International Journal of Engineering and Technology Innovation, vol. 16, no. 3, 2026, pp. 299-314

A Review of Mixed Reality Applications in the Built Environment Using a Task–Technology–Context Framework

Saddam Hussain Khurram[1,*], Zia Ud Din[2], Shengjun Miao[1], Khurram Iqbal Ahmad Khan[3], Aboubakar Siddique[1], Naheed Akhtar[4], Xiangfan Shang[5]

[1]School of Resources and Safety Engineering, University of Science and Technology Beijing, Beijing, China

[2]College of Technology, University of Houston, Texas, USA

[3]School of Civil and Environmental Engineering, National University of Science and Technology, Islamabad, Pakistan

[4]Department of Civil Engineering, Polo-II, 3030- 790 University of Coimbra, Portugal

[5]China Academy of Safety Science and Technology, Beijing, China

Received 16 March 2026; revised 11 May 2026; accepted 14 May 2026

DOI: https://doi.org/10.46604/ijeti.2026.16277

Abstract

Mixed reality (MR) technologies are increasingly used in the built environment to support visualization, coordination, and task execution across project stages. However, there is limited systematic understanding of the relationships among task demands, technology platforms, and implementation contexts throughout the project lifecycle. This paper aims to present a systematic analytical review of 68 peer-reviewed studies using a task-technology-context (TTC) framework. MR applications are classified by lifecycle stages, task attributes, technology platforms, and evaluation environments. The findings reveal a strong focus on construction-phase operations and well-defined associations between task types and technology selection. Most studies were conducted in controlled environments, highlighting a gap between experimental validation and real-world implementation. The results show that MR effectiveness depends not only on technological capability but also on its alignment with task requirements and contextual factors. The TTC framework provides a structured approach for evaluating MR adoption and guiding future lifecycle- and context-based research.

Keywords: mixed reality, built environment, project lifecycle, analytical review, task–technology–context

1. Introduction

The Architecture, Engineering, and Construction (AEC) industry faces persistent challenges in productivity, safety, and information management, with productivity growth lagging behind other large-scale industries[1]. Mixed reality (MR) technologies are being actively considered to address these challenges through enhanced visualization, coordination, and task execution. However, a critical gap remains: there is no systematic understanding of how task demands, technology platforms, and implementation contexts interrelate across the project lifecycle. This lack of integrated understanding limits both research design and practical adoption.

In this regard, immersive and visualization-based technologies have been gaining increasing attention due to their potential to improve information integration and decision-making in construction projects. To clarify the terminology used throughout this paper: virtual reality (VR) fully immerses users in a digital environment, replacing the physical world. Augmented reality (AR) overlays digital information onto the physical world without direct interaction between virtual and

* Corresponding author. E-mail address: d202161001@xs.ustb.edu.cn

physical elements. MR enables interactive digital-physical integration, where digital objects can interact with physical spaces in real-time. extended reality (XR) serves as an umbrella term encompassing VR, AR, and MR. This paper adopts a pragmatic functional focus, where studies are included when digital information is overlaid onto physical built-environment contexts, regardless of whether they are labeled AR, MR, or XR in the original publication.

One of these technologies, MR, which is sometimes mentioned alongside AR and XR, has become a promising approach for integrating digital information into physical workplaces. MR applications have been investigated for immersive design review, on-site layout guidance, safety training, inspection, and remote collaboration by overlaying digital models, instructions, or sensor data onto real-world contexts [2-4]. The hardware platforms, including head-mounted displays and mobile devices, along with enhanced integration with building information modeling (BIM), have led to a growing amount of research in this field [5-6].

In line with this increase, various researchers have sought to synthesize knowledge on MR and other technologies in the AEC industry. Early review studies mainly focused on categorizing AR and VR applications and determined possible applications in construction activities [7]. More recent work has concentrated on particular areas, including BIM-enabled MR systems [8-9], construction safety applications [3,10], and task-oriented applications such as assembly and inspection [11]. Although these studies offer useful generalizations about technological capabilities and research trends, they remain largely descriptive.

The major weakness of current studies is the limited critical analysis of how MR systems are tested and implemented across various contexts. Specifically, less attention has been given to the difference between controlled experimental conditions and real-life construction environments [2, 12]. The distinction is important because construction sites are dynamic and complex environments, characterized by changing light conditions, physical limitations, connectivity issues, and high cognitive load on workers, all of which may affect technology performance and adoption.

Another critical issue is the distribution of the MR applications throughout the project lifecycle. The reviewed studies suggest that MR applications are more commonly reported during the design and construction phases [4, 9], whereas a relative scarcity of studies is noted for operation and maintenance (O&M), even though O&M has been identified as important to long-term asset performance and lifecycle value [13-14]. Such an imbalance underscores a deficiency in lifecycle-oriented studies and raises the question of how much MR contributes to long-term innovation beyond project delivery. Fig. 1 provides a conceptual overview of typical MR-enabled activities of design, construction, operation, and maintenance, illustrating the scope of MR applications at the various lifecycle stages. Although the framework focuses on these stages, end-of-life phases, such as deconstruction and circular asset management, are identified as future research opportunities in MR. The figure illustrates the role of MR capabilities, including spatial visualization, real-time data overlay, and context-driven guidance, in supporting task-level activities across different project stages.

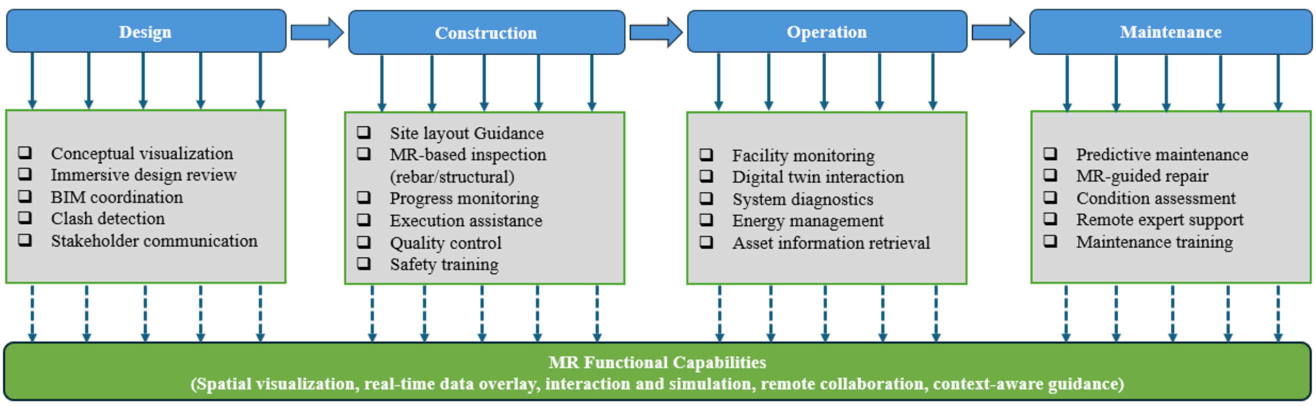

Fig. 1 Conceptual overview of MR applications across the built environment lifecycle

These constraints suggest the need for a more systematic analysis methodology that goes beyond listing applications and examines patterns in MR implementation across tasks, technologies, and situations. The lack of consistent terminology in the literature complicates this challenge, with MR, AR, VR, and XR used interchangeably, especially in real-world applications involving digital overlays [3-4]. A pragmatic strategy is thus needed to aid in uniform classification and analytical comparison.

