continuous system improvement. To enhance engagement levels, platforms must prioritize creating intuitive user experiences tailored to the diverse processes of construction teams. Shojaei et al. (2021) recommend designing user-friendly interfaces that incorporate interactive features such as real-time commenting and 3D model sharing. Similarly, O'Grady et al. (2021) underscore the importance of providing personalization tools, enabling users to customize their workspaces based on specific needs. They further argue that increased engagement enhances team collaboration, allowing users to interact more effectively with project data and tools. To sustain long-term engagement, Yalçın (2024) suggests integrating gamification elements, such as reward systems and leaderboards, to motivate users. However, the greatest challenge lies in maintaining consistent participation among diverse user groups with varying roles and expertise, particularly in large-scale projects with rapidly changing demands. Addressing this requires comprehensive training strategies, including online tutorials, instructional videos, and hands-on support (Vittori et al., 2021). Besides, collecting and analyzing user behavior data can drive continuous platform improvements, ensuring the system adapts to the evolving needs of projects. Additionally, establishing a strong user community where members can share experiences and best practices will further promote active and sustainable engagement, ultimately enhancing the overall efficiency and success of the project.

Second, the significance of the criterion *"Effectiveness of Collaboration on Communication Platforms"* (24%) is highlighted through its focus on the ease and effectiveness of sharing information and fostering cooperative efforts among stakeholders using communication platforms. Research by Balali et al. (2020) and Dias Barkokebas and Li (2021) demonstrates that these systems can bridge geographical and professional gaps, facilitating tighter project management. However, integrating diverse communication methods and tools into a single platform requires careful planning to prevent inefficiencies and ensure alignment with existing workflows. To achieve this, several specific measures should be implemented. Initially, establishing clear and standardized workflows among stakeholders is essential. This includes defining roles, responsibilities, and access permissions for each team member (Turk et al., 2022). Next, hosting training sessions and providing guidance on effectively using communication platforms will help users familiarize themselves with new features and processes (Heinrich et al., 2022). Plus, implementing a robust version control and change management system is critical to ensure information consistency and avoid data conflicts (Olbina and Glick, 2022). Additionally, as Sarker (2021) suggests, integrating data analytics and visualization tools into the communication platform can enable stakeholders to comprehend and make decisions based on accurate information more effectively. At last, establishing a continuous feedback and improvement mechanism by gathering user input will contribute to ongoing enhancements of the communication platform. By adopting these measures, BIM and ImT integration projects can optimize collaboration and communication efficiency, ultimately improving the quality and performance of construction projects.

Third, the criterion *"User Training and Acceptance for Communication Tools"* (15%) requires significant attention, as it reflects the effectiveness of training provided to users for operating communication tools and the rate of subsequent adoption. To implement this effectively, the focus should be on how training is delivered and how user acceptance is enhanced. Flynn (2022) suggests a modular training approach, starting with fundamental concepts and gradually advancing to cater to the diverse proficiency levels of construction teams. Specifically, a combination of live demonstrations and online learning sessions can be organized, allowing users to adjust the learning pace according to their individual needs. Afolabi et al. (2022) emphasize the importance of creating a safe testing environment where users can familiarize themselves with the new tools without fear of impacting real projects. This can be achieved through simulated scenarios based on actual project situations, enabling users to practice and build confidence in their skills. Additionally, Servey et al. (2020) propose adopting a "train-the-trainer" approach, where internal experts receive in-depth training and subsequently guide their colleagues, creating a ripple effect within the organization. Comprehensive training programs like these are essential for building user confidence and encouraging widespread adoption of communication platforms. Systems perceived as valuable to workflows and easy to learn tend to achieve higher acceptance rates. To further improve user acceptance, it is crucial to communicate the specific benefits of the tools for each project role and to collect regular feedback to refine training processes (Urbancová et al., 2024). By combining these methods, organizations can overcome skill and psychological barriers, thereby optimizing the use of communication and collaboration platforms in the integrated BIM-ImT environment. This approach ensures long-term success in system implementation and utilization.

Fourth, the criterion *"Accessibility and Outreach of Collaboration Platforms"* (9%) is described as the system's ability to provide broad access and ease of use to a diverse user base on collaboration platforms. This factor determines the inclusivity and usability of the platforms, ensuring that all team members, regardless of their technical proficiency, can effectively engage with the system (O'Grady et al., 2021). To achieve this goal, developers need to adopt universal design principles and implement specific measures. For instance, Shojaei et al. (2021) highlight the importance of creating intuitive and customizable user interfaces, enabling users to adjust their working environment to meet individual needs. Similarly, Vtyurina et al. (2019) recommend supporting multiple languages and providing accessibility options such as screen readers and voice controls to ensure inclusivity for a wide range of users. In addition, Getenet and Tualaulelei (2023) suggest integrating interactive training tools and online tutorials to help new users quickly familiarize themselves with the platform. Optimizing performance on mobile devices and ensuring multi-platform compatibility are also crucial for expanding outreach. Moreover, as Urbancová et al. (2024) point out, regularly collecting user feedback and conducting usability tests are vital for continuously improving the user experience. Balancing accessibility with the ability to meet the complex technical demands of BIM and ImT projects remains a challenge. It requires ongoing innovation in the design and development of collaboration platforms. By addressing these considerations, platforms can ensure inclusivity while maintaining functionality, thereby enhancing team collaboration and project outcomes.

Fifth, *"Participant Recruitment for Platform Testing"* (4%) is a non-technical but equally significant criterion in the integration of BIM and ImT, focusing on ensuring diversity and representativeness among participants and implementing effective recruitment strategies. Recruiting a diverse group of participants for communication platform testing ensures that the system is robust, adaptable, and aligned with real-world conditions. Feedback from a variety of users enables developers to identify and address limitations, enhancing the platform's effectiveness in supporting multidisciplinary collaboration. Yu et al. (2022) emphasize the importance of representativeness in testing processes to ensure the platform meets the needs of all stakeholders, from designers and engineers to project managers and on-site workers. To achieve this, McRobert et al. (2018) recommend developing a multi-channel recruitment strategy that combines traditional and digital methods, such as leveraging social media, professional forums, and partnerships with industry associations. Building on this, Campbell et al.

(2020) suggest using purposeful sampling techniques to ensure the inclusion of diverse user groups. Furthermore, McMaughan et al. (2021) highlight the importance of building trust through community engagement and transparency about research objectives. To overcome time and geographical constraints, researchers can adopt decentralized testing approaches, allowing participants to interact remotely with the platform. Additionally, designing flexible feedback collection methods, such as online surveys, video interviews, and virtual focus groups, can enhance participation and improve the quality of data collected. By implementing these strategies, organizations can ensure that platform testing yields comprehensive insights, leading to systems that are inclusive, effective, and ready to address the diverse needs of BIM and ImT integration projects.

Sixth, the influence of the criterion *"Cognitive Load in Using Communication Platforms"* (3%) is regarded as the extent to which the BIM-ImT integrated system simplifies or complicates users' cognitive processes and performance when utilizing communication platforms in construction environments. Han et al. (2021) emphasize that reducing complexity in platform interfaces enables users to concentrate on critical tasks without feeling overwhelmed. To minimize cognitive load in BIM-ImT environments, developers should prioritize designing intuitive and user-friendly interfaces. Norouzi et al. (2015) propose the use of consistent icons and color schemes across the system, as well as organizing information in a logical and accessible manner. This is particularly crucial in construction management, where workflows often require rapid decision-making under tight deadlines. Additionally, Liu et al. (2022) highlight the importance of providing contextual guidance and visual cues to assist users in learning and using the system effectively. Another effective strategy involves breaking down complex tasks into smaller, manageable steps to prevent users from being overloaded with excessive information. Furthermore, Yelizarov and Gamayunov (2014) suggest incorporating customizable features that allow users to tailor the interface to their individual needs and preferences, further reducing cognitive strain. Finally, regularly collecting user feedback and conducting usability tests can help identify and resolve pain points in interactions with the BIM-ImT integrated system. By implementing these strategies, developers can create communication platforms that effectively reduce cognitive load, enabling users to focus on critical tasks without becoming overwhelmed. This approach not only decreases the likelihood of errors in high-pressure scenarios but also enhances overall system usability and productivity in the construction industry.

Finally, the contribution of the criterion *"Task Management on Collaboration Platforms"* (3%) is acknowledged as essential for understanding how integration affects the intricacy of tasks and the pressure users feel to complete tasks promptly on collaboration platforms. Task management tools play a crucial role in enhancing coordination and productivity within construction workflows. Han et al. (2021) emphasize that platforms featuring intuitive task assignment and tracking capabilities can optimize workflows, minimize delays, and strengthen team collaboration.

Specifically, Fuentes-del-Burgo et al. (2024) propose integrating features such as Kanban boards and Gantt charts into BIM-ImT collaboration platforms, allowing users to effectively manage tasks within 3D environments. This not only improves time management but also enhances transparency and accountability within teams. Delgado et al. (2020) highlight the importance of seamless integration with existing workflows to avoid unnecessary complexity. They recommend customizing user interfaces based on roles and permissions, reducing complexity and increasing accessibility for project members with varying technical expertise. Complementing this, Akhtar et al. (2019) suggest incorporating data analytics tools to automate resource allocation and schedule forecasting, enabling project managers to make more timely and accurate decisions. Effective task management directly influences project timelines by ensuring clear accountability and efficient progress monitoring. By adopting these strategies, BIM-ImT collaboration platforms can not only improve task management efficiency but also foster a more collaborative and flexible working environment. This approach ensures the platforms meet the diverse needs of complex construction projects, driving success through streamlined and well-coordinated task execution.

