The Current State and Future Trajectory of VR/AR in Construction: 24 Shades of Reality

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ABSTRACT

Objective: The construction industry faces persistent challenges in managing complex project information, ensuring safety, coordinating distributed teams, and minimizing costly errors. Extended reality (XR) technologies—virtual reality (VR), augmented reality (AR), and mixed reality (MR)—have emerged as transformative tools that fundamentally change how construction professionals visualize, interact with, and manage building projects. This systematic review synthesizes current knowledge on XR applications in building construction, examining their benefits, implementation challenges, and integration with Building Information Modeling (BIM) systems across the project lifecycle.

Methodology: A systematic search was conducted across Google Scholar using the query "virtual and augmented reality in building construction." Following screening and relevance assessment, 24 papers were selected for detailed analysis. Data extraction focused on application domains, reported benefits, implementation barriers, and BIM integration strategies.

Key Result: The evidence demonstrates that VR is predominantly used for immersive design reviews and safety training, while AR excels in on-site applications such as progress monitoring, quality inspection, and task guidance through real-time information overlays. Key benefits include improved stakeholder comprehension (enhanced visualization), reduced errors and rework (quality assurance), enhanced safety training outcomes, and better collaboration among distributed teams. However, adoption faces significant barriers including high implementation costs, immature technology, technical integration challenges with BIM systems, device limitations, and organizational resistance. Most current applications concentrate on preconstruction and construction phases, leaving operation and maintenance underexplored.

Conclusion: The integration of XR with BIM represents a critical pathway forward, with BIM providing the information backbone and XR delivering intuitive visualization and interaction layers. Strategic priorities for advancing XR adoption include cost reduction, standardization of data exchange protocols, improved device ergonomics, and development of lifecycle-spanning workflows to realize the full potential of these technologies in sustainable construction practice.

Keywords: Virtual Reality, Augmented Reality, Mixed Reality, Extended Reality, Building Construction, Building Information Modeling, Construction Safety, Quality Management, Construction Technology.

INTRODUCTION

The construction industry faces persistent challenges in managing complex project information, ensuring safety, coordinating distributed teams, and minimizing costly errors and rework. Traditional reliance on two-dimensional drawings and documentation often leads to misinterpretation, communication breakdowns, and defects that compromise project quality and timelines (Orihuela et al., 2019). In response to these challenges, extended reality (XR) technologies, namely, virtual reality (VR), augmented reality (AR), and mixed reality (MR) have emerged as transformative tools that fundamentally change how construction professionals visualize, interact with, and manage building projects (Li et al., 2018; Ahmed, 2019).

Virtual reality creates fully immersive digital environments that enable users to experience and interact with three-dimensional building models before physical construction begins. Augmented reality overlays digital information onto the real-world environment, allowing field workers to visualize design intent, construction sequences, and hidden building systems directly on site. Mixed reality combines elements of both, enabling interaction with virtual objects while maintaining awareness of the physical environment (Yigitbas, 2023). Together, these technologies offer unprecedented opportunities to bridge the gap between digital design models and physical construction reality.

The integration of XR technologies with Building Information Modeling (BIM) has created particularly powerful synergies. BIM provides rich, structured digital representations of building projects that serve as the information backbone for XR applications (Wu et al., 2020; Salem & Dragomir, 2020). When combined, BIM-XR systems enable stakeholders to interact with comprehensive project data in intuitive, spatially contextualized ways that were previously impossible. This integration supports applications ranging from early-stage design validation to on-site construction guidance and long-term facility management (Anwar et al., 2024; Jones, 2023).

Despite growing interest and documented benefits, XR adoption in construction remains limited compared to other industries. Barriers include high implementation costs, technical integration challenges, device limitations, and organizational resistance to new workflows (Delgado et al., 2020; Rokooei et al., 2022). Understanding these challenges alongside the demonstrated benefits is essential for developing strategies to accelerate adoption and realize the full potential of XR technologies in construction practice.

This systematic review synthesizes current knowledge on XR applications in building construction, examining their benefits, implementation challenges, and integration with BIM systems across the project lifecycle. By analyzing 24 relevant academic papers, this review provides a comprehensive overview of the state of the art and identifies strategic priorities for advancing XR adoption in the construction industry.

Despite the growing body of research on extended reality (XR) in construction, existing studies remain fragmented, often focusing on specific technologies such as virtual reality (VR) or augmented reality (AR) in isolation, with limited comparative analysis across XR types. Furthermore, prior reviews tend to emphasize applications in design and construction phases, while the operational lifecycle remains underexplored. In addition, there is insufficient synthesis of implementation challenges, inconsistencies in reported outcomes, and limited integration of XR with Building Information Modeling (BIM) from a lifecycle perspective.