To this end, this paper employs a systematic analytical method to investigate the use of MR technologies in the built environment. It concerns the identification of regularities in the interactions among task requirements, technological capabilities, and contextual conditions through the prism of the TTC framework. The TTC framework is embraced as an analytical construct in this study and is used to facilitate the organized interpretation of MR applications, rather than as a predictive model.

Through this, the paper contributes to the body of literature on construction innovation by providing a critical synthesis of current research on MR and by defining future research directions to ensure greater context and lifecycle sensitivity. The results are intended to help researchers design studies that more closely reflect the conditions of practical deployment and to help practitioners assess the role MR technologies may play in the complex construction environment. This research deals with the following research questions:

RQ1: How are MR applications distributed across different phases of the built environment project lifecycle?
RQ2: How do task characteristics influence the selection of MR technology platforms in built environment applications?
RQ3: What contextual factors shape the evaluation and implementation settings of MR technologies in existing studies?

In contrast to previous reviews that mainly provide descriptive classifications, this research adopts a more analytical perspective, examining the relationships among tasks, technologies, and contextual conditions. The study concentrates on a representative sample, which allows a more robust understanding of the trends in MR application and their consequences in real-life practice. The results can inform future studies on construction innovation by promoting more contextual studies and helping practitioners in assessing MR technologies for application in the complex built environment. Although previous reviews have mainly focused on listing MR applications or specific use cases, the present study contributes to the literature by offering an integrated analytical explanation of the relationship among tasks, technology, and context. In contrast to descriptive reviews, the proposed methodology identifies common trends in the selection, application, and assessment of MR technologies across various contexts, providing a more explanatory view for MR adoption in the built environment.

2. Research Methodology

This study examined 68 peer-reviewed articles related to the use of MR technologies in the built environment. The relationships between project lifecycle stages, task requirements, technology platforms, and implementation contexts were investigated through the TTC framework. The selected studies were classified and compared based on task attributes, evaluation environments, and types of MR technology to identify key trends, correlations, and existing research gaps.

2.1 Research Design and Scope

This study uses a systematic search and analytical review method to discuss the use of MR technologies in the built environment. Rather than striving to offer a comprehensive, systematic synthesis, the paper focuses on a representative sample of peer-reviewed journal articles to facilitate further analytical understanding of MR applications. Targeted searches were conducted in popular academic databases, such as Web of Science and Scopus, covering literature published from 2015 to 2024. The search was limited to articles that discussed applications of MR, AR, or XR within the architecture, engineering, and construction (AEC) field. A total of 68 studies were identified based on their relevance to task execution, technology implementation, and deployment in context. These studies constitute the analytical dataset used to determine trends in each phase of the project lifecycle, task characteristics, technology platforms, and assessment environments.

Given the inconsistent use of terminology in the literature, a pragmatic interpretation of MR-related concepts was adopted. Studies addressing MR, AR, or XR were included where the primary focus involved the overlay of digital information onto physical built-environment contexts. This approach aligns with common practice in construction and engineering research, where functional application is emphasised over strict technical distinctions [3-4]. The study aims to provide an analytical interpretation of MR application patterns across lifecycle stages and implementation contexts based on a representative dataset to facilitate further analytical interpretation.

2.2 Data Identification and Selection Procedure

The process of literature selection involved an iterative screening process. Titles and abstracts were initially screened to determine relevance to MR applications in the built environment. Studies were included if they provided sufficient information on task execution, technology use, or implementation context. Full-text screening was then conducted to verify eligibility in accordance with predetermined inclusion criteria. Only peer-reviewed journal articles published in English and directly concerned with MR applications in AEC situations were used. Research papers lacking methodological or application-related detail were filtered out. This sampling strategy ensured that the final dataset is a narrow, specific subset of the literature that can be interpreted analytically. The 68 studies comprising the analytical dataset are listed in the references section. A footnote at the beginning of the reference list indicates that all references constitute the analytical dataset for this review.

To ensure transparency and consistency, selection decisions were guided by predefined inclusion criteria requiring that studies: (i) address construction or built-environment contexts, (ii) explicitly employ MR, AR, or XR technologies, and (iii) discuss application, evaluation, or implementation aspects. The resulting publications constitute the analytical dataset used in subsequent classification and analysis. Fig. 2 illustrates the overall process for identifying and screening the literature through a structured multi-stage procedure.

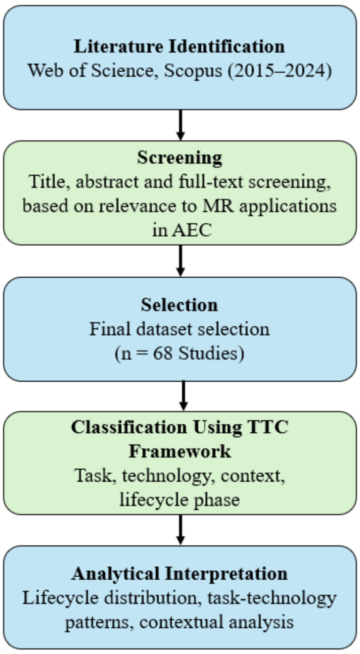

Fig. 2 Methodological workflow of the structured analytical review adopted in this study

2.3 Data Extraction and Analytical Classification

In each chosen study, key analytical attributes were identified to aid systematic classification. These included project lifecycle phases (design, construction, operation, and maintenance), task type, technology platform, and assessment circumstances. The lifecycle classification helped to identify the distribution of MR applications in various phases of the built environment lifecycle. For example, the distribution shown in Fig. 3 is derived from this classification and presents the proportion of studies in each lifecycle phase. Task categories have been created inductively based on recurring application goals, such as visualization, guided execution, collaboration, inspection, and training. The technology platforms were classified into head-mounted displays, handheld devices, and wearable systems to enable a uniform comparison. The classification process was conducted iteratively, with categorized attributes cross-checked to ensure consistency.

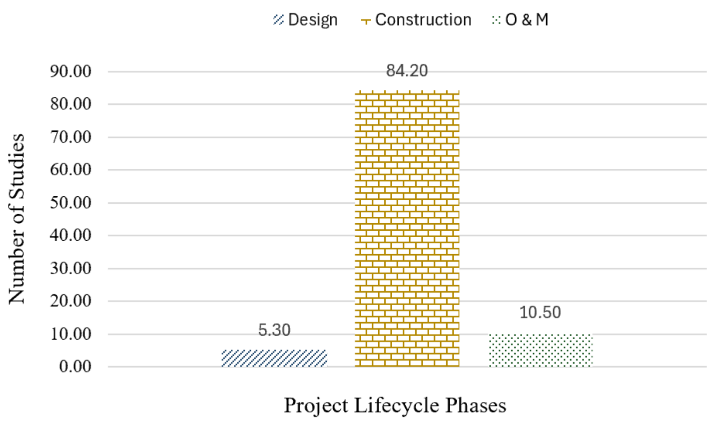

Fig. 3 Distribution of Mixed Reality applications across built environment project lifecycle phases (n = 68)

Fig. 3 shows the breakdown of Mixed Reality (MR) applications across the built-environment project lifecycle, based on the analyzed dataset. The findings indicate a highly skewed distribution, with the construction phase accounting for 84.2% of the reviewed literature. Conversely, 5.3% and 10.5% of the studies are linked to the design stage and to operations and maintenance (O&M), respectively. The figure highlights a clear lifecycle imbalance in MR research, with a strong bias toward construction-phase applications.