5.3 Challenges and future directions

Integrating BIM and ImT into building projects holds immense potential to transform the construction industry. However, widespread implementation of these technologies still encounters several critical limitations, as evidenced by existing scholarly work (see Figure 14). First, the process toward seamless integration of BIM and ImT is frequently obstructed by technical limitations and interoperability challenges. Balali et al. (2020) highlighted difficulties in efficiently translating BIM data into immersive environments due to current software systems' inability to handle complex data exchanges. This issue is exacerbated by the lack of fully automatic plugins necessary for direct data transfers between BIM software and AR/VR applications, as noted by Chen et al. (2020). These constraints hinder real-time interactions, crucial for accurate project visualization and management. Scalability of BIM-ImT integrations presents significant concerns. Boton (2018) and Getuli et al. (2020) showed that while successful in controlled or small-scale settings, large-scale implementations often face unaddressed complexities. Ensuring solutions are adaptable and effective across various project sizes without compromising functionality or efficiency is a core challenge. Real-time synchronization of data between BIM and ImT platforms is another critical issue. Jing Du et al. (2018) discussed maintaining up-to-date data across systems, vital given the dynamic nature of construction projects. Inefficiencies in data synchronization can lead to delays, miscommunications, and increased costs due to outdated information reliance. Usability and user interface design also pose significant hurdles. Complex interfaces and insufficient user guidance make technology less accessible to stakeholders, as noted by Wang et al. (2018) and Li et al. (2022). Simplifying interactions and improving user interfaces could enhance satisfaction and broader adoption. Communication and collaboration barriers complicate BIM and ImT's effective use in construction projects. Dinis et al. (2020) and Potseluyko et al. (2022) pointed out that asynchronous data sharing often causes significant delays in information dissemination, leading to project delays and increased costs. Besides, the validation and testing of BIM-ImT integration solutions under real-world conditions are frequently lacking. Boton (2018) suggested that testing often remains confined to controlled environments, which do not adequately reflect actual construction sites' varied conditions. This limitation highlights the need for more comprehensive testing scenarios replicating real-world conditions.

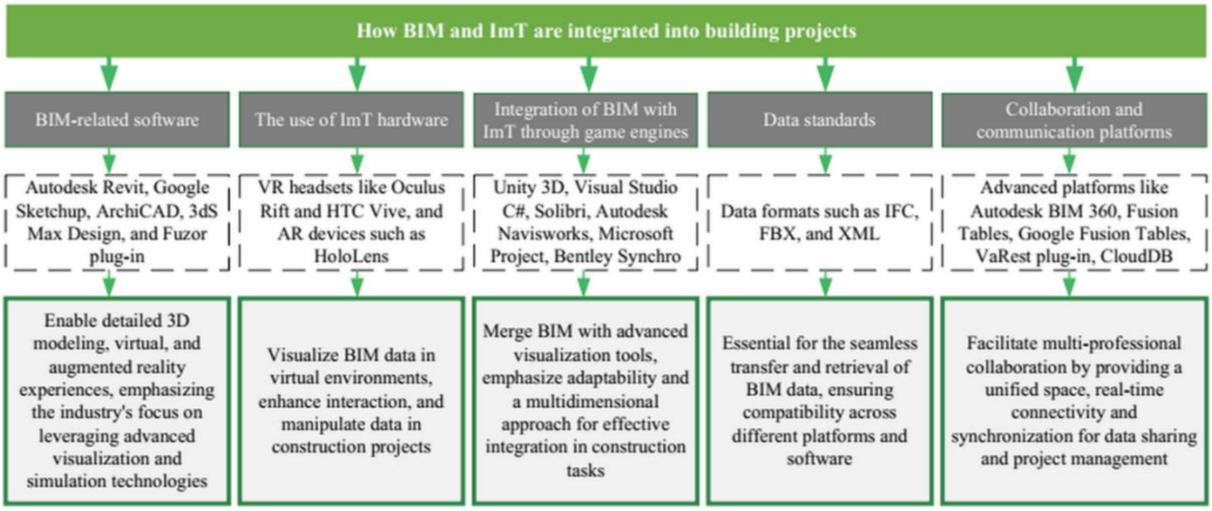
Challenges	Impacts	Future directions
Technical limitations and interoperability issues	• Hinder the seamless translation of BIM data into immersive environments, obstructing real-time interactions and delaying project visualization and management	• Develop advanced algorithms and fully automated plugins to facilitate real-time data synchronization between BIM and ImT platforms
Adjustability	• Effective in small-scale projects but face difficulties in large-scale implementations, reducing efficiency and increasing deployment costs	• Expand research on applying BIM-ImT technologies to large-scale projects and test adaptability under real-world conditions
Real-time data synchronization issues	• Lack of synchronization leads to delays, miscommunications, and increased project costs due to reliance on outdated information	• Enhance synchronization systems to ensure seamless real-time data updates across BIM and ImT platforms
Complex and unintuitive interfaces	• Alienate non-expert users, lowering adoption rates and complicating widespread deployment of BIM and ImT technologies	• Design intuitive, user-friendly interfaces requiring minimal training to improve accessibility and ease of use for diverse stakeholders
Lack of standardization and clear guidelines	• Reduces compatibility and data communication between platforms, hindering interdisciplinary collaboration and increasing project risks	• Develop comprehensive industry standards and regulatory frameworks to facilitate effective data exchange and collaboration across platforms
Insufficient real-world testing	• Testing often remains confined to controlled environments, failing to reflect the diverse conditions of actual construction sites	• Conduct comprehensive testing scenarios in real-world conditions, including complex construction environments, to evaluate practical integration effectiveness
High investment and maintenance costs	• High costs deter small and medium enterprises, limiting widespread adoption across the construction sector	• Perform detailed cost-benefit analyses and implement targeted financial strategies to optimize costs and improve accessibility to BIM-ImT technologies
Communication and collaboration barriers	• Asynchronous data sharing and lack of coordination among stakeholders cause information delays, affecting timelines and increasing project costs	• Develop advanced communication and collaboration platforms that integrate seamlessly with current workflows, ensuring real-time connectivity and synchronization

Figure 14: Summary of key challenges and future directions.

In light of the challenges highlighted in integrating BIM and ImT, focused research efforts should be underscored and identified in existing studies to enable the full potential transformation of the construction industry. Moving forward, enhancing data management is imperative. Improved synchronization systems are essential, as Du et al. (2018) and Jing Du et al. (2018) identified the need for advanced algorithms to facilitate real-time data exchanges across BIM and ImT platforms. Developing these systems would eliminate lags, ensuring seamless project updates and improving efficiency. Usability and accessibility of BIM and ImT interfaces also require significant attention. Current system complexities often alienate non-expert users, limiting broader adoption. Future research should focus on designing more intuitive user interfaces that require minimal training, making these technologies accessible to a wider range of stakeholders. While BIM-ImT integrations have shown success in controlled environments, their ability and application in diverse real-world settings are underexplored. Extending research to include large-scale projects and various environmental conditions will be crucial for assessing the adaptability and effectiveness of these solutions. Advanced simulation and visualization techniques present a promising avenue for future studies. These tools could extend beyond current applications, such as ergonomic assessments (Dias Barkokebas and Li, 2021), to include more complex simulations offering deeper insights into a broader range of construction activities and worker interactions. Integrating cutting-edge technologies like machine learning (ML) and AI could significantly enhance decision-making processes within BIM and ImT frameworks. Exploring how these technologies can automate risk assessments, enhance predictive maintenance, and optimize resource allocation could drive further advancements in the construction sector. Collaborative efforts across various disciplines are essential for successful BIM and ImT integration. Studies should encourage collaboration among technologists, engineers, architects, and end-users, as demonstrated by the successful integration of Autodesk Revit and Unity3D in creating immersive environments. These collaborations ensure that solutions are practical and meet the diverse needs of all stakeholders, such as the widespread use of Oculus Rift and HTC Vive for enhancing virtual reality experiences in construction. Furthermore, the research highlights the need for developing industry-wide standards and clear regulatory guidelines to facilitate the efficient exchange of 3D content using formats like FBX and to foster real-time collaboration through platforms like Autodesk BIM 360 and Trimble Connect. The absence of these standards and guidelines significantly hampers technology adoption and integration across the construction industry. Efforts should focus on developing standardized protocols and regulatory frameworks to facilitate the widespread adoption of BIM and ImT in a legally compliant manner. Addressing these key areas will advance BIM and ImT capabilities, leading to more efficient, cost-effective, and adaptable construction processes.

6. CONCLUSION

The literature associated with the integration of BIM and ImT is substantially broadened by studies exploring various facets of this convergence within construction management. However, how the integration between BIM and ImT is perceived as well as the technical-related and non-technical criteria that influence this integration, especially for building projects, remains less explored. It is seen that building projects encompass a wide array of complexities and environmental considerations. This review specifically focuses on how BIM and ImT are applied throughout the entire project lifecycle, providing an in-depth examination of current methodologies and strategies. A meticulous search through academic databases culminated in the selection of 56 pertinent studies, providing a comprehensive overview of the current landscape and identifying gaps for future research (see Figure 15). The key findings can be encapsulated in the following summary:



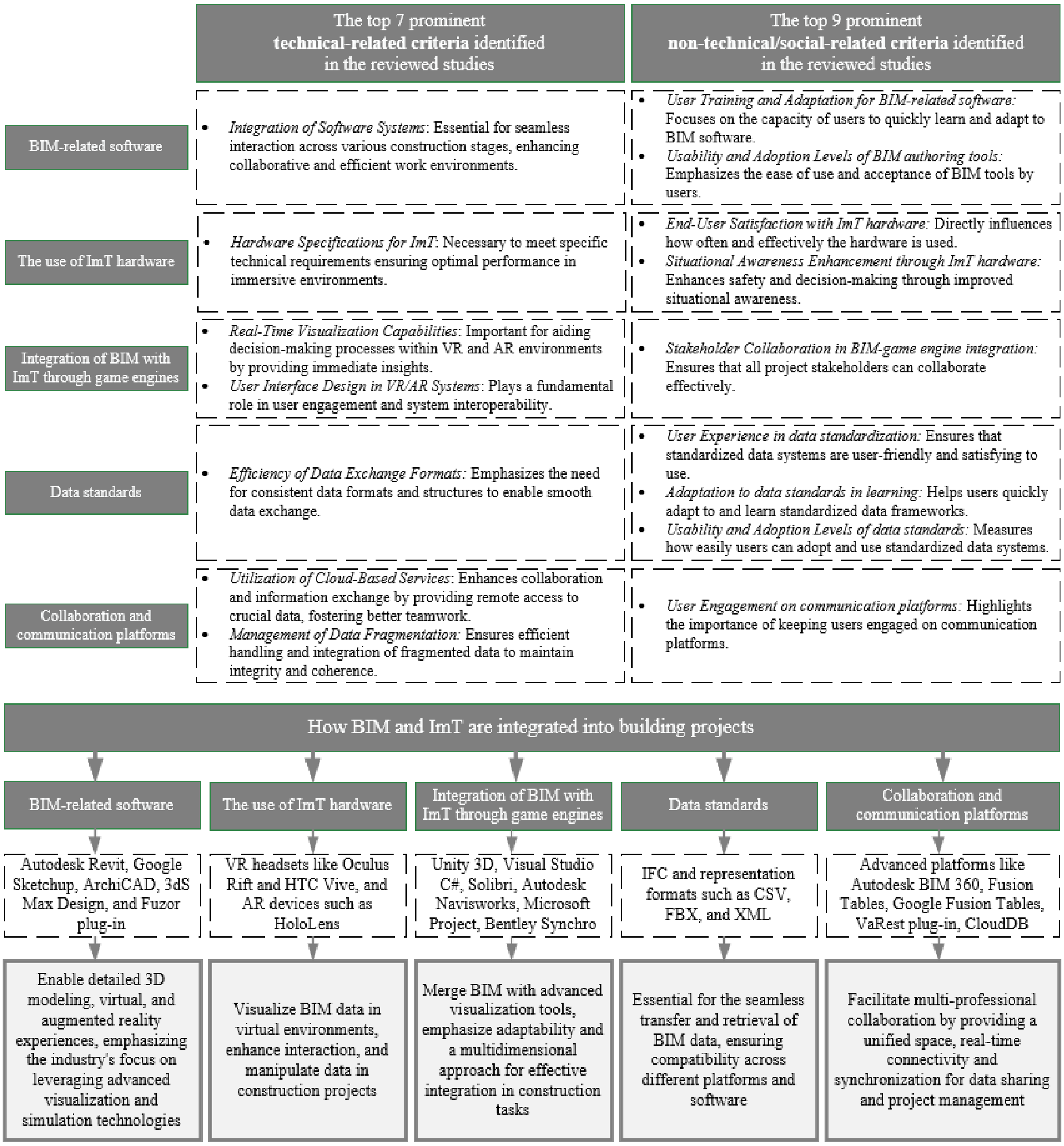


Figure 15: Summary of the main literature findings.

- The results demonstrated that the integration of BIM and ImT in the construction industry has significantly evolved, as evidenced by the widespread adoption and versatile applications of various software and hardware. Autodesk Revit is a cornerstone in BIM-related software, extensively mentioned in 40 studies for its robust parametric modeling and seamless VR/AR integration. Besides, Oculus Rift and HTC Vive are prominently utilized as immersive technology hardware, cited in an equal number of studies for enhancing virtual reality experiences for construction professionals. Unity3D is considered as a pivotal software integration tool for creating and managing immersive environments, underscoring its utility in bridging BIM data with real-time interactive platforms. The FBX format is prevalent for facilitating the efficient exchange and management of 3D content across different systems. Collaborative platforms like Autodesk BIM 360 and Trimble Connect play a critical role in fostering real-time collaboration and data accessibility among multidisciplinary teams. These integrations not only enhance visualization capabilities and simulation accuracy but also improve collaborative workflows, driving advancements in construction project management through technological integration.

- The analysis also indicated that the integration of BIM and ImT is profoundly influenced by several technical and non-technical criteria. On the technical front, the integration of software systems is crucial for seamless interaction across various construction stages, enhancing collaborative and efficient work environments. Hardware specifications for ImT are necessary to meet specific technical requirements, ensuring optimal performance in immersive environments. Real-time visualization capabilities are important for aiding decision-making processes within VR and AR environments by providing immediate insights. User interface design in VR/AR systems plays a fundamental role in user engagement and system interoperability. The efficiency of data exchange formats emphasizes the need for consistent data formats and structures to enable smooth data exchange. Additionally, the utilization of cloud-based services enhances collaboration and information exchange by providing remote access to crucial data, fostering better teamwork. Furthermore, the management of data fragmentation ensures efficient handling and integration of fragmented data to maintain integrity.
- Meanwhile, the non-technical or social-related criteria focus on the human aspect of technology adoption. User training and adaptation for BIM-related software are essential, enabling users to quickly learn and adapt to new technologies. Usability and adoption levels of BIM tools critically affect their integration into existing workflows. The importance of end-user satisfaction and situational awareness with ImT hardware cannot be overstated, as these factors significantly influence the frequency and effectiveness of the technology's use, impacting safety and decision-making. Stakeholder collaboration in BIM-game engine integration is vital for effective joint decision-making. In terms of data standards, user experience and adaptation are crucial for ensuring that standardized systems are user-friendly and satisfying to use. Additionally, usability and adoption levels of data standards measure how easily users can integrate these systems. Effective collaboration and communication platforms are essential, ensuring high user engagement and seamless information sharing, which support dynamic project management and the overall success of BIM and ImT integration.

In addition, this study makes substantial contributions to the field by bridging theoretical concepts with practical execution and informing policy development, thus aiding relevant stakeholders in effectively navigating the complexities of BIM and ImT integration in the construction sector:

- This review significantly enriches the theoretical framework by analyzing the interdisciplinary connections between BIM and ImT technologies like VR and AR. It advances understanding of their interaction within the construction industry and underscores the importance of an integrated approach to building management systems. By elucidating these complex relationships, the study paves the way for further research into digital transformation in construction.
- Practically, the findings offer actionable insights for industry practitioners, particularly in enhancing the adoption and application of BIM and ImT. The use of tools like Autodesk Revit, Oculus Rift, HTC Vive, and Unity3D exemplifies robust integration strategies. Highlighting their effectiveness in real-world settings, the research provides a blueprint for leveraging these technologies for better project management, safety protocols, and operational workflows.
- On a policy level, the study underscores the need for standards and best practices in BIM and ImT integration. Emphasizing data standards and system interoperability, it calls for industry-wide protocols to ensure consistency and reliability. Policymakers and industry associations can use these insights to develop guidelines supporting secure and effective technology deployment in construction.
- For project leaders, this research offers a strategic perspective on managing BIM-ImT adoption. It examines user engagement, learning processes, and stakeholder collaboration, providing insights for fostering environments that embrace technological innovation and address critical human factors.
- Furthermore, the study highlights the importance of developing interactive tools and applications, enhancing user interfaces, and improving interoperability. Software vendors and hardware manufacturers can leverage these insights to better meet customer needs, leading to higher adoption rates and more effective integration of BIM and ImT.

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APPENDIX

Table 2: Summary of the scholarly sources that used BIM and ImT in building projects.

Author	**Application Area**	**BIM and ImT Approach**				
		BIM-related software	**ImT hardware**	**Integration with game engines**	**Data standards**	**Collaboration and communication platforms**
Balali et al. (2020)	Interior finish material selection and cost estimation in VR environment during preliminary design phase	Autodesk Revit	Oculus Rift HMD, Alienware laptop with Intel Core i7 and NVIDIA GTX1080	Unity 3D	Not specified; FBX and COLLADA format used	Not specified
	Key findings and Contributions: The study developed a VR-based framework that enables stakeholders to interactively select interior finish materials while visualizing real-time cost impacts in an immersive environment. The system successfully demonstrated integration between BIM models and cost databases, allowing users to make informed decisions through immersive visualization. The approach reduced design changes during construction phase and improved stakeholder communication, resulting in potential cost reductions of 5-30% through early end-user involvement.					
Han et al. (2021)	Construction site hazard recognition, analysis, and decision-making with focus on cognitive load measurement using immersive technologies	Not specified	VR headset, VR handle	Not specified	Not specified	Not specified
	Key findings and Contributions: The study developed a VR-based immersive system to evaluate how task mode and time pressure affect cognitive load in construction safety hazard recognition. Results showed that double-tasking significantly increased cognitive load and lowered task performance compared to single-tasking. Time pressure had a double-edged effect - enhancing performance in single tasks but degrading performance in multi-tasking scenarios. The findings led to practical recommendations for balancing employee wellbeing and site productivity through proper task allocation and scheduling.					
Shojaei et al. (2021)	Construction management education and training using immersive video technology for content delivery	Not specified	Head-mounted display (HMD), laptop screens	Not specified	Not specified	Not specified
	Key findings and Contributions: The study developed and evaluated a novel educational approach using 360° and 180° 3D immersive videos for construction management training. Results showed students strongly preferred immersive videos over conventional flat videos, with 66% favoring 360° videos and 34% choosing 180° 3D videos. The head-mounted display emerged as the preferred delivery method (84% of students), and spatial audio significantly enhanced site awareness and environmental understanding. The approach demonstrated potential for improving construction education through increased accessibility, engagement, and realistic site experience simulation.					