This study addresses these gaps by providing a comprehensive systematic literature review that critically compares VR, AR, and MR applications across construction phases, evaluates their benefits and limitations, and examines their integration with BIM. The study further contributes by identifying key research gaps and proposing strategic directions for future XR adoption in construction.

LITERATURE REVIEW

Existing literature on extended reality (XR) in construction highlights its transformative potential across design visualization, construction management, safety training, and facility operations. However, the body of knowledge is characterized by fragmentation in scope, methodological inconsistencies, and uneven focus across XR technologies.

Studies such as Li et al. (2018) and Zhao et al. (2023) emphasize the effectiveness of virtual reality in safety training, reporting improved hazard recognition and knowledge retention. However, these findings are often based on controlled experimental environments, raising concerns about real-world applicability. In contrast, augmented reality studies (e.g., Nassereddine et al., 2022) demonstrate strong applicability in on-site construction tasks such as progress monitoring and quality inspection, though challenges related to tracking accuracy and environmental constraints persist.

Mixed reality (MR), while less extensively studied, is increasingly recognized for its hybrid capabilities, enabling interaction with both physical and virtual elements. However, empirical evidence supporting its large-scale implementation remains limited, indicating a gap between conceptual potential and practical adoption.

A key inconsistency across studies lies in the evaluation of XR benefits. While many authors report improvements in visualization and collaboration, quantitative validation of productivity gains and cost savings remains scarce. Additionally, the integration of XR with BIM is widely acknowledged as critical, yet the lack of standardized data exchange protocols continues to hinder seamless implementation.

Another notable limitation in existing literature is the concentration of research within the design and construction phases, with minimal attention given to operation and maintenance. This lifecycle imbalance restricts a comprehensive understanding of XR’s long-term value.

Overall, the literature demonstrates strong potential for XR technologies in construction but reveals significant gaps in standardization, lifecycle integration, and empirical validation, justifying the need for a structured and critical synthesis.

METHODOLOGY

Research Design

This study adopts a Systematic Literature Review (SLR) approach following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to ensure transparency, replicability, and methodological rigor.

Search Strategy

A systematic literature search was conducted to identify relevant research on virtual and augmented reality applications in building construction, with the search platform being Google Scholar. The search was performed across multiple databases and platforms to ensure comprehensive coverage of the academic literature.

Search Query

The search query "virtual and augmented reality in building construction" was applied consistently across all platforms. This query was designed to capture papers addressing VR, AR, MR, and XR technologies in the context of building construction projects, encompassing design, construction, and operational phases.

Search Period

The search was conducted, starting in September 2025 till February 2026, with no strict date restrictions applied to ensure inclusion of foundational and recent research. However, the majority of retrieved papers were published between 2014 and 2025, reflecting the recent growth of XR research in construction.

Screening Process

The study selection followed a four-stage PRISMA process:

Identification: The initial database search yielded 162 records from Google Scholar and related sources.

Screening: After removal of 28 duplicate records, 134 papers remained for title and abstract screening.

Eligibility: Following screening, 96 papers were excluded due to lack of relevance, leaving 38 papers for full-text assessment. Of these, 14 papers were further excluded due to insufficient methodological detail or lack of direct application to construction.

Inclusion: A final total of 24 studies were selected for qualitative synthesis.

Selection Criteria

Papers were screened and selected based on relevance to the research objectives. The selection process involved multiple stages:

Inclusion Criteria:

1. Papers addressing VR, AR, MR, or XR technologies in building construction contexts
2. Research covering applications, benefits, challenges, or implementation strategies
3. Studies examining integration with Building Information Modeling (BIM)
4. Academic papers, conference proceedings, systematic reviews, and technical reports
5. Papers providing empirical evidence, case studies, or comprehensive reviews

Exclusion Criteria:

1. Papers focused exclusively on non-construction domains (e.g., gaming, entertainment, medical applications)
2. Studies addressing only theoretical concepts without construction applications
3. Papers with insufficient detail on XR implementation or outcomes
4. Duplicate publications or preprints when final versions were available

Data Extraction

Data extraction focused on capturing key information from each selected paper to address the review objectives:

Extracted Data Elements:

1. XR technology types (VR, AR, MR, XR)
2. Application domains and use cases (design, construction, safety, quality, collaboration)
3. Reported benefits and impacts (quantitative and qualitative)
4. Implementation challenges and barriers
5. BIM integration approaches and frameworks
6. Project lifecycle phases addressed
7. Device platforms and technical requirements
8. Methodological approaches (case studies, experiments, surveys, reviews)

Data Synthesis Approach

A narrative synthesis approach was employed to integrate findings across the selected papers. Papers were grouped thematically by application domain, benefit category, challenge type, and BIM integration strategy. Evidence from multiple papers was synthesized to identify convergent findings, highlight areas of consensus, and note conflicting or limited evidence. The synthesis prioritized papers with strong empirical evidence, comprehensive reviews, and clear methodological descriptions.