2.4 Analytical Framework: Task–Technology–Context

To enable structured interpretation of the classified data, this study employs a TTC analytical framework. The framework decomposes MR applications into three interrelated dimensions: task characteristics, technology platforms, and implementation context. By applying this framework, each study in the dataset is systematically examined to identify how MR technologies are selected and deployed in relation to specific task demands and contextual conditions.

The TTC framework functions as an analytical tool rather than a validated theoretical model, supporting consistent comparison and interpretation across studies. In contrast to previous literature that often examines task needs, technological affordances, and contextual conditions separately, this framework enables a comprehensive analysis of recurring associations among these dimensions. Fig. 2 presents the TTC analytical framework adopted in this study.

2.5 Analytical Strategy and Study Limitations

The coded dataset was analyzed using descriptive and comparative analytical techniques to identify distributions, associations, and recurring patterns across the TTC dimensions. Analysis focused on examining how MR applications vary across project lifecycle phases, how task characteristics influence technology selection, and how contextual conditions shape evaluation practices. Findings are reported using aggregated classifications and illustrative summaries to support analytical interpretation rather than statistical inference.

This study faces several limitations due to the use of structured analytical reviews. The analysis is based on a collection of 68 peer-reviewed journal articles retrieved from major academic databases and limited to English-language publications. Although the dataset is considered representative, it may not fully reflect all recent developments in MR research. Moreover, the level of detail presented in individual studies can vary across sources, which may influence the granularity of classification results. These restrictions are accepted to provide transparency and put the interpretation of the findings in perspective. All classifications and figures were checked to ensure their consistency and accuracy in analysis.

3. Results: Analytical Patterns of Mixed Reality Applications in the Built Environment

The findings are representative, not comprehensive, of all research on MR. The following section presents the analytical results derived from the classified literature dataset using the TTC framework. It investigates the distribution of MR applications across project lifecycle phases, the relationship between task characteristics and technology platform choice, and the influence of implementation contexts on evaluation practices. The analysis is a mix of descriptive and analytical interpretations, with emphasis on the observed patterns and associations rather than on statistical inference. The same methods have been used in earlier MR research on trends in applications and contextual deployment features [2-3], and in reviews investigating the task-oriented and technology-driven patterns in built environment research [4].

3.1 Distribution of MR Applications across Project Lifecycle Phases (*RQ1*)

Analysis of the dataset indicates that MR applications are unevenly distributed across the built-environment project lifecycle. Most studies focus on early project delivery phases, while comparatively fewer studies address later-life asset operations. During the design phase, MR applications are commonly observed in multiple studies used to support immersive visualization, design review, and stakeholder communication, in which digital design intent is spatially contextualised to enhance understanding and coordination [4, 15]. This concentration reflects broader digitalisation trends in architecture, engineering, and construction that emphasise visualization and model-based coordination as key drivers of immersive technology adoption [8-9].

In the construction phase, MR applications are widely reported for layout guidance, installation and assembly support, inspection-related activities, and safety or skill development tasks [16-20]. Many construction-oriented implementations employ overlay-based guidance and in-situ visualization to assist task execution, reduce rework, and improve access to design information under field conditions [21-23]. Safety-focused applications are also prominent, reflecting continued interest in the use of immersive technologies for construction risk communication and training [3, 23-25].

By contrast, applications associated with O&M activities appear less frequently in the dataset. Where present, O&M-oriented MR studies typically focus on asset information retrieval, facility inspection, maintenance guidance, and procedure training within existing facilities [14, 26-28]. This pattern aligns with observations in related built-environment research suggesting that many digital construction innovations remain concentrated in capital delivery stages, despite their recognised potential in facility management contexts [13-14]. An overview of MR application themes across different project lifecycle phases is summarized in Table 1.

Table 1 Overview of MR application themes across built environment project phases

Phase	Task	Description
Design	Enhanced visualisation & spatial comprehension	Contextualizing digital information in the physical world to improve understanding [4, 15, 29].
Construction	Layout, inspection, assembly, MEP-related activities; remote collaboration & decision support; knowledge transfer & training	On-site layout, clash detection [14, 16, 22, 26-27, 30-40]; improving accuracy with in-context visual instructions [17-19, 28, 32, 41-49, 50]; remote communication and progress monitoring [5, 6, 23, 51-55, 58-60]; safety training [20, 24-25, 59].
O & M	Asset visibility & maintenance support	Supporting operation and maintenance (O&M) phase [14, 26-27, 30, 34, 39].

This distribution shows that most research focuses on construction-stage applications, where MR technologies have most commonly been used for tasks such as layout guidance, assembly assistance, inspection, and safety training. The high percentage may reflect the direct, practical advantages of MR for on-site task execution, visualization, and error minimization in physical construction operations. On the other hand, the comparatively low prevalence of MR applications during the design process suggests that, although MR has the potential to aid immersive design review and coordination, it is not as widely studied as construction-focused applications. This may be due to the earlier adoption of other digital tools. The average presence of studies in the operation and maintenance stage (10.5%) indicates emerging interest in MR applications for asset management, inspection, and maintenance support. Nonetheless, the relatively low percentage indicates that the integration of MR under long-term operational conditions remains underexplored.

Overall, this pattern suggests that future research should place greater emphasis on expanding MR applications in design and operational phases to support more comprehensive lifecycle integration. This imbalance also reflects a broader tendency in built environment research to prioritize short-term, demonstrable applications over long-term, contextually complex implementations.

The distribution corresponds approximately to 57 studies in construction, 4 in design, and 7 in operation and maintenance, highlighting a strong concentration of MR research in construction-phase applications. This suggests that there are many applications during the construction phase of MR research compared to other stages of the project lifecycle. The dominance of construction-related studies indicates that MR technologies are primarily applied to site operations, visualization, coordination, safety, and task execution. In contrast, the limited studies conducted during the design phase suggest that incorporating MR technologies in the early design and conceptual stages remains under-researched. Likewise, operation and maintenance applications receive comparatively little attention despite their potential to support facility management and long-term asset monitoring. Overall, the results show that MR research is unevenly distributed across the project lifecycle, with a distinct focus on construction activities.

3.2 Task-Oriented Application Patterns (*RQ2*)

Visualization-related tasks were identified in approximately 40 studies, while guided execution tasks were reported in nearly 35, indicating their prominence in MR applications. The task-based analysis reveals several recurring categories within the built environment, with visualization and spatial comprehension emerging as a dominant application area. In these cases, MR is used to contextualize digital models and information within physical environments, supporting activities such as design reviews and constructability assessments [29, 58], as well as layout and maintainability-related tasks that require accurate spatial interpretation [4]. These visualization-oriented applications are frequently integrated with BIM-enabled workflows, allowing users to access model-based information directly within the project environment during planning and execution stages [8]. Such integration enhances situational awareness and supports more informed decision-making in complex construction scenarios [9].