<table>
<tr><th rowspan="2">Author</th><th rowspan="2">Application Area</th><th colspan="5">BIM and ImT Approach</th></tr>
<tr><th>BIM-related software</th><th>ImT hardware</th><th>Integration with game engines</th><th>Data standards</th><th>Collaboration and communication platforms</th></tr>
<tr><td rowspan="2">Shayesteh et al. (2023)</td><td>Safety training and evaluation for human-robot collaboration (HRC) in construction using virtual reality and physiological sensing</td><td>Autodesk Revit</td><td>HTC Vive Pro Eye HMD, Vive Trackers, Leap Motion, Emotiv Epoc Flex EEG headset, E4 Empatica wristband</td><td>Unity</td><td>Not specified</td><td>Unity Canvas UI</td></tr>
<tr><td colspan="6">Key findings and Contributions: The study developed and validated a virtual avatar-based training platform integrated with physiological sensing for construction worker safety in human-robot collaboration. Results demonstrated significant improvement in workers' safety performance after training, with average scores increasing from 2.23 to 4.17. The developed deep neural network achieved 86% accuracy in assessing cognitive load during training using multimodal physiological signals (EEG, EDA, PPG), outperforming single-source assessment methods. The platform successfully combined immersive visualization with objective training evaluation through physiological monitoring.</td></tr>
<tr><td rowspan="2">Alizadehsalehi et al. (2020)</td><td>Integration of BIM and XR technologies in the AEC industry, with focus on workflow development and implementation frameworks</td><td>Autodesk Revit 2019</td><td>Oculus Rift, HTC Vive, Samsung HMD (VR), Microsoft HoloLens (MR)</td><td>Unity, Unreal</td><td>Not specified; RVT, NWC, TXT, DWG formats used</td><td>Autodesk BIM360, Autodesk Viewer</td></tr>
<tr><td colspan="6">Key findings and Contributions: The study developed a comprehensive BIM-to-XR integration framework using IDEF0 modeling methodology, demonstrating successful implementation through the NASA-Mars habitat project case study. The framework established a systematic five-step workflow for converting BIM models to XR environments, addressing interoperability challenges and enabling real-time visualization. Results showed that integrating BIM with XR technologies enhanced project communication, decision-making, and stakeholder collaboration while identifying key implementation barriers including hardware costs, file size limitations, and workflow complexity.</td></tr>
<tr><td rowspan="2">Du et al. (2018)</td><td>Design coordination and collaborative decision-making in AEC/FM projects</td><td>Autodesk Revit</td><td>Oculus Rift DK2, Samsung Gear VR, Google Cardboard</td><td>Unity 3D</td><td>Not explicitly mentioned; FBX format used</td><td>Cloud-based infrastructure with client-server architecture</td></tr>
<tr><td colspan="6">Key findings and Contributions: The study developed a BIM-VR real-time synchronization system called BVRS, which allows users to update BIM model changes in VR headsets automatically and simultaneously. BVRS was tested in various design change scenarios, including changing object dimensions, locations, and types. The results confirmed the usability and efficiency of the system. The BVRS process can be made reciprocal, allowing changes made in VR to be reflected back in the Revit model. This real-time synchronization capability addresses the information latency issues in current BIM-to-VR workflows, potentially improving collaborative decision-making in AEC/FM projects.</td></tr>
<tr><td>Du et al. (2018a)</td><td>Cloud-based multiuser virtual reality system for remote project communication in AEC industry</td><td>Autodesk Revit 2015</td><td>Oculus Rift Development Kit HMD version 2.0, Oculus Rift consumer HMD version</td><td>Unity 3D 5.3.2</td><td>Not specified; FBX format used for data exchange</td><td>Photon Unity Networking (PUN)</td></tr>
</table>

Author	Application Area	BIM and ImT Approach				
		BIM-related software	ImT hardware	Integration with game engines	Data standards	Collaboration and communication platforms
			1.0, HTC VIVE			
	Key findings and Contributions: The study developed CoVR, a cloud-based multiuser VR system that facilitates interpersonal project communication in an interactive VR environment. CoVR demonstrated improved interpersonal interactions and enhanced communication in construction tasks, with users performing better in building inspection compared to traditional VR systems. The system integrates BIM data, game engine capabilities, and cloud networking to create a shared virtual experience, potentially reducing misunderstandings and communication costs in construction processes.					
Chen et al. (2020)	Efficient mechanisms for BIM-to-AR/VR data transfer in the Architecture, Engineering, Construction, and Operations (AECO) industry, focusing on semantic information preservation and geometric model simplification	Autodesk Revit 2018	Android smartphone (OnePlus 3 with Snapdragon 820 CPU, Adreno 530 GPU, 6 GB RAM)	Unity	IFC, FBX format for data exchange	Not specified
	Key findings and Contributions: The study addresses inefficiencies in BIM-to-AR/VR data transfer by proposing an ontology-based approach to preserve semantic information and implementing tailored polygon reduction algorithms for geometric models. These mechanisms significantly reduce the number of polygons (up to 77.6% for cylindrical components), enhance frame rates in AR/VR applications, and improve data interoperability between BIM and AR/VR platforms. The research demonstrates that optimized data transfer can streamline visualization workflows while maintaining information integrity and improving application fluency in immersive environments.					
Delgado et al. (2020)	Exploration of AR/VR applications in AEC, with a focus on use-case identification, adoption analysis, and a proposed research agenda.	Not specified	Head-mounted displays (HMDs), tablets, mobile devices	Not specified	IFC referenced for BIM interoperability challenges	Multi-user VR environments discussed but no specific platforms named
	Key findings and Contributions: The study identifies six primary AR/VR use-cases in AEC-stakeholder engagement, design support, design review, construction support, operations/management, and training-highlighting VR's higher adoption levels compared to AR. It provides a three-tier research agenda addressing engineering-grade devices, workflow/data management, and new capabilities such as real-time simulations and multi-user collaboration frameworks. The research emphasizes the need for improved hardware robustness, better data interoperability, and workforce upskilling to overcome barriers to adoption.					

Author	**Application Area**	**BIM and ImT Approach**				
		BIM-related software	**ImT hardware**	**Integration with game engines**	**Data standards**	**Collaboration and communication platforms**
Rahimian et al. (2020)	Construction progress monitoring	Autodesk Revit, Autodesk Navisworks	HTC Vive VR headset	Unity	IFC; Representative format: FBX	Not specified
	Key findings and Contributions: The study developed a prototype integrating machine learning, BIM, and VR for automated construction progress monitoring. It overlays processed site images onto BIM models in VR, enabling on-demand as-built vs. as-planned comparisons. This system supports remote management, improves progress tracking accuracy, and enhances stakeholder communication, demonstrating potential for efficient, interactive construction monitoring.					
Olbina and Glick (2022)	Construction management education	Autodesk Revit	Oculus Rift, Microsoft HoloLens	Unity	Not specified	Not specified
	Key findings and Contributions: The study demonstrates that integrating hands-on construction activities with VR and AR enhances students' visualization skills and understanding of construction materials and methods. Students reported significant improvements in their ability to visualize building structures when using VR compared to traditional 2D drawings. The research highlights the effectiveness of combining physical models with immersive technologies in construction management education, suggesting that this approach can be beneficial for enhancing learning outcomes and communication skills among students. The findings advocate for broader adoption of such integrated teaching methods in construction curricula.					
Yu et al. (2022)	Construction safety training	Autodesk Revit 2021	HTC Vive, Facebook Oculus, Android OS-compatible devices	Unity (version 2018.4.17)	Not specified; Representative format: FBX format	Not specified
	Key findings and Contributions: The study developed an Immersive Virtual Reality-based Safety Training System (IVSTS) to improve construction workers' safety performance in hazardous scenario identification (HSI) and personal protective equipment (PPE) selection. The system demonstrated significant improvements in safety learning outcomes, particularly for novice workers, with a 37.55% improvement in HSI and a 16.92% improvement in PPE selection. The research highlights the effectiveness of IVSTS in addressing construction hazards across six worker specialties and 17 hazardous scenarios, emphasizing its potential to replace traditional lecture-based safety training methods while reducing risks for novice workers who face higher accident rates.					
Dias Barkokebas and Li (2021)	Ergonomic risk assessment in industrialized construction tasks	Not specified	HTC Vive VR system (including headset, hand controllers, and base stations)	Unreal Engine 4.22	Not specified	Not specified
	Key findings and Contributions: The study developed a VR-based ergonomic assessment methodology to proactively identify ergonomic risks during workstation design in industrialized construction. By comparing VR simulations with physical mock-ups, the system achieved 86% and 80% accuracy in RULA and REBA assessments, respectively. This approach reduces reliance on costly physical prototypes and provides ergonomic feedback early in the design process. The findings demonstrate VR's potential for accurate ergonomic risk analysis, improving worker safety while minimizing costs and time in workstation design.					
Du et al. (2017)	Collaborative decision-making in the AEC/FM industry	Autodesk Revit 2019	Oculus Rift DK2 VR headset	Unity3D	IFC	Cloud-based synchronization system (BVRS)

Author	**Application Area**	**BIM and ImT Approach**				
		BIM-related software	**ImT hardware**	**Integration with game engines**	**Data standards**	**Collaboration and communication platforms**
	Key findings and Contributions: The study introduced BVRS, a real-time BIM-VR synchronization system that automates metadata exchange via a cloud-based workflow. It allows simultaneous updates of BIM model changes in VR headsets, facilitating collaborative design and decision-making processes. By addressing inefficiencies in traditional manual file conversion workflows, BVRS enhances user engagement and usability in VR applications for construction projects. The system's successful application in real-time design change scenarios demonstrates its potential to improve communication and project management efficiency in the AEC/FM industry.					
Wang et al. (2018)	Quantity surveying education and practice	Autodesk Revit 2016	Head-mounted display, 360-degree display	Unity	Not specified; Representative format: FBX	Not specified
	Key findings and Contributions: The study developed a VR-embedded BIM immersive system for quantity surveying education and practice, enhancing students' and practitioners' understanding of architectural designs. The system improved visualization skills, decision-making efficiency, and precision in quantity surveying work. Survey results showed significant agreement on the system's benefits, including better understanding of architectural and MEP systems, improved quantity surveying job performance, and enhanced learning outcomes compared to traditional textbooks. The research demonstrates the potential of integrating VR and BIM technologies to address challenges in construction education and practice.					
Abbas et al. (2019)	Communication effectiveness in construction projects	Autodesk Revit	HTC Vive VR headset	Fuzor Virtual Design Construction software	Not specified; Representative format: FBX	Not specified
	Key findings and Contributions: The study compared face-to-face (FtF) communication with immersive virtual reality (IVR)-based communication for construction project discussions. While IVR provided comparable discussion quality, richness, and openness to FtF communication, it was less effective in accuracy and appropriateness due to the absence of non-verbal cues like facial expressions or gestures. The research highlights IVR's potential for remote collaboration but emphasizes the need for advancements in human-human interaction within virtual environments to enhance its effectiveness as a communication tool in construction projects.					
Wu et al. (2019)	Construction education and workforce development	Not specified	Autodesk Revit 2019	Unity	Not specified	Not specified
	Key findings and Contributions: The study explored the effectiveness of VR and MR in bridging the expertise gap between novice students and expert professionals in construction design assessments. Results indicated that student novices could achieve design outcomes comparable to those of experts when using VR and MR mock-ups, despite their lack of experience. The findings suggest that VR and MR can facilitate tacit knowledge acquisition and accelerate the development of workplace expertise among students. The research emphasizes the potential of these technologies to enhance instructional design in construction education, providing valuable insights for curriculum development aimed at addressing skills shortages in the industry.					
Han and Leite (2021)	Construction design review tasks	Autodesk Revit, Autodesk Navisworks	Oculus Rift CV1 VR headset	Unity	Not specified; Representative format: FBX	Not specified
	Key findings and Contributions: The study quantified the impact of head-mounted displays (HMDs) on user performance in construction design review tasks compared to desktop-based VR. HMD users detected significantly more design errors (48-59% improvement) and made fewer mistakes in installation sequencing (18-33% reduction). The research demonstrates that HMDs can substantially enhance effectiveness in specific design review applications, providing guidance for intentional implementation of VR in the construction industry. The methodology developed also improves on existing approaches for validating technology impacts by controlling for extraneous variables.					