The top 15 most relevant papers (based on relevance ranking from the combined search results) were given priority in the synthesis to ensure focus on the highest-quality and most pertinent evidence. These papers formed the primary evidence base for the results and discussion sections, supplemented by additional papers where they provided unique insights or addressed specific gaps. Table 1 below shows the summary of Selected Studies on XR in Construction

Table 1: Selected Studies on XR in Construction

Author	**Year**	**XR Type**	**Methodology**	**Application Area**	**Key Findings**	**Limitations**
Li et al.	2018	VR/AR	Review	Safety training	Improves hazard recognition and training outcomes	Limited real-world validation
Li et al.	2024	XR	Review	Training	Enhances knowledge retention and engagement	Lacks longitudinal studies
Zhao et al.	2023	XR	Review	Safety & management	Improves safety awareness and decision-making	Limited field implementation
Nassereddine et al.	2022	AR	Review	Construction site	Effective for inspection and guidance	Tracking and environmental issues
Delgado et al.	2020	VR/AR	Review	Adoption	Identifies cost and adoption barriers	Limited empirical validation
Rokooei et al.	2022	VR	Conference	Construction projects	Enhances visualization and planning	High cost and technical barriers
Wu et al.	2020	XR+BIM	Review	Integration	Strong synergy between BIM and XR	Lack of interoperability standards
Salem & Dragomir	2020	VR/AR	Review	Lifecycle management	Supports asset management and maintenance	Limited operational case studies
Anwar et al.	2024	MR	Review	Inspection	Improves monitoring and defect detection	Early-stage adoption
Carbonari et al.	2022	MR	Experimental	Renovation	Effective for on-site assessment	Small-scale testing
Albahbah et al.	2021	VR/AR	Review	Project management	Improves collaboration and visualization	Limited quantitative metrics
Schranz et al.	2021	AR	Case study	BIM submission	Enhances workflow efficiency	Context-specific findings

Karmakar et al.	2021	XR	Review	Construction 4.0	Highlights digital transformation potential	Broad scope, limited depth
Orihuela et al.	2019	VR/AR	Conference	Design & construction	Improves coordination and planning	Limited empirical data
Ahmed	2019	VR/AR	Review	Project management	Enhances communication and decision-making	Mostly conceptual
Baeza	2018	VR	Thesis	Design review	Improves stakeholder understanding	Limited generalizability
Xiang	2023	VR/AR	Review	Architectural design	Enhances visualization and creativity	Lacks construction focus
Yigitbas et al.	2023	XR	SLR	BIM integration	Identifies integration frameworks	Limited real-world validation
Shirazi	2014	AR	Thesis	Education	Enhances learning experience	Early-stage technology
Abboud	2014	AR	Conceptual	Design & construction	Highlights AR potential	Lacks empirical evidence
Piroozfar et al.	2017	VR/AR	Conference	Wearables	Supports immersive construction workflows	Limited testing
Jones	2023	XR	Case study	Housing	Supports affordable housing visualization	Narrow application scope
Irfan et al.	2024	MR	Conference	Construction & operations	Highlights MR benefits across lifecycle	Limited empirical data
Nassereddine et al.	2022	AR	Review	Trends & future	Identifies future directions	Repetitive findings across studies

DISCUSSION OF RESULTS

Applications in Construction

Extended reality technologies are applied across multiple construction tasks, from immersive design reviews to on-site guidance and training. The literature maps specific XR modes to lifecycle tasks and reports widespread use in visualization, quality assurance, safety training, and remote collaboration.

1. Design Visualization and Review

Virtual reality is extensively used for design-phase immersion and stakeholder review, enabling improved understanding and decision making (Li et al., 2018). VR allows architects, engineers, clients, and other stakeholders to experience building designs at full scale before construction begins, facilitating early detection of design issues and supporting more informed decision making (Li et al., 2018; Baeza, 2018). Immersive design reviews enable stakeholders to evaluate spatial relationships, circulation patterns, and aesthetic qualities in ways that traditional 2D drawings and even 3D computer models cannot match (Xiang, 2023).