The second group involves guided execution and procedural support, including assembly and installation support, inspection processes, and deviation identification. These applications generally implement overlay cues and step-by-step instructions to support physically demanding construction activities and mitigate the risk of human error [17, 42]. They are also used in structured inspection and verification procedures that require adherence to predetermined steps [18-19, 44]. Furthermore, guided execution has been observed in MEP activities, where spatial coordination and sequence compliance play a significant role in proper installation and reducing rework [48].

The third category is connected to remote collaboration and decision support, in which MR-enabled platforms are used to communicate between on-site staff and off-site specialists. These applications facilitate communication, problem-solving, and coordination by sharing common visual contexts. Common applications include remote assistance and collaborative progress monitoring [53-54], as well as overcoming design-field mismatches through synchronized visualization environments [57, 58, 60]. These applications help solve long-standing coordination problems in construction projects and are frequently positioned as a means of improving project responsiveness and reducing project delays [61]. They are also associated with efficient decision-making, as they enable real-time expert input without requiring on-site presence [23].

The fourth category is associated with training and knowledge transfer, especially safety training and skill development. In these applications, MR is used to support simulated or controlled experiential learning, enabling users to learn hazard recognition, operational procedures, and task sequences without real-world consequences [20, 59]. These are usually applied in safety education settings and structured learning environments to enhance user competence and awareness [20, 59]. Applications in training are also used in O&M systems, where MR is used to provide procedural direction and knowledge transfer towards continued asset management procedures [34, 39]. Although their use is not as widespread as that of construction-stage applications, there is an opportunity to further develop lifecycle-oriented training applications.

3.3 Technology Platform Selection and Application Contexts (*RQ2*)

Multiple technology platforms are reported across the dataset for delivering MR functionality in built-environment applications. Head-mounted displays (HMDs) are commonly linked to applications that emphasize hands-free interaction, immersive visualization, and spatially persistent overlays. HMD-based implementations have been observed in multiple studies, including laboratory-based evaluations and controlled demonstrations, particularly for complex assembly or precision-oriented tasks [40, 62-63]. They are also employed in communication and collaboration scenarios involving immersive shared views or annotation-based support [40, 53, 60]. The distribution of MR technology platforms and their associated application contexts is summarized in Table 2.

Table 2 Technology categories and commonly associated MR use cases in the built environment

Technology category	Primary research affordances	Commonly associated tasks & references	Analysis of contextual fit
Head-mounted displays (HMDs)	High immersion, hands-free interaction, spatial persistence.	Complex assembly & precision tasks [12, 16, 31, 36, 44, 49, 62, 66]; detailed inspection & visualization [14-15, 17, 28-29, 40]; immersive design review & collaboration [35, 38, 40, 53, 60]; maintenance & procedure guidance [6].	Predominantly evaluated in controlled or simulated environments; limited evidence of sustained field deployment.
Handheld devices (smartphones/tablets)	High accessibility, portability, lower cost, ease of deployment.	On-site visualization & information retrieval [15, 22, 26, 33, 51, 64]; remote collaboration & decision support [6, 54, 58]; O&M, training & inspection tasks [20, 27, 34, 39, 43, 45-46]; assembly and layout guidance tasks [19, 41, 47, 67].	Frequently reported in site-oriented and facility-related applications.
Wearable devices (smart glasses)	Balance of hands-free operation and situational awareness.	Instruction delivery & remote guidance [21, 23, 30, 32, 49, 51, 53, 65]; inspection & safety training [25, 65].	Limited number of studies; applications remain exploratory.

Head-mounted displays were used in about 30 studies, whereas handheld devices were used in over 40, because they are more accessible and easier to implement. Smartphones and tablets are handheld platforms widely used across various application settings, especially where portability, ease of use, and rapid deployment are paramount. Such implementations are typically used on-site to view and access information [26, 51], to communicate progress updates, and to support operational and maintenance-related tasks that require rapid access to asset or model data [22, 33, 54]. They are widely used in research focused on practical feasibility and can be integrated into existing workflows due to their familiarity and relatively low barriers to adoption [39, 54, 64].

A smaller subset of studies investigates wearable or hybrid devices, such as smart glasses, positioned between handheld platforms and fully immersive HMDs. These devices are typically described as emerging alternatives that balance hands-free operation with situational awareness, used in instructional delivery, guidance, and safety-related applications [25, 65].

3.4 Evaluation Settings and Implementation Contexts (*RQ3*)

Analysis of reported evaluation settings shows that MR studies are predominantly conducted in controlled or simulated environments, including laboratories, experimental testbeds, and mock-up facilities. These settings support feasibility testing, usability evaluation, and controlled comparison by limiting contextual variability and enabling repeatable protocols [19, 63]. Controlled evaluations are particularly common in studies focusing on task performance, visualization accuracy, and training outcomes [18, 25, 49].

Field-oriented studies conducted on active construction sites or operational facilities are less consistently reported. When present, such studies often take the form of feasibility demonstrations, pilot deployments, or case-based implementations that describe contextual challenges and constraints in real project environments [12, 54-55]. In facility-related contexts, MR applications are reported for inspection, access to asset information, and maintenance support, though sustained or longitudinal deployment remains limited [14, 26, 28]. Overall, these results indicate that although MR capabilities have been widely explored, the depth of contextual embedding and implementation maturity vary substantially across studies [2].

Beyond descriptive classification, the results reveal clear patterns in the alignment between task requirements and technology selection. For example, immersive head-mounted displays are predominantly used for precision-oriented tasks such as assembly and inspection, while handheld devices are more frequently used for communication and information retrieval in field environments. These recurring associations indicate that MR adoption is not arbitrary but follows identifiable task–technology alignment patterns influenced by contextual constraints.

From a theoretical perspective, these patterns provide empirical support for the core premise of task-technology fit theory within the built environment context. Specifically, when task demands (e.g., precision, spatial awareness) align with technology affordances (e.g., immersion, hands-free operation), the adoption outcomes are more consistently positive in the reported studies. This reinforces the analytical value of the TTC framework in explaining how MR technologies are selected and applied across tasks and contexts.

4. Discussion

Existing MR research is predominantly conducted in controlled evaluation settings, resulting in a gap between experimental validation and practical applicability. The following discussion interprets this gap alongside patterns observed in task characteristics, technology platforms, and implementation contexts. Overall, the results suggest a tendency to prioritize technologically demonstrable scenarios over contextually robust implementations.

4.1 Interpreting MR Application Patterns Using the Task–Technology–Context Framework

The analytical results indicate that task characteristics play a central role in shaping how MR technologies are applied and evaluated in built environment contexts. Tasks requiring high levels of spatial understanding and visual alignment—such as layout planning, assembly, and inspection—are consistently associated with immersive or semi-immersive MR solutions [16-17, 19, 29]. These applications benefit from overlay-based guidance and spatial cues that improve precision and reduce cognitive effort when translating between digital and physical representations [40, 62].