Author	Application Area	BIM and ImT Approach				
		BIM-related software	ImT hardware	Integration with game engines	Data standards	Collaboration and communication platforms
Li et al. (2022)	Cognition load in altered and stressful construction tasks	Autodesk Revit	HTC Vive VR headset	Unity3D	Not specified	Not specified
	Key findings and Contributions: The paper presents a process model for XR-enabled experimental research in construction engineering and management, emphasizing its potential for controlled, reproducible studies involving human participants. XR technologies enable immersive environments for investigating complex CEM problems, enhancing data collection through tools like eye tracking and neurophysiological sensors. The study demonstrates XR's ability to address challenges in traditional methods, such as ecological validity and reproducibility, through two illustrative case studies on cognitive load in stressful tasks and earthquake preparedness. The findings highlight XR's transformative role in advancing methodological rigor and interdisciplinary research in the CEM domain.					
Lucena and Saffaro (2022)	Construction safety and hazard identification	Not specified	Google Cardboard (low-cost VR device)	Not specified	Not specified	Not specified
	Key findings and Contributions: The study proposed guidelines for exploring construction sites in VR environments to improve hazard identification using low-cost devices like Google Cardboard. It concluded that a protocol-guided exploration method significantly enhances hazard identification compared to unguided exploration by systematically focusing users' attention on various hazard categories. The research emphasized the importance of combining VR technology with structured protocols to maximize the effectiveness of virtual site inspections, providing a cost-effective approach to improving construction safety management practices.					
Latini et al. (2023)	Productivity, comfort, and behavioral research in office environments	Autodesk Revit	HTC VIVE PRO Eye head-mounted display	Unity	Not specified; Representative format: FBX format	Not specified
	Key findings and Contributions: The study validated the use of immersive virtual environments (IVEs) for assessing occupants' productivity, comfort, and behavior in office spaces. Results demonstrated excellent levels of presence and immersivity in the virtual environment, confirming its ecological validity. Statistical analysis revealed no significant differences between real and virtual environments in terms of productivity, thermal and visual comfort, and intention of interaction. This confirms the criterion validity of IVEs for these research areas. The findings support the use of virtual reality as a promising approach for user-centered design in the AEC sector, enabling exploration of various environmental stimuli and layouts to enhance living and working conditions from early design stages.					
Le et al. (2015)	Construction safety education	Autodesk Revit 2013	HTC VIVE PRO Eye head-mounted display, mobile devices (smartphones, tablets)	Unity	Not specified; Representative format: FBX	Not specified
	Key findings and Contributions: The study demonstrated that integrating VR and AR with mobile computing can address limitations of current construction safety education and improve future construction personnel's safety competency. The interactive and experiential features of the proposed system were found to enhance hazard identification skills and awareness of safe work procedures. The approach showed potential to improve construction safety education, though scenario creation was time-consuming.					
Getuli et al. (2021)	Construction safety training and management	Not specified	Smartphone-based mobile VR solution	Unity	Not specified	Not specified

Author	Application Area	BIM and ImT Approach				
		BIM-related software	ImT hardware	Integration with game engines	Data standards	Collaboration and communication platforms
	Key findings and Contributions: The study developed a standardized protocol for integrating BIM and VR technologies into construction safety training. A 5-step process was proposed and tested in a case study, addressing planning, management, and administration of VR training sessions. The protocol leverages game technology to create a coherent data flow from BIM to VR training delivery. The research demonstrated the feasibility of implementing BIM-VR integrated safety training in real construction projects, while identifying areas for further development to reduce implementation barriers related to specialized ICT knowledge requirements.					
Getuli et al. (2020)	Construction workspace planning and safety management	Autodesk Revit	HTC Vive Pro	Unity	Not specified	Not specified
	Key findings and Contributions: The study presents a novel methodology for workspace planning in construction that integrates immersive VR with BIM. By simulating construction activities in VR, the methodology allows for the elicitation of workers' knowledge, enhancing the accuracy of workspace configurations. The case study demonstrated significant improvements in safety-related communication among project partners and the formal representation of this information in Health and Safety Plans. The findings underscore the potential of combining BIM and VR to address complexities in construction planning while improving safety outcomes on job sites.					
Mo et al. (2018)	Construction safety training	Autodesk Revit	HTC VIVE VR headset	Unity3D	Not specified; Representative format: FBX	Not specified
	Key findings and Contributions: The study developed a data-driven approach to automatically identify design elements for virtual reality safety training scenarios from real-world accident reports. It integrates human factors engineering and machine learning techniques with gaming technology to generate more realistic and relevant training content. The approach was demonstrated to improve accuracy and efficiency in scenario design for VR-based construction safety training programs.					
Pham et al. (2018)	Mobile construction safety education	Autodesk Revit	360-degree panoramic VR technology, mobile devices	Not specified	Not specified	VIFITS system (includes chatroom for discussions)
	Key findings and Contributions: The study introduces the Virtual Field Trip System (VIFITS) designed to enhance construction safety education through immersive 360-degree VR experiences. VIFITS consists of three modules for safety information dissemination, virtual field trip experiences, and safety knowledge assessment, effectively engaging students in safety learning. The prototype was validated using real construction scenarios, demonstrating significant improvements in students' safety knowledge acquisition compared to traditional methods. The results indicate that VIFITS can effectively bridge the gap in practical safety training for construction students, offering a scalable solution for educational institutions to enhance safety training delivery.					
Le et al. (2015a)	Construction safety education and training	Autodesk Revit	Oculus Rift DK2 VR headset	Unity3D	Not specified; Representative format: FBX	Second Life (SL) virtual world platform
	Key findings and Contributions: The study developed a social VR system for construction safety education that enables collaborative learning through role-playing and interactive scenarios. The system integrates BIM models with VR to create realistic training environments. Results showed the VR-based approach enhanced students' hazard recognition skills and safety knowledge retention compared to traditional methods. The collaborative aspects facilitated peer learning and improved engagement. This research demonstrates VR's potential to provide experiential safety training in a risk-free virtual environment.					

Author	**Application Area**	**BIM and ImT Approach**				
		BIM-related software	**ImT hardware**	**Integration with game engines**	**Data standards**	**Collaboration and communication platforms**
Jacobsen et al. (2022)	Construction safety training and education, specifically hazard detection and rectification in virtual and physical environments	Blender for constructing 3D objects	HTC Vive head-mounted display (HMD), controllers, and trackers	Unity 3D	Not specified	Not specified
	Key findings and Contributions: The study demonstrated the effectiveness of automated run-time data collection in virtual reality (VR) for objective assessment of construction safety training. The research developed a framework for generating and automatically assessing VR user data, providing insights into individual performance in safety education, cognition, and work task productivity. The study also explored the transfer of VR training benefits to a physical setup using LiDAR technology, offering a potential alternative for construction sites without VR capabilities. The findings suggest that this approach can enhance personalized safety training and improve hazard awareness in the construction industry.					
Kim et al. (2021)	Construction safety, specifically risk habituation to struck-by hazards in road construction environments	3ds Max 2019 and Maya 2019 for 3D modeling	Head-mounted display (HMD) with embedded eye-tracking system	Unreal Engine 4 (UE4)	Not specified	Not specified
	Key findings and Contributions: The study demonstrated that a VR environment can effectively elicit and measure workers' risk habituation to struck-by hazards over a short period. Experiencing VR-simulated accidents significantly mitigated risk habituation, with effects sustained over time. The research provides a novel approach to quantitatively measure and mitigate the decline in workers' vigilant behaviors due to habituation, offering valuable insights for improving construction site safety management. The findings highlight the potential of VR-based behavioral interventions in enhancing workers' hazard awareness and promoting safer workplace practices.					
Adami et al. (2022)	Human-robot interaction (HRI) for remote operation of construction robots	Autodesk Revit 2019	HTC Vive head-mounted display (HMD), Virtuix Omni VR treadmill	Unity 3D	Not specified; Representative format: FBX format	Not specified
	Key findings and Contributions: The study demonstrated that VR-based training significantly improves construction workers' trust in robots, self-efficacy in robot operation, and situational awareness compared to traditional in-person training. The immersive VR environment allowed workers to safely practice remote operation of a demolition robot in various scenarios, fostering better understanding and confidence in robotic systems. While VR-based training showed potential to reduce mental workload, no significant difference was found compared to in-person methods. The findings highlight VR's transformative role in enhancing human-robot interaction and preparing workers for the adoption of robotics in dynamic construction environments.					
Shringi et al. (2023)	Safety training for tower crane operations in off-site construction, specifically for lifting and installation of prefabricated modules	Autodesk Revit	Samsung Odyssey head-mounted display (HMD)	Unity3D	Not specified; .fbx format used for importing BIM models into Unity3D	Not specified