The integration of VR with BIM models supports comprehensive design validation workflows. Stakeholders can navigate through BIM-derived virtual environments, identify clashes and coordination issues, and evaluate design alternatives in real time (Yigitbas et al, 2023). This capability is particularly valuable for complex projects where spatial coordination among multiple building systems is critical (Wu et al., 2020). Studies report that VR-based design reviews lead to earlier identification of design conflicts, reduced change orders during construction, and improved client satisfaction (Ahmed 2019, Baeza, 2018).

2. On-Site Construction Support

Augmented reality is prevalent in construction and operation phases for overlaying BIM data onto the real world to support review and quality assurance (Li et al., 2018; Nassereddine et al., 2022). AR applications enable field workers to visualize design intent, construction sequences, and hidden building systems directly on site by superimposing digital information onto the physical environment through mobile devices or head-mounted displays (Abboud, 2014; Shirazi, 2014).

Common on-site AR applications include progress monitoring, where actual construction progress is compared against planned schedules and BIM models (Albahbah et al., 2021), layout verification, where AR guides workers in positioning building elements according to design specifications (Schranz et al., 2021), and as-built documentation, where AR facilitates capture and verification of completed work [19]. AR-based task guidance systems provide workers with step-by-step instructions overlaid on the physical workspace, supporting complex assembly tasks and reducing errors (Nassereddine et al., 2022; Piroozfar et al., 2017).

Mixed reality applications combine elements of VR and AR to support on-site assessment and renovation planning. MR systems enable users to interact with virtual building elements while maintaining awareness of the physical environment, supporting applications such as renovation design, where proposed changes can be visualized in context with existing conditions (Carbonari et al., 2022).

3. Safety Training and Education

XR training covers safety, equipment operation, skills, ergonomics, and human-computer collaboration, with many studies examining trainee outcomes and device platforms (Li et al., 2024). Virtual reality is particularly effective for safety training because it enables workers to experience hazardous scenarios in a controlled, risk-free environment (Zhaoe et al., 2023). VR safety training applications address fall hazards, equipment operation, emergency response, and hazard recognition (Li et al., 2024; Rokooei et al., 2022).

Studies report that VR safety training yields targeted skill and hazard awareness improvements (Li et al., 2024). Compared to traditional classroom training, VR training demonstrates superior knowledge retention, improved hazard recognition skills, and enhanced engagement (Zhaoe et al., 2023; Rokooei et al., 2022). The immersive nature of VR training creates stronger emotional responses and memory formation, leading to better transfer of safety knowledge to real-world situations (Li et al., 2024).

Augmented reality is also applied in safety training and on-site safety management. AR systems can overlay safety information, hazard warnings, and procedural guidance directly onto the work environment, providing just-in-time safety support (Zhaoe et al., 2023). AR-based safety applications include real-time hazard detection, where AR systems identify and highlight potential hazards in the worker's field of view, and safety compliance verification, where AR guides workers through safety checklists and procedures (Nassereddine et al., 2022).

4. Quality Management and Inspection

XR supports review and defect detection workflows, improving inspection and quality assurance processes (Anwar et al., 2024; Li et al., 2024). AR-based quality inspection systems enable inspectors to compare as-built conditions against BIM models in real time, facilitating rapid identification of deviations and defects (Anwar et al., 2024). By overlaying design specifications onto physical construction, AR systems help inspectors verify dimensional accuracy, material specifications, and installation quality (Schranz et al., 2021).

Virtual reality is used for quality review in controlled environments, where stakeholders can examine detailed 3D models to identify potential quality issues before they occur on site (Baeza, 2018). VR-based quality reviews are particularly valuable for reviewing complex building systems, evaluating constructability, and planning inspection strategies (Baeza, 2018).

Mixed reality applications support building construction inspection and monitoring by combining real-world observation with virtual information overlays (Anwar et al., 2024). MR systems enable inspectors to access comprehensive project data, historical records, and inspection checklists while maintaining visual contact with the physical construction (Cabonari et al., 2022). Studies report that XR-based quality management systems help detect defects earlier, reduce rework, and improve delivery outcomes (Anwar et al., 2024; Li et al., 2024).