The selection of a technology platform further influences application design and performance. As identified in Section 3, head-mounted displays are commonly used in studies emphasizing immersive interaction and hands-free operation, particularly within controlled experimental settings [40, 62]. In contrast, handheld devices are more frequently associated with applications that prioritize accessibility, information retrieval, and communication in site- or facility-based environments [18, 25, 63]. These patterns indicate that MR technology selection is not only closely aligned with task requirements, but is also shaped by practical constraints such as deployment complexity, environmental conditions, and experimental control [2, 12].

The practical implication is clear for industry practitioners: technology selection benefits from a systematic analysis of task characteristics rather than a preference for more technologically advanced devices. For example, immersive head-mounted displays are appropriate for precision-oriented assembly tasks but may impose an unnecessary cognitive burden for simple information retrieval, where handheld devices are more effective. Mismatches between device affordances and task demands emerge from the literature as a primary contributor to reported implementation difficulties.

Contextual factors—including physical, organizational, and environmental conditions—emerge as a critical yet often less explicitly addressed dimension in MR research. Many studies rely on laboratory-based or simulated environments where variables such as lighting, connectivity, and workflow interruptions can be controlled [19, 63]. However, field-oriented studies highlight challenges related to environmental variability, user workload, and integration with existing practices on active construction sites or operational facilities [12, 54, 56]. These factors significantly influence both task execution and technology performance, affecting the transferability of results.

By integrating task requirements, technological capabilities, and contextual conditions, the TTC framework provides a structured explanation for the observed gap between experimental performance and real-world implementation. Rather than serving as a predictive model, the framework functions as an analytical construct that captures the interdependencies among these dimensions. Fig. 4 illustrates how task requirements, technology characteristics, and contextual conditions interact to influence MR application performance and adoption outcomes. The framework highlights that MR effectiveness emerges from the alignment of these three dimensions rather than from technological capability alone.

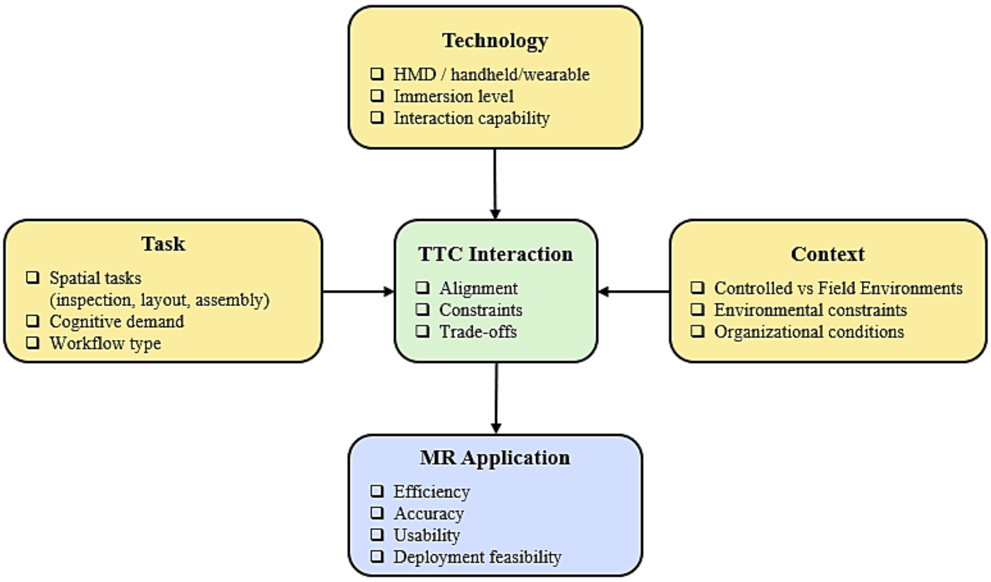

Fig. 4 TTC framework illustrating the interaction between task, technology, and context in MR applications

4.2 Implications for Future Research

The results indicate several ways to further develop MR research in the built environment. Future studies should not be limited to single-case studies but should employ comparative, context-sensitive experimental designs to test MR technologies across a wider range of tasks and environments. In addition, longitudinal field research is required to evaluate the sustainability of MR adoption in the working environment. To begin with, the prevalence of controlled evaluation contexts implies that more focus should be placed on field-based validation. Although laboratory experiments are important in initial development, overreliance on controlled environments limits understanding of MR performance under real-world settings [2, 19]. Pilot deployments and longitudinal studies should therefore be included in future research to ensure the environmental variability and organizational dynamics are captured [12, 56].

Second, the disproportionate distribution across the lifecycle of MR applications implies little consideration of operation and maintenance (O&M) requirements. Despite the investigation of MR in inspection, asset management, and training in the operational setting, its use remains less common than in the design and construction stages [14, 26-28]. Further research in O&M settings is needed to enable a more complete digital innovation lifecycle and long-term asset performance [13].

Third, the observed task-technology associations imply the need to assess the appropriateness of technology rather than focusing on technological advancement. Most studies place a lot of emphasis on hardware capabilities without sufficiently assessing alignment with task demands and contextual limitations [40, 62]. Cross-comparative analyses of various device categories may provide a better understanding of trade-offs among usability, robustness, and workflow integration [39, 54].

Lastly, more studies should be conducted to investigate human–technology interaction in real-world work settings. Although previous research has typically centered on task performance and usability, little attention has been given to factors such as cognitive load, situational awareness, and long-term user adaptation [25, 63]. Incorporating both ergonomics and human-computer interaction perspectives would provide a more comprehensive understanding of MR adoption in practice.

Finally, to translate the analytical insights of this review into actionable guidance, future research should extend the TTC framework from a retrospective analytical tool to a prospective design instrument. Specifically, pilot field studies that apply the TTC framework prospectively—using its three dimensions to guide MR deployment decisions before implementation—could examine the framework’s applicability in realistic built environment scenarios. Such studies should prioritize the under-researched operation and maintenance phases, as these represent the greatest opportunity for lifecycle-oriented MR innovation. Compared with controlled laboratory experiments, these field deployments could generate richer empirical data on human-technology interactions (e.g., cognitive load and situational awareness) and contextual influences (e.g., lighting variability and workflow integration).

4.3 Implications for Practice and Innovation

In practical terms, the TTC framework emphasizes the importance of considering MR technologies not merely in terms of technical capability but also in relation to task demands and contextual conditions. Practitioners can utilize this framework by evaluating MR adoption based on three major factors: (i) the type of task, (ii) the suitability of the technology platform, and (iii) constraints within the implementation environment. Pilot implementations may help practitioners interested in adopting MR explicitly evaluate the technology’s performance under site-specific conditions, such as environmental variability, connectivity limitations, and workflow integration issues [12, 54].

The adoption of MR can be more productive if introduced gradually, rather than as a complete solution. Integrative applications that support existing BIM workflows, mobile systems, or maintenance practices are more likely to be adopted successfully than applications that require significant alterations to established processes [8-9]. Accordingly, MR should be perceived as an enabling element of the larger digital transformation strategies rather than as a single technology. Overall, the discussion offers a systematized approach for aligning MR innovation with practical conditions in the built environment, therefore supporting research development and informed decision-making in practice.