Author	Application Area	BIM and ImT Approach				
		BIM-related software	ImT hardware	Integration with game engines	Data standards	Collaboration and communication platforms
	Key findings and Contributions: The study developed a framework for creating immersive safety training by combining BIM and VR for tower crane operations in off-site construction. The framework enhances hazard perception and situational awareness of crane operators through realistic visualizations and interactive simulations. The research demonstrated that VR-based safety training can effectively prepare operators for site-specific challenges, potentially reducing accidents and improving safety performance. The approach also enables inexperienced contractors to adopt off-site prefabrication methods by mitigating safety risks through context-aware training.					
Bao et al. (2022)	Real-time construction safety training using VR, with a focus on cross-platform accessibility and user interaction	Autodesk Revit	HTC Vive Focus Plus head-mounted display (HMD); also supports non-immersive devices like desktops and mobile phones	Not applicable; instead, WebGL and WebXR were used for rendering and immersive VR development in web browsers	Industry Foundation Classes (IFC2X3 format) used for BIM data exchange	WebRTC for real-time voice communication; WebSocket for real-time data sharing in VR environments
	Key findings and Contributions: The study proposed a cross-platform VR framework (CPVR) for safety training in construction, leveraging web technologies to enhance accessibility and interoperability. By using IFC files, the framework eliminates the need for format conversion, enabling real-time interaction, communication, and scenario-based training across multiple devices. Validation through user testing demonstrated improved safety awareness, engagement, and collaboration among workers, while managers gained tools to assess safety knowledge effectively. The CPVR framework offers a scalable solution to address challenges in traditional VR safety training systems.					
Boton (2018)	Constructability analysis meetings in construction, specifically using VR and BIM 4D simulation for collaborative planning and decision-making	Autodesk Revit for 3D modeling; Navisworks Manage for 4D simulation	Valyz VR system, including a controller with Constellation, movement tracking system, and 3D glasses	Unity 3D	Not specified; FBX format used for transferring models	No dedicated platform mentioned; sessions were co-located and synchronous
	Key findings and Contributions: The study proposed a comprehensive framework for supporting constructability analysis meetings using immersive VR-based collaborative 4D simulation. It demonstrated the potential of VR to enhance constructability reviews by improving spatial understanding and enabling multi-perspective evaluations of construction schedules. However, limitations such as restricted interactivity in the VR environment and challenges in exporting timeline data were identified. The research highlights the value of VR in fostering collaboration among stakeholders while suggesting future improvements to enhance usability and integration in construction workflows.					
Chen et al. (2021)	Fire safety management and firefighter training, specifically improving situational awareness during	Autodesk Revit	HTC Vive Focus Plus head-mounted display (HMD) with built-in cameras	Unity 3D	IFC; FBX format was for importing models into Unity 3D	WebRTC and WebSocket were utilized for real-time communication and data sharing in

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<tr><td rowspan="2"></td><td>fire emergencies in high-rise buildings</td><td></td><td></td><td></td><td></td><td>team-based VR training</td></tr>
<tr><td colspan="6">Key findings and Contributions: The study proposed a framework integrating BIM, IoT, and AR/VR to enhance situational awareness for firefighters during fire emergencies. Real-time sensor data was integrated into BIM for dynamic fire monitoring, while VR provided immersive training scenarios simulating fire hazards. AR enabled real-time route navigation during emergencies. Preliminary tests demonstrated the system's potential to improve decision-making efficiency, situational awareness, and safety performance in fire rescue operations. However, limitations such as hardware latency and reliance on pre-existing BIM models were noted, suggesting areas for future improvement.</td></tr>
<tr><td rowspan="2">Dinis et al. (2020)</td><td>Improving project communication in the AEC industry, particularly for retrofitting projects</td><td>Autodesk Revit</td><td>HTC VIVE head-mounted display (HMD) and controllers</td><td>Unity</td><td>IFC;
Representative format: Plain Text Data Format (.ptx) for point cloud export, Object (.obj) file for mesh export</td><td>Not specifically mentioned for collaboration;
WebRTC for real-time voice communication in VR environment</td></tr>
<tr><td colspan="6">Key findings and Contributions: The study proposed a workflow combining laser scanning and VR within a BIM environment to enhance communication in construction projects. The approach allows non-BIM users to interact with as-is building data in VR, add voice annotations, and automatically update the BIM model. This method improves stakeholder engagement, facilitates design brief development, and supports information flow during retrofitting projects. The framework demonstrates potential for bridging communication gaps between different project stakeholders and enhancing decision-making processes in the AEC industry.</td></tr>
<tr><td rowspan="2">Garbett et al. (2021)</td><td>Multi-user collaborative BIM-AR system for design and construction</td><td>Autodesk Revit</td><td>Mobile devices (e.g., Samsung Galaxy S7, Apple iPad Air 2) for AR application;
Large touch screen devices for collaborative workspace</td><td>Unity (version 5.6.2F1)</td><td>Not specified;
Representative format: FBX for transferring 3D models from Revit to Unity</td><td>Client-Server database using MySQL for real-time data sharing and synchronization</td></tr>
<tr><td colspan="6">Key findings and Contributions: The study developed a multi-user collaborative BIM-AR system that enables real-time interaction and data sharing across different platforms. The system demonstrated potential for improving communication between stakeholders, enhancing understanding of design elements, and saving time in project discussions. It allows users to add annotations and view changes instantly, facilitating more efficient decision-making processes in geographically dispersed teams. The research validated the concept of real-time, interactive, collaborative AR as an effective tool for supporting workflows within distributed construction teams, providing an intuitive visualization experience that enhances project communication and understanding.</td></tr>
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Author	Application Area	BIM and ImT Approach				
		BIM-related software	ImT hardware	Integration with game engines	Data standards	Collaboration and communication platforms
Marzouk and Zaher (2015)	Construction project progress tracking and monitoring using mobile devices and cloud-based systems	Autodesk Revit 2014 for creating 3D models; Navisworks 2014 for 5D modeling and simulation	Smartphones and tablets (e.g., Sony Xperia C smartphone with a 5-inch TFT capacitive touchscreen)	Not specified	Representative format: DWFX for 2D/3D drawings and CSV for data transfer to Navisworks	Autodesk 360 for cloud-based sharing, organization, and collaboration on project data
	Key findings and Contributions: The study introduced the "BIM-Track" Android application as a mobile solution for real-time progress tracking in construction projects. By integrating cloud computing, image processing, and BIM, the system enables efficient monitoring of project performance through 5D modeling and image analysis. The application supports data synchronization between mobile devices and cloud platforms, allowing users to compare actual progress with planned schedules and costs. A case study demonstrated its capability to enhance decision-making by providing accurate project updates, reducing manual errors, and improving communication among stakeholders.					
Panya et al. (2023)	Design change management in building projects using BIM integrated with VR and AR	Autodesk Revit	Not specified	Unreal Engine 4 (UE4)	Not specifed; FBX format used	Custom cloud-based system for saving and sharing design changes
	Key findings and Contributions: The study presents an interactive design change methodology integrating BIM with VR and AR to reduce rework in design changes. The approach extends BIM functionality by incorporating as-built data from web sources into VR/AR environments, allowing real-time visualization and selection of multiple design options. This method improves collaboration, reduces redesign efforts, and maintains information flow integrity. The system demonstrates effectiveness in presenting change options for wall elements based on thermal requirements, potentially enhancing decision-making and reducing time and effort in the design change process.					
Shahinmoghadam et al. (2021)	Real-time thermal comfort assessment in building enclosures using an integrated BIM, IoT, and VR approach	Autodesk Revit	HTC Vive Focus Plus head-mounted display (HMD) and cost-effective thermal imaging sensors (FLIR Lepton)	Unreal Engine 4	IFC for BIM data exchange	IFTTT for cloud-based data integration and HTTP communications for real-time data access
	Key findings and Contributions: The study developed a novel system integrating BIM, IoT, and VR to facilitate real-time monitoring of thermal comfort conditions based on the PMV-PPD model. The system demonstrated effective visualization of live sensor data in immersive environments, enabling users to assess thermal comfort dynamically. Validation tests indicated strong alignment between the system's outputs and actual thermal sensations experienced by occupants. The research highlights the potential of combining these technologies to enhance indoor environmental quality monitoring and decision-making in building management. Future work will focus on refining sensor integration and exploring augmented reality applications for enhanced user interaction.					

Author	**Application Area**	**BIM and ImT Approach**				
		BIM-related software	**ImT hardware**	**Integration with game engines**	**Data standards**	**Collaboration and communication platforms**
Vittori et al. (2021)	Subjective thermal response and indoor comfort perception in office environments	Autodesk Revit 2019	Oculus Go headset	Not specified	Not specified; FBX format used	Autodesk Cloud Service
	Key findings and Contributions: The study proposed a novel analysis framework and field test method to better understand and monitor people's environmental perception using immersive virtual environments modeled in a parametric platform. A physical office room was redesigned through VR with a 76% satisfaction rate for sense-of-presence feeling. The research investigated the effects of three triggers on thermal perception: glass filter, window aspect ratio, and artificial lighting color temperature. Window aspect ratio and lighting color temperature significantly produced placebo effects on thermal comfort, with subjects feeling relatively warmer in high aspect ratio window conditions and low color temperature lighting. The findings suggest that non-thermal triggers can affect indoor thermal perception and potentially induce better thermal satisfaction and energy-saving behaviors if properly considered. This novel method can assist in human-centric building design for energy efficiency enhancements.					
Wang et al. (2022)	Virtual trial assembly (VTA) of complex steel structures using a BIM platform	Autodesk Revit	Not specified	Not specified; Dynamo visual programming environment used instead	Not specified; FBX format used for transferring 3D models	Not specified
	Key findings and Contributions: The study proposed an innovative framework for implementing VTA of steel structures on a BIM platform, ensuring effective information transfer from design to manufacturing stages. A VTA program prototype was developed using Revit's Dynamo environment, incorporating EOPA and GPA algorithms for geometric inspection and assembly testing. The framework demonstrated improved efficiency in detecting assembly issues and reduced the risk of data loss compared to third-party inspection software. Validation on a real-world bridge project showcased the method's effectiveness for large bolted steel components, offering potential for extension to other prefabricated structure types.					
Park et al. (2013)	Construction defect management using BIM, AR, and ontology-based data collection	Autodesk ArchiCAD for 3D modeling	Webcam, mobile devices (smartphone or tablet PC)	Not specified	OmniClass classification system; WRL (Virtual Reality Modeling Language) format used	Not specified
	Key findings and Contributions: The study presents a comprehensive framework for proactive construction defect management, integrating BIM, AR, and ontology-based data collection. The proposed system includes a defect data collection template, a defect-specific domain ontology, and AR-based automatic inspection methods. Lab tests demonstrated the potential of marker-based AR and image-matching techniques for omission and dimension error inspections. The framework aims to shift defect management from reactive to proactive approaches, potentially reducing defect occurrences, improving information flow, and enhancing overall construction quality management.					
Meža et al. (2014)	Construction site monitoring and progress tracking using BIM-based AR	Graphisoft ArchiCAD 16	Smartphones and tablet computers	Not specified	IFC; Representative format: OBJ	BIM server with web interface

