

# Immersive Learning in Construction and Civil Engineering Education

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## Abstract

Immersive learning has gained increasing attention in construction and civil engineering education as institutions confront the demands of Industry 4.0 and the learning preferences of Generation Z. Although virtual, augmented, mixed, and extended reality (VR/AR/MR/XR) technologies have demonstrated strong potential to enhance experiential, interactive, and scenario-based instruction, their adoption remains fragmented and underdeveloped - particularly in developing countries such as Vietnam. This study conducts a PRISMA-guided systematic review of 33 peer-reviewed publications to examine global applications of immersive learning in construction and civil engineering higher education. The findings reveal six dominant thematic domains: safety and hazard recognition, design and visualization, construction methods and procedures, project management and collaboration, robotics and equipment training, and energy and environmental simulation. Building on these themes, the study proposes the Immersive Learning Integration Framework for Construction and Civil Engineering Education (ILIF-CEE), which organizes immersive learning into five dimensions: learning objectives, technology types, interaction and immersion mechanisms, learning outcomes, and implementation enablers and barriers. The framework provides a structured foundation for integrating immersive tools into Architecture, Engineering, and Construction (AEC) curricula and for supporting institutional digital-transformation strategies. The study contributes consolidated evidence based on the reviewed publications, identifies critical challenges, and outlines practical implications for educators and policymakers seeking to adopt immersive learning.

## 1. Introduction

The rapid digital transformation of the architecture, engineering, and construction (AEC) sector - driven by Industry 4.0 technologies such as virtual reality (VR), augmented reality (AR), mixed reality (MR), extended reality (XR), robotics, automation, and Building Information Modelling (BIM) - is reshaping how construction professionals learn, communicate, and solve problems. While construction has historically lagged behind other industries in productivity and technological adoption, recent analyses from the World Economic Forum indicate that emerging technologies are now critical enablers for addressing labour shortages, safety risks, design complexity, and sustainability pressures across the built environment [1].

Within this broader transformation, immersive learning technologies have gained increasing prominence in construction and civil engineering education. Research over nearly three decades - from early virtual safety systems such as SAVR [2] to contemporary XR environments used for design visualization, hazard recognition, and procedural training - shows that immersive environments enhance learner engagement, spatial reasoning, and experiential practice. Systematic reviews [3-5] further confirm that immersive learning supports deeper conceptual understanding by enabling learners to interact with information situated in realistic, multisensory, and feedback-rich contexts.

These findings reflect a pedagogical shift towards experiential learning, consistent with Kolb's theory that knowledge is created through the transformation of experience [6]. Immersive technologies activate multiple stages of Kolb's learning cycle - concrete experience, reflective observation, abstract conceptualization, and active experimentation - thereby supporting the development of higher-order cognitive and practical skills essential for the AEC workforce.

At the same time, the learner demographic in higher education is changing. Studies on Generation Z [7, 8] highlight that today's students prefer interactive, visual, technology-enhanced learning environments and demonstrate higher motivation and performance when exposed to multimodal, simulation-based instruction. This trend aligns with the increasing demand for digitally fluent engineers who can operate in BIM-enabled, data-driven project ecosystems [9, 10].

Despite clear pedagogical benefits, the adoption of immersive learning in construction education remains uneven across institutions and regions. Barriers include high equipment costs, insufficient digital infrastructure, limited instructor capacity, unclear curricular integration models, and concerns about scalability and sustainability [11, 12]. These challenges are especially pronounced in developing countries, where digital transformation in education often lags behind industry expectations.

Given this context, there is a critical need to synthesize the global evidence base and identify thematic patterns that can guide the structured integration of immersive technologies in construction and civil engineering programs. Responding to this need, the present study conducts a PRISMA-based systematic review of 33 peer-reviewed publications to examine how immersive learning has been adopted worldwide and to distill its core pedagogical contributions. Based on this synthesis, the study develops the Immersive Learning Integration Framework for Construction and Civil Engineering Education (ILIF-CEE), which organizes immersive learning into five dimensions: learning objectives, technology types, interaction and immersion mechanisms, learning outcomes, and implementation enablers and barriers.

This framework aims to support educators, administrators, and policymakers in designing evidence-based instructional strategies, aligning immersive learning with competency development goals, and advancing digital transformation in AEC education - particularly in contexts where resource constraints and implementation uncertainties persist.

## 2. Background and Related Work

### 2.1 Immersive Learning in Engineering and Technical Education

Immersive learning refers to the use of VR, AR, MR, and XR environments to provide highly interactive, experiential, and situated learning experiences. These technologies enable students to engage with complex spatial and procedural tasks in ways that traditional didactic methods cannot support [5]. Immersive environments enhance presence, realism, and multi-sensory engagement, which are essential for developing technical competencies, spatial cognition, and procedural proficiency in engineering-related fields.

From a pedagogical perspective, immersive learning aligns with experiential learning theory and constructivist approaches, where learners acquire knowledge through active exploration and reflection [6]. Cognitive load theory also explains the benefits of immersive visualization: VR/AR can reduce extraneous cognitive load by presenting information in an integrated, context-rich environment [4]. Empirical studies have demonstrated that immersive tools improve understanding of abstract concepts, increase learner engagement, and support more effective skill development in domains such as mechanical engineering, architecture, and structural analysis [13, 14].

Overall, immersive learning has been widely recognized as a transformative approach in technical education, offering opportunities to bridge theory-practice gaps and support more individualized and interactive learning pathways for Generation Z students who exhibit strong preferences for digital, visual, and experiential modes of instruction.