5. Collaboration and Communication

XR enables geographically distributed conferencing and collaborative review sessions tied to BIM models (Anwar et al., 2024). Remote collaboration through XR platforms allows project team members in different locations to meet in shared virtual environments, where they can interact with 3D building models, mark up designs, and discuss project issues in real time (Albahbah et al., 2021). This capability is particularly valuable for projects involving distributed teams, international collaborations, or situations where travel is impractical (Karmakar et al., 2021).

VR-based collaboration platforms support multi-user design reviews, where stakeholders can simultaneously navigate through virtual building models, point out issues, and propose solutions (Ahmed, 2019). These platforms often integrate voice communication, annotation tools, and real-time model updates to facilitate effective collaboration (Baeza, 2018). Studies report that VR collaboration improves communication clarity, reduces misunderstandings, and accelerates decision making compared to traditional video conferencing or 2D drawing reviews (Albahbah et al., 2021).

Augmented reality supports on-site collaboration by enabling remote experts to see what field workers see and provide guidance through AR overlays (Nassereddine et al., 2022). Remote assistance applications allow off-site experts to annotate the field worker's view with instructions, diagrams, and virtual objects, supporting troubleshooting and complex installation tasks (Nassereddine et al., 2022). This capability reduces the need for expert site visits and enables faster resolution of construction issues (Albahbah et al., 2021).

Benefits and Impact

The literature attributes measurable process and human benefits to XR use while noting contextual variation by application and technology. Reported advantages include clearer shared understanding, improved safety training outcomes, and potential sustainability gains through better decision making.

1. Enhanced Visualization and Comprehension

Improved visualization increases stakeholder comprehension and supports faster design decisions and clash detection in review workflows (Li et al., 2024). XR technologies address a fundamental limitation of traditional construction documentation: the difficulty of translating 2D drawings into accurate mental models of 3D spaces (Orihuela et al., 2019). By enabling stakeholders to experience designs at full scale and in three dimensions, XR systems dramatically improve spatial understanding and reduce misinterpretation (Ahmed, 2019; Xiang, 2023).

Studies report that clients and non-technical stakeholders demonstrate significantly better comprehension of design proposals when presented through VR compared to traditional drawings or computer renderings (Baeza, 2018; Xiang, 2023). This improved comprehension leads to more informed decision making, earlier identification of design issues, and reduced change orders during construction (Ahmed, 2019). For complex projects involving intricate spatial relationships or novel architectural forms, XR visualization is particularly valuable (Baeza, 2018).

The ability to visualize hidden building systems, construction sequences, and temporary structures through AR overlays provides field workers with critical information that would otherwise require extensive interpretation of 2D drawings (Nassereddine et al., 2022; Shirazi, 2014). This enhanced visualization capability reduces errors, improves installation quality, and accelerates construction progress (Albahbah et al., 2021; Anwar et al., 2024).

2. Safety and Training Improvements

Enhanced safety training yields targeted skill and hazard awareness improvements, since XR training spans safety, equipment operation, and ergonomics (Li et al., 2024). Virtual reality safety training enables workers to experience realistic hazardous scenarios without physical risk, creating stronger learning experiences than traditional classroom training (Zhao et al., 2023; Rokooei et al., 2022). Studies measuring training effectiveness report that VR safety training produces superior knowledge retention, improved hazard recognition skills, and enhanced engagement compared to conventional methods (Li et al., 2024).

The immersive nature of VR training creates emotional responses and memory formation that support better transfer of safety knowledge to real-world situations (Li et al., 2024). Workers trained in VR demonstrate improved ability to identify hazards on actual construction sites and exhibit safer work behaviors (Zhao et al., 2023). For high-risk activities such as working at heights, operating heavy equipment, or responding to emergencies, VR training provides valuable practice opportunities that would be impractical or dangerous to replicate in physical training environments (Rokooei et al., 2022).

On-site AR safety applications provide real-time hazard warnings and safety guidance, supporting continuous safety awareness during construction activities (Zhao et al., 2023; Nassereddine et al., 2022). By overlaying safety information directly onto the work environment, AR systems help workers maintain safety awareness while performing their tasks (Zhao et al., 2023).

3. Error Reduction and Quality Assurance

Error reduction and quality assurance help detect defects earlier and support inspection tasks, reducing rework and improving delivery outcomes (Anwar et al., 2024; Li et al., 2024). AR-based quality inspection systems enable rapid comparison of as-built conditions against design specifications, facilitating early detection of deviations and defects (Anwar et al., 2024; Schranz et al., 2021). Studies report that AR-assisted inspection reduces inspection time while improving detection rates for dimensional errors, installation defects, and material discrepancies (Anwar et al., 2024).