5. Study Limitations

Several limitations in this study should be taken into account when interpreting the results. The discussion is informed by a selected number of peer-reviewed articles, which, although representative, may not capture the full range of developing MR applications. Moreover, the results are based on secondary data published in the literature and thus represent observed research trends rather than empirically determined performance results. The method of analysis is based on classification and pattern recognition rather than quantitative comparison of effect sizes or relative efficacy of MR applications across studies. Similar restrictions have also been observed in previous MR studies investigating application trends [2] and in reviews of technology-task relationships in the built environment [4]. Accordingly, the findings ought to be viewed as reflecting current research trends rather than as proof of effect.

Second, the dataset is limited to journal articles published in English and indexed in major academic databases. Relevant insights reported in conference proceedings, industry reports, or practitioner-oriented publications were not included. Given the applied and rapidly evolving nature of MR technologies in the built environment, some emerging practices and implementation experiences may therefore not be fully represented in the analyzed dataset [12, 56].

Third, the classification of project lifecycle phases, task categories, technology platforms, and evaluation contexts relies on information reported by the original authors. Variations in terminology, reporting depth, and methodological emphasis across studies may introduce interpretive subjectivity, particularly when distinguishing between controlled, simulated, and field-oriented evaluation settings [19, 63]. While consistent classification criteria were applied throughout the analysis, some overlap between categories is unavoidable.

Fourth, the study adopts a pragmatic interpretation of MR-related terminology, including studies labelled as augmented reality or extended reality when their functional characteristics align with the analytical objectives [3-4]. Although this approach supports broader analytical coverage, it may obscure finer technical distinctions between MR, AR, and XR implementations. Future research with a narrower technical focus may provide more granular insights into specific system architectures or interaction paradigms.

Finally, the TTC framework employed in this study functions as an analytical interpretation tool rather than a validated predictive model. While it supports structured examination of relationships among tasks, technologies, and contexts, it has not been empirically tested through quantitative measurement. Further empirical studies are therefore required to assess the explanatory and predictive value of the framework across diverse built-environment contexts and application scenarios [68].

6. Conclusion

The study investigated how MR technologies can be applied in the built environment through the lens of the TTC framework. It identified key research patterns and limitations in current MR implementation by analyzing MR applications across various stages of the project lifecycle, requirements across different tasks, technology platforms, and evaluation contexts. The results offer an analytical understanding of the joint effect of task requirements, technological capabilities, and contextual conditions on MR adoption and applicability in the built environment. The key findings are summarized as follows:

(1) The focus of MR research is largely on the design and construction phases of the project lifecycle, where immersive visualization, layout guidance, and task-specific support are most frequently showcased [4, 8-9]. In contrast, applications related to operation and maintenance are relatively limited despite their importance for long-term performance of asset and facility management [13-14, 26-27].

(2) The selection of MR technology is highly dependent on task properties. Head-mounted displays are more commonly used for immersive visualization and hands-free interaction tasks, while handheld and mobile devices are more common in site-oriented applications for communication, accessibility, and information retrieval [19, 40, 62].

(3) Existing MR evaluations are still dominated by controlled and simulated environments, leaving a gap between experimental validation and real-world implementation [2, 12]. There are still practical deployment issues and constraints that are not fully addressed.

(4) The TTC framework emphasizes the need to assess MR technologies based on the interplay of task demands, capabilities of the technology, and contextual conditions, instead of focusing solely on technical performance [2, 68].

(5) Future work should prioritize context-aware evaluation, implementation, integration into the lifecycle, and long-term deployment studies, to enable the practical use of MR in real construction environments [12, 25, 56, 63].

Funding

There was no specific grant from a public, private, or not-for-profit funding agency for this research.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] F. Barbosa, J. Woetzel, and J. Mischke, "Reinventing Construction: A Route to Higher Productivity," McKinsey Global Institute, Technical Report, 2017.

[2] J. M. D. Delgado, L. Oyedele, P. Demian, and T. Beach, "A Research Agenda for Augmented and Virtual Reality in Architecture, Engineering and Construction," Advanced Engineering Informatics, vol. 45, article no. 101122, 2020.

[3] X. Li, W. Yi, H. L. Chi, X. Wang, and A. P. C. Chan, "A Critical Review of Virtual and Augmented Reality (VR/AR) Applications in Construction Safety," Automation in Construction, vol. 86, pp. 150–162, 2018.

[4] M. Noghabaei, A. Heydarian, V. Balali, and K. Han, "Trend Analysis on Adoption of Virtual and Augmented Reality in the Architecture, Engineering, and Construction Industry," Data, vol. 5, no. 1, article no. 26, 2020.

[5] P. E. D. Love, J. Zhou, and J. Matthews, "Project Controls for Electrical, Instrumentation and Control Systems: Enabling Role of Digital System Information Modelling," Automation in Construction, vol. 103, pp. 202–212, 2019.

[6] T. H. Lin, C. H. Liu, M. H. Tsai, and S. C. Kang, "Using Augmented Reality in a Multiscreen Environment for Construction Discussion," Journal of Computing in Civil Engineering, vol. 29, no. 6, article no. 04014088, 2015.

[7] X. Wang, M. J. Kim, P. E. D. Love, M. J. Kim, and S. C. Kang, "Augmented Reality in Built Environment: Classification and Implications for Future Research," Automation in Construction, vol. 32, pp. 1–13, 2013.

[8] B. Schiavi, V. Havard, K. Beddiar, and D. Baudry, "BIM Data Flow Architecture with AR/VR Technologies: Use Cases in Architecture, Engineering and Construction," Automation in Construction, vol. 134, article no. 104054, 2022.

[9] A. Sidani, F. M. Dinis, J. Duarte, L. Sanhudo, D. Calvetti, J. S. Baptista, et al., "Recent Tools and Techniques of BIM-Based Augmented Reality: A Systematic Review," Journal of Building Engineering, vol. 42, article no. 102500, 2021.

[10] H. Khorrami Shad, K. T. W. Yiu, R. Lovreglio, and Z. Feng, "State-of-the-Art Analysis of the Integration of Augmented Reality with Construction Technologies to Improve Construction Safety," Smart and Sustainable Built Environment, vol. 13, no. 6, pp. 1434–1449, 2024.

[11] I. B. Alkan and H. B. Basaga, "Augmented Reality Technologies in Construction Project Assembly Phases," Automation in Construction, vol. 156, article no. 105107, 2023.

[12] P. Dallasega, F. Schulze, and A. Revolti, "Augmented Reality to Overcome Visual Management Implementation Barriers in Construction: A MEP Case Study," Construction Management and Economics, vol. 41, no. 3, pp. 232–255, 2023.

[13] S. Khan, K. Panuwatwanich, and S. Usanavasin, "Integrating Building Information Modeling with Augmented Reality: Application and Empirical Assessment in Building Facility Management," Engineering, Construction and Architectural Management, vol. 31, no. 7, pp. 2809–2828, 2024.

[14] X. Xie, Q. Lu, D. Rodenas-Herraiz, A. K. Parlikad, and J. M. Schooling, "Visualised Inspection System for Monitoring Environmental Anomalies during Daily Operation and Maintenance," Engineering, Construction and Architectural Management, vol. 27, no. 8, pp. 1835–1852, 2020.