Author	Application Area	BIM and ImT Approach				
		BIM-related software	ImT hardware	Integration with game engines	Data standards	Collaboration and communication platforms
	Key findings and Contributions: The study developed a component-based BIM-AR system for construction site monitoring. It demonstrated that AR can provide unrestricted access to BIM information on-site, simplifying project progress monitoring. However, challenges were identified in hardware capacity, visual occlusion, and georeferencing. The research highlighted the need for improved 4D and 5D BIM integration and emphasized the potential of AR to bridge the gap between digital models and real-world construction environments.					
Kwon et al. (2014)	Defect management for reinforced concrete (RC) work	Graphisoft ArchiCAD	Samsung Galaxy Tab 10.1 (Android-based), laptop, web-cam	Not specified	Not specified; Representative format: WRL (Virtual Reality Modeling Language)	Not specified
	Key findings and Contributions: The study developed two defect management systems: an image-matching system for remote quality inspection and a mobile DM-AR app for on-site dimension error and omission detection. These systems demonstrated effectiveness in automating defect detection for RC work, reducing site managers' workloads, and enabling proactive defect prevention. The research highlighted the potential of integrating BIM, image-matching, and AR technologies to enhance construction defect management, while also identifying limitations in marker-based systems and the need for future development of markerless AR tracking.					
El Ammari and Hammad (2019)	Facilities management (FM) tasks, including inspection and maintenance	Autodesk Revit	Android tablet (Samsung Galaxy Tab S2), Oculus Rift VR headset with touch controllers	Unity3D	IFC; FBX format used	Custom system using Unity3D for real-time collaboration between AR and IAV modules
	Key findings and Contributions: The study developed a collaborative BIM-based mixed reality system called CBIM3R-FMS to support facilities management tasks. It demonstrated improved efficiency in task completion, with an 85% reduction in time for identifying tagged tasks using the interactive visual collaboration (IVC) approach. The system showed good effectiveness (90.20%) and high user satisfaction. However, challenges were identified in user privacy concerns and the need for hands-free AR solutions for field workers.					
Han and Leite (2022)	Generic XR model development for various AEC applications throughout project lifecycle	Autodesk Revit	VR headset (Oculus Rift), AR/MR device (iPad)	Unity3D	IFC; FBX format used	Not specified
	Key findings and Contributions: The study proposed a Generic Extended Reality (GenXR) model to streamline BIM-to-XR processes for multiple XR applications in AEC projects. The model demonstrated applicability across VR, AR, and MR prototypes, supporting various AEC use cases. It significantly reduced development time by 63.8% to 66.7% in subsequent iterations after initial setup. The research highlighted the potential for more efficient XR implementation in construction projects, enabling new use cases like VR-based design coordination during construction.					
Alirezaei et al. (2022)	Cost and schedule risk management in construction projects	Autodesk Revit	Commercial smartphones	Unity3D	Not specified; FBX format used	Cloud database (CloudDB)

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<tr><td></td><td colspan="6">Key findings and Contributions: The study developed an integrated BIM-AR risk management system for online inspection of project cost and schedule risks. The system demonstrated improved risk communication, timeliness, and perception among users. It enabled real-time risk data collection, automated risk analysis, and BIM model updates. The color-coded AR visualizations enhanced stakeholders' understanding of project risks. However, challenges remained in system ergonomics and synchronization of automated/non-automated subsystems.</td></tr>
<tr><td rowspan="2">Potseluyko et al. (2022)</td><td>Timber frame self-build housing sector</td><td>Autodesk Revit</td><td>HTC Vive VR headset</td><td>Unreal Engine 4</td><td>IFC; FBX format used</td><td>Unreal Engine 4 Collaboration Viewer Template for real-time multi-user interaction</td></tr>
<tr><td colspan="6">Key findings and Contributions: The study developed a game-like BIM-based VR interface for small and medium-sized timber frame kit home manufacturers. It demonstrated improved client communication, spatial understanding, and design customization through an interactive house configurator. The solution reduced project lifecycles, increased sales conversion rates, and enhanced sustainability considerations. The automated workflow and templates proved effective for companies with limited resources, offering a practical framework for integrating BIM and VR in the self-build sector.</td></tr>
<tr><td rowspan="2">Bahri et al. (2019)</td><td>Furniture management and room layout in BIM</td><td>BIM Holoview and Furnie</td><td>Microsoft HoloLens</td><td>Unity, Microsoft HoloToolkit library</td><td>Not specified</td><td>Not specified</td></tr>
<tr><td colspan="6">Key findings and Contributions: The study developed a BIM system using mixed reality (MR) and spatial mapping techniques with Microsoft HoloLens. The system enabled interactive furniture placement, allowing users to move, resize, and rotate virtual items within real environments. It demonstrated improved spatial understanding and design customization through collision detection and occlusion handling. The research highlighted the potential of MR in enhancing BIM visualization and interaction, while also identifying challenges in user interface design and real-time environment mapping.</td></tr>
<tr><td rowspan="2">Rohil and Ashok (2022)</td><td>Urban development and construction planning visualization</td><td>Autodesk Revit</td><td>AR glasses (HoloLens), tablets, mobile phones</td><td>Unity</td><td>Not specified; FBX format used</td><td>Not specified</td></tr>
<tr><td colspan="6">Key findings and Contributions: The study developed a software-driven approach to visualize 3D urban development layouts using augmented reality (AR). It demonstrated improved spatial understanding and design customization through full-scale AR walkthroughs. The research highlighted AR's potential in enhancing urban planning processes, including terrain mapping, watershed analysis, and cultural heritage preservation. However, challenges were identified in computational complexity, networking requirements, and the need for stable high-speed connections in static environments.</td></tr>
<tr><td rowspan="2">Zaher et al. (2018)</td><td>Construction project monitoring and progress tracking</td><td>Autodesk Revit</td><td>Smartphones, tablets</td><td>Unity3D</td><td>Not specified; CSV format used</td><td>Google Fusion tables for cloud-based data sharing and updating</td></tr>
<tr><td colspan="6">Key findings and Contributions: The study developed a system comprising "BIM-U" Android app for on-site progress updates and "BIM-Phase" AR channel for 4D/5D model visualization. It demonstrated improved efficiency in progress tracking, reducing manual data collection and transcription errors. The system enabled real-time updates, enhanced visualization of planned vs actual progress, and facilitated cost control through parameters like CPI and SPI. However, challenges remained in integrating all functionalities into a single application and addressing potential time lags between updates.</td></tr>
</table>

Author	Application Area	BIM and ImT Approach				
		BIM-related software	ImT hardware	Integration with game engines	Data standards	Collaboration and communication platforms
Getuli et al. (2022)	Construction site and emergency management for safety training	Autodesk Revit	Google Cardboard VR headset for Android smartphones	Unity3D	Not specified	Unity3D Collaboration Viewer Template for real-time multi-user interaction
	Key findings and Contributions: The study developed a comprehensive site object library comprising 168 items for creating BIM-based VR safety training scenarios. It demonstrated improved efficiency in producing virtual construction environments by standardizing and facilitating the time-consuming content creation process. The library's hierarchical structure and object information sheets enhanced usability for safety training scenario development. The research highlighted the potential for extending this framework to other VR applications in construction, such as constructability analysis.					
Gheisari and Irizarry (2016)	Facility management practices	Autodesk Revit	Handheld mobile devices	Not specified	Not specified	Not specified
	Key findings and Contributions: The study investigated human and technological requirements for implementing BIM-based mobile augmented reality (MAR) in facility management. It found that facility managers frequently use smartphones and tablets, and are interested in BIM capabilities like locating building components and 3D visualization. While most lacked AR experience, they saw potential value in BIM-MAR integration after viewing a demonstration scenario. The research highlighted opportunities and challenges for developing BIM-MAR systems aligned with facility managers' needs and work practices.					
Ratajczak et al. (2019)	Construction performance improvement, project monitoring and control	Autodesk Revit	Lenovo Phab 2 Pro smartphone (with Google Tango AR technology)	Unity3D	Not specified; FBX and XML formats used	Firebase SDK database for real-time data sharing
	Key findings and Contributions: The study developed a BIM-based AR application (AR4C) integrated with a location-based management system for construction monitoring. It demonstrated improved efficiency in accessing project information and visualizing progress on-site. The system enabled real-time tracking of construction tasks, performance metrics, and 3D model visualization in AR. However, challenges remained in model alignment accuracy and full integration of all planned functionalities. The research highlighted the potential for enhancing construction productivity through automated progress monitoring and context-specific information delivery.					
Kamari et al. (2020)	Sustainability life cycle and cost assessment for building façade alternatives	Autodesk Revit	Smartphones with Google Cardboard or slip-on VR headsets	Unity3D (for Enscape plugin)	Not specified	Enscape cloud rendering service for generating QR codes linked to 360-degree VR images
	Key findings and Contributions: The study demonstrated that BIM-enabled VR improved users' perception of cost and sustainability aspects for façade alternatives, especially for non-construction experts. It revealed that participants generally preferred cost-effective solutions over purely sustainable ones. The research highlighted the potential of integrating BIM, VR, cost estimation, and life cycle assessment tools to enhance decision-making in sustainable building design, while also identifying challenges in user interface design and the need for more immersive VR experiences.					
O’ Grady et al. (2021)	Circular economy strategies in prefabricated modular construction	Autodesk Revit 2019	VR headset (not specified)	Unity3D	Not specified; FBX format used	Unity3D Collaboration Viewer Template for real-time multi-user interaction

Author	Application Area	BIM and ImT Approach				
		BIM-related software	ImT hardware	Integration with game engines	Data standards	Collaboration and communication platforms
	Key findings and Contributions: The study developed a BIM-based VR environment to visualize and educate on circular economy strategies in a modular building. It demonstrated improved understanding of hidden building features, material provenance, and disassembly processes. The research highlighted the potential of integrating BIM, VR, and circular economy principles to enhance design for disassembly, material reuse, and waste reduction in construction. The study also emphasized the importance of digital twins in facilitating material banks and promoting the reuse of building components.					