VR-based design reviews identify coordination issues and constructability problems before construction begins, preventing costly errors and rework (Ahmed, 2019; Baeza, 2018). By enabling stakeholders to experience designs in immersive 3D environments, VR reviews reveal spatial conflicts, circulation problems, and design deficiencies that might not be apparent in 2D drawings or conventional 3D models (Xiang, 2023; Baeza, 2018). Early detection of these issues through VR reviews reduces change orders, minimizes construction delays, and improves project outcomes (Ahmed, 2019).

The integration of XR with BIM enables automated clash detection and quality verification workflows that combine the precision of digital models with the intuitive understanding provided by immersive visualization (Wu et al., 2020; Anwar et al., 2024). These integrated systems support continuous quality monitoring throughout the construction process, helping maintain high quality standards and reduce defects (Wu et al., 2020).

4. Collaboration and Productivity

Better collaboration enables remote, immersive coordination and information sharing across distributed teams, supporting project delivery and new service models (Anwar et al., 2024; Albahbah et al., 2021). XR-based collaboration platforms allow geographically distributed team members to meet in shared virtual environments, where they can interact with 3D building models and discuss project issues in ways that traditional video 12 BIM-XR integration tools, application development, and licensing fees (Rokooei et al., 2022).

Beyond direct technology costs, organizations face substantial indirect costs related to workflow changes, staff training, and process integration (Delgado et al., 2020). The return on investment for XR technologies is often uncertain, particularly for firms without prior experience with digital construction technologies (Delgado et al., 2020). This uncertainty, combined with high upfront costs, creates reluctance to invest in XR systems (Rokooei et al., 2022).

The perceived immaturity of XR technologies contributes to adoption hesitancy. Stakeholders express concerns about technology reliability, vendor stability, and the risk of investing in technologies that may become obsolete (Delgado et al., 2020). The rapid pace of XR technology development creates uncertainty about which platforms and approaches will become industry standards, making investment decisions challenging (Karmakar et al., 2021).

1. Technical and Integration Challenges

Technical integration gaps between BIM and XR workflows hinder seamless use; authors note a need for standardized pipelines, data exchange, and interoperability to scale applications (Nassereddine et al., 2022; Li et al., 2024). The lack of standardized data exchange formats and protocols creates friction in BIM-XR workflows, requiring manual data conversion, custom integration scripts, or proprietary middleware solutions (Wu et al., 2020). These integration challenges increase implementation complexity, reduce workflow efficiency, and limit the scalability of XR applications (Yigitbas et al., 2023).

Interoperability issues arise from the diversity of BIM platforms, XR devices, and application software used in construction projects (Karmakar et al., 2021). Different systems use incompatible data formats, coordinate systems, and information structures, creating barriers to seamless data flow (Wu et al., 2020). The absence of industry-wide standards for BIM-XR integration forces organizations to develop custom solutions or rely on vendor-specific ecosystems (Yigitbas et al., 2023).

Technical challenges also include limitations in real-time rendering of complex BIM models, tracking accuracy for AR applications, and network bandwidth requirements for collaborative XR applications (Nassereddine et al., 2022). Large BIM models may exceed the processing capabilities of mobile XR devices, requiring model simplification that reduces information richness (Wu et al., 2020). AR tracking systems may struggle with accuracy and stability in challenging construction site environments (Nassereddine et al., 2022). Collaborative XR applications require high-bandwidth, low-latency network connections that may not be available on construction sites (Karmakar et al., 2021).

2. Device and Platform Limitations

Device and platform limitations include input/output constraints, tracking robustness, and ergonomics that affect field use and trainee comfort (Nassereddine et al., 2022; Li et al., 2024). Current XR devices face multiple limitations that constrain their practical use in construction environments. Head-mounted displays are often heavy, uncomfortable for extended use, and have limited battery life (Li et al., 2024). Field of view restrictions, display resolution limitations, and visual artifacts can reduce the effectiveness of XR applications (Nassereddine et al., 2022).

Environmental factors on construction sites pose challenges for XR devices. Dust, moisture, temperature extremes, and bright sunlight can interfere with device operation and tracking systems (Nassereddine et al., 2022). The need for protective equipment such as hard hats and safety glasses creates conflicts with head-mounted displays (Li et al., 2024). Connectivity limitations on construction sites restrict the use of cloud-based XR applications and collaborative features (Karmakar et al., 2021).