[15] D. Rajaratnam, D. M. L. P. Weerasinghe, M. Abeynayake, B. A. K. S. Perera, and J. J. Ochoa, "Potential Use of Augmented Reality in Pre-Contract Design Communication in Construction Projects," Intelligent Buildings International, vol. 14, no. 6, pp. 661–678, 2022.

[16] J. Chalhoub and S. K. Ayer, "Effect of Varying Task Attributes on Augmented Reality Aided Point Layout," Journal of Information Technology in Construction, vol. 24, pp. 95–111, 2019.

[17] H. L. Chi, M. K. Kim, K. Z. Liu, J. P. P. Thedja, J. Seo, and D. E. Lee, "Rebar Inspection Integrating Augmented Reality and Laser Scanning," Automation in Construction, vol. 136, article no. 104183, 2022.

[18] S. Hasanzadeh and J. M. de a Garza, “Productivity-Safety Model: Debunking the Myth of the Productivity-Safety Divide through a Mixed-Reality Residential Roofing Task,” Journal of Construction Engineering and Management, vol. 146, no. 11, article no. 04020124, 2020.

[19] C. Kwiatek, M. Sharif, S. Li, C. Haas, and S. Walbridge, “Impact of Augmented Reality and Spatial Cognition on Assembly in Construction,” Automation in Construction, vol. 108, article no. 102935, 2019.

[20] J. Ramos-Hurtado, F. Muñoz-La Rivera, J. Mora-Serrano, A. Deraemaeker, and I. Valero, “Proposal for the Deployment of an Augmented Reality Tool for Construction Safety Inspection,” Buildings, vol. 12, no. 4, article no. 500, 2022.

[21] J. Chalhoub and S. K. Ayer, “Exploring the Performance of an Augmented Reality Application for Construction Layout Tasks,” Multimedia Tools and Applications, vol. 78, no. 24, pp. 35075–35098, 2019.

[22] M. Foroughi Sabzevar, M. Gheisari, and L. J. Lo, “Improving Access to Design Information of Paper-Based Floor Plans Using Augmented Reality,” International Journal of Construction Education and Research, vol. 17, no. 2, pp. 178–198, 2021.

[23] M. Foroughi Sabzevar, M. Gheisari, and L. J. Lo, “AR-QR Code for Improving Crew Access to Design and Construction Information,” Automation in Construction, vol. 154, article no. 105017, 2023.

[24] F. Dai, A. Olorunfemi, W. Peng, D. Cao, and X. Luo, “Can Mixed Reality Enhance Safety Communication on Construction Sites? An Industry Perspective,” Safety Science, vol. 133, article no. 105009, 2021.

[25] I. Jeelani, K. Han, and A. Albert, “Automating and Scaling Personalized Safety Training Using Eye-Tracking Data,” Automation in Construction, vol. 93, pp. 63–77, 2018.

[26] S. Chung, C. S. Cho, J. Song, K. Lee, S. Lee, and S. Kwon, “Smart Facility Management System Based on Open BIM and Augmented Reality Technology,” Applied Sciences, vol. 11, no. 21, article no. 10283, 2021.

[27] P. H. Diao and N. J. Shih, “BIM-Based AR Maintenance System (BARMS) as an Intelligent Instruction Platform for Complex Plumbing Facilities,” Applied Sciences, vol. 9, no. 8, article no. 1592, 2019.

[28] D. C. Nguyen, T. Q. Nguyen, R. Jin, C. H. Jeon, and C. S. Shim, “BIM-Based Mixed-Reality Application for Bridge Inspection and Maintenance,” Construction Innovation, vol. 22, no. 3, pp. 487–503, 2022.

[29] I. A. Khalek, J. M. Chalhoub, and S. K. Ayer, “Augmented Reality for Identifying Maintainability Concerns during Design,” Advances in Civil Engineering, vol. 2019, no. 1, article no. 8547928, 2019.

[30] S. Biel, “Concept of Using the BIM Technology to Support the Defect Management Process,” Archives of Civil Engineering, vol. 67, no. 2, pp. 209–229, 2021.

[31] A. Degani, W. B. Li, R. Sacks, and L. Ma, “An Automated System for Projection of Interior Construction Layouts,” IEEE Transactions on Automation Science and Engineering, vol. 16, no. 4, pp. 1825–1835, 2019.

[32] V. Dudhee and V. Vukovic, “Building Information Model Visualisation in Augmented Reality,” in Digitalization in Construction, Routledge, pp. 75–92, 2023.

[33] S. Fenais, S. T. Ariaratnam, S. K. Ayer, and N. Smilovsky, “Integrating Geographic Information Systems and Augmented Reality for Mapping Underground Utilities,” Infrastructures, vol. 4, no. 4, article no. 60, 2019.

[34] L. Hou, H. L. Chi, W. Tarng, J. Chai, K. Panuwatwanich, and X. Wang, “A Framework of Innovative Learning for Skill Development in Complex Operational Tasks,” Automation in Construction, vol. 83, pp. 29–40, 2017.

[35] P. Herbers and M. König, “Indoor Localization for Augmented Reality Devices Using BIM, Point Clouds, and Template Matching,” Applied Sciences, vol. 9, no. 20, article no. 4260, 2019.

[36] A. H. Kyaw, A. H. Xu, G. Jahn, N. van den Berg, C. Newnham, and S. Zivkovic, “Augmented Reality for High Precision Fabrication of Glued Laminated Timber Beams,” Automation in Construction, vol. 152, article no. 104912, 2023.

[37] W. Li, Y. Wang, H. Yang, Z. Ye, P. Li, Y. A. Liu, et al., “Development of a Mixed Reality Method for Underground Pipelines in Digital Mechanics Experiments,” Tunnelling and Underground Space Technology, vol. 132, article no. 104833, 2023.

[38] M. K. Rohil and Y. Ashok, “Visualization of Urban Development 3D Layout Plans with Augmented Reality,” Results in Engineering, vol. 14, article no. 100447, 2022.

[39] Q. T. T. Huong, P. L. Quang, and N. L. Hoai, “Applying BIM and Related Technologies for Maintenance and Quality Management of Construction Assets in Vietnam,” International Journal of Sustainable Construction Engineering and Technology, vol. 12, no. 5, pp. 125–135, 2021.

[40] J. Zhang, X. Xia, R. Liu, and N. Li, “Enhancing Human Indoor Cognitive Map Development and Wayfinding Performance with Immersive Augmented Reality-Based Navigation Systems,” Advanced Engineering Informatics, vol. 50, article no. 101432, 2021.

[41] A. Alvanchi, N. Didehvar, M. Jalilehvand, P. Adami, and S. Shahmir, "Semi-Augmented Reality, a Novel Approach to Improve Customer Safety in the Pre-Sale Process of Under Construction Buildings," International Journal of Engineering, Transactions B: Applications, vol. 34, no. 10, pp. 2198–2205, 2021.

[42] J. Chalhoub, S. K. Ayer, and K. H. McCord, "Augmented Reality to Enable Users to Identify Deviations for Model Reconciliation," Buildings, vol. 11, no. 2, article no. 77, 2021.