Table 3: Summary list of (preliminary) technical-related criteria influencing BIM-ImT Integration.

Technical-related Criteria	**Reference(s)**
Integration of Software Systems - The effectiveness of integrating BIM software with ImT platforms in terms of compatibility and data exchange efficiency.	Alizadehsalehi et al. (2020), Balali et al. (2020), Delgado et al. (2020), Du et al. (2017), Han et al. (2021), Du et al. (2018a), O'Grady et al. (2021), Olbina and Glick (2022), Rahimian et al. (2020), Shayesteh et al. (2023)
Optimization of Software for 3D Interactions - The optimization level of software programs for better interaction and data exchange of 3D BIM models within immersive environments.	Balali et al. (2020), O'Grady et al. (2021)
Incorporation of Automation and AI in VR/AR - The impact of automation and AI on enhancing industry responsiveness and productivity in VR/AR settings.	Balali et al. (2020), Han and Leite (2021)
Utilization of Cloud-Based Services - The extent to which cloud services enhance remote access, collaboration, and information exchange in BIM and ImT.	Balali et al. (2020), Du et al. (2018a), O'Grady et al. (2021)
Standardization of Data Across Systems - The adequacy of standardizing data formats and structures for consistent data exchange between BIM and ImT.	Delgado et al. (2020), Park et al. (2013), Shayesteh et al. (2023)
Real-Time Visualization Capabilities - The role of real-time visualization in decision-making and understanding within VR/AR environments.	Balali et al. (2020), Delgado et al. (2020), O'Grady et al. (2021)
Hardware Specifications for ImT - The importance of meeting hardware technical specifications for optimal performance in ImT.	Abbas et al. (2019), Han and Leite (2022), Han et al. (2021), Shayesteh et al. (2023)
Efficiency of Data Exchange Formats - How well the data exchange formats between BIM and ImT platforms facilitate accurate and efficient data transfer.	Alizadehsalehi et al. (2020), O'Grady et al. (2021), Park et al. (2013), Rahimian et al. (2020)
User Interface Design in VR/AR Systems - The effectiveness of user interface designs in VR/AR systems for visualizing live data and promoting engagement.	Li et al. (2022), Olbina and Glick (2022), Yu et al. (2022)
Integration of VR/AR with Other Systems - The integration level of VR/AR systems with other built environment software systems.	Delgado et al. (2020), Le et al. (2015), O'Grady et al. (2021)
Security and Privacy in AR/VR Technologies - The measures addressing security and privacy concerns in AR/VR technologies.	Delgado et al. (2020), Potseluyko et al. (2022), Shayesteh et al. (2023)
Role of the Middleware Layer - The criticality of the middleware layer in connecting BIM and game engines for data translation.	Delgado et al. (2020), Du et al. (2018a), O'Grady et al. (2021)
Simplification of Geometric Models - How simplifying 3D models affects data transfer and performance in VR/AR applications.	Chen et al. (2020), Potseluyko et al. (2022)
Semantic Transfer Using Ontology - The effectiveness of ontology-based approaches in semantic information transfer between BIM and ImT.	Chen et al. (2020), Meža et al. (2014)
Integration of Sensing Technologies - The impact of integrating sensing technologies for real-time monitoring in immersive environments.	Li et al. (2022), Lucena and Saffaro (2022)
Design of VR/AR Environments - The quality of VR/AR environment designs in terms of visuals, audio, and interaction features.	Li et al. (2022), Olbina and Glick (2022), Yu et al. (2022)

Technical-related Criteria	Reference(s)
Reproduction of Photorealistic Models - The accuracy of photorealistic 3D model reproduction in immersive environments.	Li et al. (2022), Park et al. (2013)
Computational Environment for Data Processing - The capability of the computational environment to support complex data processing within ImT.	Latini et al. (2023), Lucena and Saffaro (2022)
Accuracy of 3D Models - The precision of 3D model representations within immersive environments.	Latini et al. (2023), O'Grady et al. (2021)
Management of Data Fragmentation - The effectiveness of managing data fragmentation in BIM models for VR/AR applications.	Bao et al. (2022), Latini et al. (2023), Park et al. (2013)
Bandwidth, Speed, and Latency in Data Transfer - The level of bandwidth, speed, and latency provided by technologies like 5G for ImT data transfer.	Bahri et al. (2019), Park et al. (2013), Potseluyko et al. (2022)

Table 4: Summary list of (preliminary) social-related criteria influencing BIM-ImT Integration.

Non-technical/Social-related Criteria	Reference(s)
User Engagement on communication platforms - The level of active involvement and enthusiasm users show when interacting with the communication platforms	Balali et al. (2020), Han et al. (2021), Shojaei et al. (2021), Han and Leite (2022), O'Grady et al. (2021), Lucena and Saffaro (2022), Gheisari and Irizarry (2016), Boton (2018), Vittori et al. (2021), El Ammari and Hammad (2019)
Effectiveness of Collaboration on communication platforms - The ease and effectiveness of sharing information and cooperative efforts between stakeholders using the communication platforms	Balali et al. (2020), Rahimian et al. (2020), Han and Leite (2022), Dias Barkokebas and Li (2021), Olbina and Glick (2022), Yu et al. (2022), Boton (2018), Vittori et al. (2021)
User Training and Acceptance for communication tools - The effectiveness of training provided to users for operating communication tools and the rate of subsequent adoption	Balali et al. (2020), Olbina and Glick (2022), Yu et al. (2022), Le et al. (2015), Bao et al. (2022)
User Experience in data standardization - The user experience in terms of engagement quality and the intuitiveness of the interaction with data standardization processes	Chen et al. (2020), Delgado et al. (2020), Rahimian et al. (2020), O'Grady et al. (2021), Dias Barkokebas and Li (2021)
User Training and Adaptation for BIM-related software - The system's effectiveness in helping users acquire new skills and adapt to BIM-related software	Balali et al. (2020), Olbina and Glick (2022), Yu et al. (2022), Le et al. (2015), Bao et al. (2022)
Adaptation to data standards in learning - The system's supportiveness in helping users adapt to new data standards during learning processes	Chen et al. (2020), Rahimian et al. (2020), Han and Leite (2022), O'Grady et al. (2021)
Usability and Adoption Levels of BIM authoring tools - The practicality and extent of actual use of BIM authoring tools within operational environments	Delgado et al. (2020), Kamari et al. (2020), O'Grady et al. (2021), Le et al. (2015), Bao et al. (2022)
Usability and Adoption Levels of data standards - The practicality and extent of actual use of data standards within operational environments	Delgado et al. (2020), Kamari et al. (2020), O'Grady et al. (2021), Le et al. (2015), Bao et al. (2022)
Stakeholder Collaboration in BIM-game engine integration - The degree to which the integrated system facilitates joint decision-making among diverse project participants in BIM-game engine integration	Balali et al. (2020), Olbina and Glick (2022), Park et al. (2013), Dias Barkokebas and Li (2021)
Stakeholder Collaboration on data standards - The degree to which the integrated system facilitates joint decision-making among diverse project participants on data standards	Balali et al. (2020), Olbina and Glick (2022), Park et al. (2013), Dias Barkokebas and Li (2021)
End-User Satisfaction with ImT hardware - The satisfaction and contentment of the end-users post-utilization of the integrated ImT hardware	Balali et al. (2020), Kamari et al. (2020), Boton (2018)

Accessibility and Outreach of collaboration platforms - The system's ability to provide broad access and ease of use to a diverse user base on collaboration platforms	Shojaei et al. (2021), O'Grady et al. (2021), Shayesteh et al. (2023)
VR/AR Familiarity in BIM context - The learning curve associated with users becoming proficient in using VR/AR technologies within the BIM context	Shojaei et al. (2021), Shayesteh et al. (2023), Vittori et al. (2021)
Collaborative Processes in BIM environments - The efficiency and fluidity of the workflow facilitated by the integration of BIM and ImT systems in BIM environments	Rahimian et al. (2020), Olbina and Glick (2022), Vittori et al. (2021)
Collaborative Workflow in BIM-game engine integration - The efficiency and fluidity of the workflow facilitated by the integration of BIM and game engine systems	Rahimian et al. (2020), Olbina and Glick (2022), Vittori et al. (2021)
Situational Awareness Enhancement through ImT hardware - The system's effectiveness in enhancing users' awareness of their surroundings and situation while using ImT hardware	Lucena and Saffaro (2022), Le et al. (2015)
Evaluation and Future Directions in BIM-game engine integration - The system's capacity for supporting ongoing improvements and relevance through regular assessments and updates in BIM-game engine integration	Vittori et al. (2021), Yu et al. (2022)
Evaluation and Future Directions of data standards - The system's capacity for supporting ongoing improvements and relevance through regular assessments and updates of data standards	Vittori et al. (2021), Yu et al. (2022)
Compliance with Regulatory and Industry data standards - The level of alignment of the integrated system with current regulatory and industry-specific standards	Lucena and Saffaro (2022), Bao et al. (2022)
Participant Recruitment for platform Testing - The approach used to include participants in tests or studies of the integrated system, ensuring diversity and representativeness	Yu et al. (2022), Dias Barkokebas and Li (2021)
Non-technical/Social-related Criteria	**Reference(s)**
Cognitive Load in Using communication platforms - The degree to which the integrated system simplifies or complicates the thought processes and efficiency of users when using communication platforms	Han et al. (2021)
Task Management on collaboration platforms - How the integration affects the intricacy of tasks and the pressure felt by users to complete tasks promptly on collaboration platforms	Han et al. (2021)
Privacy and Security in BIM-game engine integration - The integrated system's mechanisms to protect user data and ensure confidentiality within the VR/AR context in BIM-game engine integration	Delgado et al. (2020)
Financial Investment and Return on ImT hardware - The cost implications and financial benefits realized from investing in ImT hardware	Vittori et al. (2021)
Worker Confidence in Operating ImT hardware - The confidence level of workers in their ability to operate and collaborate using the integrated ImT hardware	Lucena and Saffaro (2022)
Impact Assessment of BIM-game engine integration - The measurable outcomes and potential benefits of implementing the integrated system on project success in BIM-game engine integration	Kamari et al. (2020)