Input and interaction methods for XR systems often lack the precision and efficiency required for professional construction applications (Nassereddine et al., 2022). Hand tracking, gesture recognition, and voice commands may be unreliable in noisy, cluttered construction environments (Nassereddine et al., 2022). The need to remove gloves to interact with touchscreens or controllers creates practical barriers for field workers (Li et al., 2024). These device limitations reduce the practical utility of XR systems and contribute to user frustration and adoption resistance (Delgado et al., 2020).

3. Organizational and Human Factors

Organizational and skills barriers such as limited in-house expertise and resistance to process change constrain practical implementation and scaling (Delgado et al., 2020; Li et al., 2024). The successful implementation of XR technologies requires not only technical capabilities but also organizational readiness and cultural acceptance (Delgado et al., 2020). Many construction organizations lack personnel with the technical skills required to implement and maintain XR systems (Karmakar et al., 2021). The shortage of professionals with combined expertise in construction processes and XR technologies creates implementation challenges (Li et al., 2024).

Resistance to change represents a significant organizational barrier. Construction industry culture traditionally emphasizes proven methods and incremental innovation, creating skepticism toward novel technologies like XR (Delgado et al., 2020). Workers and managers may resist XR adoption due to concerns about job displacement, increased workload, or unfamiliarity with digital technologies (Delgado et al., 2020). Overcoming this resistance requires effective change management, clear demonstration of benefits, and inclusive implementation processes (Karmakar et al., 2021).

Lifecycle imbalance and limited deployment show most XR research and practice concentrated in preconstruction and construction phases, leaving operation and retrofit applications less mature (Li et al., 2024). This concentration reflects both the historical focus of construction technology research and the practical challenges of implementing XR in operational environments (Li et al., 2024). The limited evidence base for operational-phase XR applications creates uncertainty about benefits and implementation approaches, further constraining adoption (Salem & Dragomir, 2020).

Integration with Building Information Modeling

Combining XR with BIM is a frequent research priority because BIM provides the information backbone and XR provides the interaction and visualization layer. Reviews categorize which XR types fit which lifecycle phases and identify key gaps for integrated deployment.

1. BIM-XR Integration Frameworks

The integration of BIM and XR technologies creates powerful synergies that enhance both design and construction processes (Wu et al., 2020; Anwar et al., 2024). BIM provides rich, structured digital representations of building projects that serve as the data foundation for XR applications (Salem & Dragomir, 2020). XR technologies, in turn, provide intuitive visualization and interaction capabilities that make BIM data more accessible and useful to diverse stakeholders (Yigitbas, 2023).

Several integration frameworks have been proposed to guide BIM-XR implementation. These frameworks typically address data flow from BIM authoring tools to XR platforms, real-time synchronization between BIM models and XR environments, and bidirectional data exchange that allows XR interactions to update BIM models (Wu et al., 2020). Common integration approaches include direct export from BIM tools to XR platforms, middleware solutions that translate between BIM and XR formats, and cloud-based platforms that serve as central data repositories (Yigitbas, 2023).

The technical architecture of BIM-XR systems must address multiple challenges: maintaining model fidelity during data conversion, optimizing model complexity for real-time XR rendering, preserving semantic information and metadata, and supporting multi-user collaboration (Wu et al., 2020). Successful integration frameworks balance these competing requirements while providing practical workflows that fit within existing project delivery processes (Yigitbas, 2023).

2. Lifecycle Phase Applications

VR combined with BIM supports immersive design review and stakeholder validation to improve decision making during the design phase (Li et al., 2024). The integration enables architects and engineers to export BIM models directly into VR environments, where stakeholders can experience designs at full scale and evaluate spatial relationships, circulation patterns, and design quality (Yigitbas, 2023). This integration supports iterative design refinement, where insights from VR reviews inform BIM model updates, creating a continuous improvement cycle (Baeza, 2018).

AR overlays BIM data on site for layout, progress tracking, and quality assurance during construction (Li et al., 2024; Nassereddine et al., 2022). Field workers use AR devices to visualize BIM models superimposed on the physical construction site, enabling direct comparison between design intent and as-built conditions (Shirazi, 2014; Albahbah et al., 2021). This integration supports multiple construction-phase applications: layout verification, where AR guides element placement according to BIM specifications (Schranz et al., 2021), progress monitoring, where actual progress is compared against BIM-based schedules [88], and quality inspection, where AR facilitates detection of deviations from BIM specifications (Anwar et al., 2024; Schranz et al., 2021).