[43] S. Choi and J. S. Park, "Development of Augmented Reality System for Productivity Enhancement in Offshore Plant Construction," Journal of Marine Science and Engineering, vol. 9, no. 2, article no. 209, 2021.

[44] H. Kim, Z. Piao, S. Hahm, and Y. Lee, "Depicting a Landscape Architectural Installation Using Augmented Reality," Journal of Digital Landscape Architecture, vol. 2022, no. 7, pp. 443–452, 2022.

[45] F. Liu, T. Jonsson, and S. Seipel, "Evaluation of Augmented Reality-Based Building Diagnostics Using Third Person Perspective," ISPRS International Journal of Geo-Information, vol. 9, no. 1, article no. 53, 2020.

[46] H. Nassereddine, C. Schranz, M. Bou Hatoum, and H. Urban, "Mapping the Capabilities and Benefits of AR Construction Use-Cases: A Comprehensive Map," Organization, Technology and Management in Construction: An International Journal, vol. 14, no. 1, pp. 2571–2582, 2022.

[47] U. Riedlinger, F. Klein, M. Hill, C. Lambracht, S. Nieborowski, R. Holst, et al., "Evaluation of Mixed Reality Support for Bridge Inspectors Using BIM Data: Digital Prototype for a Manual Task with a Long-Lasting Tradition," i-com, vol. 21, no. 2, pp. 253–267, 2022.

[48] L. T. Tsai, H. L. Chi, T. H. Wu, and S. C. Kang, "AR-Based Automatic Pipeline Planning Coordination for On-Site Mechanical, Electrical and Plumbing System Conflict Resolution," Automation in Construction, vol. 141, article no. 104400, 2022.

[49] W. Wu, A. Sandoval, V. Gunji, S. K. Ayer, J. London, L. Perry, et al., "Comparing Traditional and Mixed Reality-Facilitated Apprenticeship Learning in a Wood-Frame Construction Lab," Journal of Construction Engineering and Management, vol. 146, no. 12, article no. 04020139, 2020.

[50] O. Alruwaythi and P. Goodrum, "A Difference in Perspective: Impact of Different Formats of Engineering Information and Spatial Cognition on Craft-Worker Eye-Gaze Patterns," Journal of Construction Engineering and Management, vol. 145, no. 11, article no. 04019065, 2019.

[51] S. Alsafouri and S. K. Ayer, "Leveraging Mobile Augmented Reality Devices for Enabling Specific Human Behaviors in Design and Constructability Review," Advances in Civil Engineering, vol. 2019, no. 1, article no. 3951986, 2019.

[52] H. Chen, L. Hou, S. Wu, G. Zhang, Y. Zou, S. Moon, et al., "Augmented Reality, Deep Learning and Vision-Language Query System for Construction Worker Safety," Automation in Construction, vol. 157, article no. 105158, 2024.

[53] J. Chen, Y. Fu, W. Lu, and Y. Pan, "Augmented Reality-Enabled Human-Robot Collaboration to Balance Construction Waste Sorting Efficiency and Occupational Safety and Health," Journal of Environmental Management, vol. 348, article no. 119341, 2023.

[54] K. El Ammari and A. Hammad, "Remote Interactive Collaboration in Facilities Management Using BIM-Based Mixed Reality," Automation in Construction, vol. 107, article no. 102940, 2019.

[55] H. S. Kim, S. K. Kim, A. Borrmann, and L. S. Kang, "Improvement of Realism of 4D Objects Using Augmented Reality Objects and Actual Images of a Construction Site," KSCE Journal of Civil Engineering, vol. 22, no. 8, pp. 2735–2746, 2018.

[56] R. E. Kassis, S. K. Ayer, M. E. Asmar, and P. Tang, "Discovering Factors that Influence the Use of Augmented Reality for Communication on Active Highway Construction Sites," Transportation Research Record: Journal of the Transportation Research Board, vol. 2677, no. 5, pp. 376–389, 2023.

[57] M. Lounakoski, J. Puhto, H. Jalo, O. Torro, and H. Pirkkalainen, "Social Extended Reality—Use Case Entities on Property Life Cycle," Journal of Information Technology in Construction, vol. 27, pp. 512–528, 2022.

[58] S. Meža, Ž. Turk, and M. Dolenc, "Measuring the Potential of Augmented Reality in Civil Engineering," Advances in Engineering Software, vol. 90, pp. 1–10, 2015.

[59] H. N. Rafsanjani and A. H. Nabizadeh, "Towards Digital Architecture, Engineering, and Construction (AEC) Industry through Virtual Design and Construction (VDC) and Digital Twin," Energy and Built Environment, vol. 4, no. 2, pp. 169–178, 2023.

[60] X. Zhao, M. Li, Z. Sun, Y. Zhao, Y. Gai, J. Wang, et al., "Intelligent Construction and Management of Landscapes through Building Information Modeling and Mixed Reality," Applied Sciences, vol. 12, no. 14, article no. 7118, 2022.

[61] S. Alsafouri and S. K. Ayer, "Mobile Augmented Reality to Influence Design and Constructability Review Sessions," Journal of Architectural Engineering, vol. 25, no. 3, article no. 04019016, 2019.

[62] J. Chalhoub and S. K. Ayer, “Using Mixed Reality for Electrical Construction Design Communication,” Automation in Construction, vol. 86, pp. 1–10, 2018.

[63] Y. Qin, E. Bloomquist, T. Bulbul, J. Gabbard, and K. Tanous, “Impact of Information Display on Worker Performance for Wood Frame Wall Assembly Using AR HMD under Different Task Conditions,” Advanced Engineering Informatics, vol. 50, article no. 101423, 2021.

[64] E. Stylianidis, E. Valari, A. Pagani, I. Carrillo, A. Kounoudes, K. Michail, et al., “Augmented Reality Geovisualisation for Underground Utilities,” PFG – Journal of Photogrammetry, Remote Sensing and Geoinformation Science, vol. 88, pp. 173-185, 2020.

[65] S. Sabeti, O. Shoghli, M. Baharani, and H. Tabkhi, “Toward AI-Enabled Augmented Reality to Enhance the Safety of Highway Work Zones: Feasibility, Requirements, and Challenges,” Advanced Engineering Informatics, vol. 50, article no. 101429, 2021.

[66] W. Li, Y. Wang, Z. Ye, Y. A. Liu, and L. Wang, “Development of a Mixed Reality Assisted Escape System for Underground Mine-Based on the Mine Water-Inrush Accident Background,” Tunnelling and Underground Space Technology, vol. 143, article no. 105471, 2024.

[67] M. Sanei, X. Yuan, F. Moreu, and S. Alampalli, “Automated Geometric Quality Inspection of Rebar Layout Using RGBD Data,” Materials Evaluation, vol. 81, no. 1, pp. 46–55, 2023.

[68] B. G. Hwang, J. Ngo, and J. Z. K. Teo, “Challenges and Strategies for the Adoption of Smart Technologies in the Construction Industry: The Case of Singapore,” Journal of Management in Engineering, vol. 38, no. 1, article no. 05021014, 2022.