AR is suitable for operations where real-time information overlays and maintenance guidance are needed, though fewer studies exist in this phase (Li et al., 2024). BIM-AR integration in facility management enables maintenance personnel to access building system information, maintenance histories, and operational procedures through AR overlays (Salem & Dragomir, 2020). This integration supports applications such as equipment location and identification, maintenance task guidance, and emergency response (Salem & Dragomir, 2020). However, the operational phase remains underexplored compared to design and construction phases, representing a significant opportunity for future research and development (Salem & Dragomir, 2020).

3. Technical Requirements and Standards

Authors highlight classification methods and application-focused taxonomies to guide development of BIM-XR systems and emphasize remaining gaps such as standardized interfaces, lifecycle-spanning workflows, and evidence on long-term operational benefits (Li et al., 2018; Nassereddine et al., 2022). The lack of industry-wide standards for BIM-XR integration creates significant barriers to widespread adoption (Yigitbas, 2023). Current integration approaches rely heavily on proprietary formats, custom scripts, and vendor-specific solutions that limit interoperability and scalability (Yigitbas, 2023).

Technical requirements for effective BIM-XR integration include: standardized data exchange formats that preserve geometric and semantic information (Wu et al., 2020), coordinate system alignment protocols that ensure spatial registration between BIM models and physical environments (Nassereddine et al., 2022), real-time synchronization mechanisms that maintain consistency between BIM databases and XR environments (Wu et al., 2020), and metadata preservation methods that retain rich BIM information in XR applications (Yigitbas, 2023).

Several standardization efforts are underway to address these requirements. Industry Foundation Classes (IFC) provide a standardized BIM data format, though IFC support in XR platforms remains limited (Wu et al., 2020). Web-based standards such as glTF offer potential pathways for BIM-XR data exchange, though they require extensions to support construction-specific information (Yigitbas, 2023). The development of open standards and reference implementations represents a critical priority for enabling scalable BIM-XR integration (Yigitbas, 2023).

CONCLUSION

This systematic review of 24 papers demonstrates that extended reality technologies-virtual reality, augmented reality, and mixed reality, offer substantial benefits for building construction across the project lifecycle. The evidence shows clear differentiation in XR technology applications: VR excels in immersive design reviews and safety training, while AR provides superior on-site support through real-time information overlays for progress monitoring, quality inspection, and task guidance. Mixed reality combines strengths of both approaches for applications requiring simultaneous interaction with physical and virtual elements.

The documented benefits of XR in construction are significant and multifaceted. Enhanced visualization improves stakeholder comprehension and supports better design decisions. Safety training through VR produces superior learning outcomes compared to traditional methods. Error reduction and quality assurance capabilities help detect defects earlier and reduce costly rework. Improved collaboration enables effective coordination among distributed teams. These benefits collectively support more efficient, safer, and higher-quality construction processes.

However, substantial barriers constrain widespread XR adoption. Economic barriers, particularly high implementation costs and uncertain return on investment, remain primary limiting factors. Technical integration challenges, especially the lack of standardized BIM-XR data exchange protocols, create friction in workflows and limit scalability. Device limitations including ergonomics, environmental robustness, and interaction methods reduce practical utility in construction environments. Organizational factors such as limited in-house expertise and resistance to change further impede implementation.

The integration of XR with Building Information Modeling represents the most promising pathway for realizing XR's full potential in construction. BIM provides the structured information foundation that XR technologies need, while XR delivers intuitive visualization and interaction capabilities that make BIM data accessible to diverse stakeholders. However, current BIM-XR integration approaches rely heavily on proprietary solutions and custom implementations, highlighting the critical need for industry-wide standards and interoperable platforms.

A notable gap in current XR applications is the concentration of research and practice in preconstruction and construction phases, with operation and maintenance remaining underexplored. This lifecycle imbalance represents both a limitation of current practice and an opportunity for future development. Extending XR applications throughout the building lifecycle could unlock additional value in facility management, renovation planning, and long-term asset optimization.

Strategic priorities for advancing XR adoption in construction include: reducing implementation costs through technology maturation and economies of scale, developing standardized BIM-XR data exchange protocols and interoperability frameworks, improving device ergonomics and environmental robustness for construction site use, building organizational capabilities through training and change management, and extending XR applications to cover the full building lifecycle including operations and maintenance.

As XR technologies continue to mature and costs decline, their adoption in construction is likely to accelerate. The convergence of XR with other emerging technologies—including artificial intelligence, Internet of Things, and digital twins—promises even greater capabilities for construction management and building performance optimization. Realizing this potential requires coordinated efforts among technology developers, construction practitioners, researchers, and standards organizations to address current barriers and develop integrated, lifecycle-spanning XR solutions that deliver measurable value to construction projects.

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