### 2.2 Immersive Learning in Construction and Civil Engineering Education

Immersive technologies have also been increasingly adopted in construction and civil engineering education, particularly for training tasks involving risk, spatial complexity, and procedural accuracy. A large body of research highlights the role of VR-based simulations in enhancing hazard identification, construction safety training, and

situational awareness in high-risk environments [15]. AR and MR applications support design visualization, constructability analysis, and integration of BIM-based information directly into real-world settings, enabling deeper comprehension of structural relationships and design intent [16].

Other emerging applications include project management training through 4D/5D simulation, collaborative VR environments for design coordination, and robotics/equipment operation training through realistic simulators [10, 17]. These tools enable safer, more cost-effective, and more engaging alternatives compared to physical mock-ups or on-site instruction.

However, despite the growing number of studies, research remains fragmented. Most publications focus on single-purpose applications, limited case studies, or prototype implementations without fully examining cross-cutting pedagogical principles, comparative effectiveness, or long-term learning outcomes. In addition, construction education in developing countries faces significant barriers including limited infrastructure, high hardware costs, and insufficient lecturer readiness - factors that are often underreported in existing literature [11]. This indicates a need for a consolidated synthesis to unify scattered evidence and identify strategic directions for immersive learning adoption.

## 2.3 Systematic Reviews and the Need for a New Analytical Framework

While several reviews have discussed VR or AR applications in engineering or general higher education, very few systematic reviews focus specifically on construction and civil engineering education or provide a structured comparative synthesis. For example, Radianti, et al. [5] conducted a broad review of immersive VR in higher education, but construction-related studies formed only a small subset [5]. Wang, et al. [18] and [3] reviewed VR in construction education but did not extend the analysis to AR, MR, or XR [3, 18]. Moreover, existing reviews do not provide a conceptual framework that integrates learning objectives, technology types, immersion characteristics, and implementation barriers into a unified model.

A PRISMA-guided approach is therefore essential to ensure methodological rigor, transparency, and traceability in the review process [19]. Beyond synthesizing existing evidence, there is also a need to generate a comprehensive conceptual model to support curriculum designers, educators, and policymakers in understanding how immersive technologies can be strategically integrated across construction education contexts.

To address these limitations, the present study not only consolidates global research evidence but also proposes the ILIF-CEE a five dimension model that captures (1) learning objectives, (2) technology types, (3) interaction and immersion levels, (4) learning outcomes and assessment strategies, and (5) implementation enablers and barriers. This framework fills a key gap by providing a structured lens through which immersive learning applications can be compared, evaluated, and contextualized for both developed and developing educational environments. This study employs a PRISMA-guided systematic review methodology to identify, screen, and synthesize peer-reviewed research on immersive learning in construction and civil engineering education. The methodology consists of four main stages: (1) search strategy design, (2) identification of relevant studies, (3) eligibility assessment through multi-stage screening, and (4) data extraction and thematic content analysis. The overall methodological workflow is described in the next section and aligned with the PRISMA 2020 recommendations [19].

## 3. Research Methodology

This study employs a rigorous two-stage methodological design combining a PRISMA-guided systematic review with a structured conceptual framework development process. Stage 1 synthesizes existing research on immersive learning within construction and civil engineering education. Stage 2 abstracts the resulting thematic patterns into the ILIF-CEE. The research workflow is illustrated in Fig. 1 and detailed below.

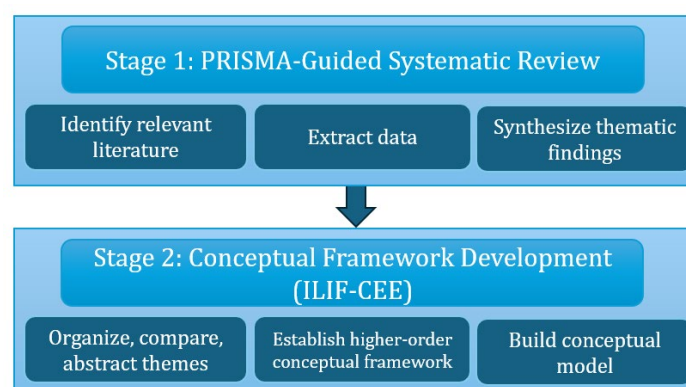


Fig. 1 Research methodology

### 3.1 Research Design

The overall research design consists of two sequential stages (Fig. 1), namely; Stage 1- PRISMA-Guided Systematic Review, a structured review was conducted following the PRISMA 2020 guidelines [19], incorporating systematic identification, screening, eligibility assessment, and data extraction. This stage produced the thematic foundations necessary for framework construction; Stage 2 - Conceptual Framework Development, findings from Stage 1 were subjected to analytical abstraction and model building based on established conceptual development methodologies [20, 21]. The resulting framework integrates technological, pedagogical, and contextual dimensions of immersive learning. This dual-stage design strengthens methodological transparency and reproducibility.

### 3.2 Stage 1: PRISMA-Guided Systematic Review

#### 3.2.1 Search Strategy and Data Sources

Scopus was selected as the primary database due to its comprehensive indexing of engineering, education, and computer science literature. A Boolean search string was formulated to capture immersive technologies within AEC education:

**TITLE-ABS-KEY** (“virtual reality” OR “augmented reality” OR “mixed reality” OR “extended reality” OR “immersive learning” OR VR OR AR OR MR OR XR)  
**AND**  
**TITLE-ABS-KEY** (“construction education” OR “civil engineering education” OR “engineering pedagogy” OR “built environment education”).

The search returned 104 publications (1996–2024), including journal articles, conference papers, and book chapters.

#### 3.2.2 Identification and Screening Procedures

A two-stage filtering procedure was applied, as depicted in Fig. 2.

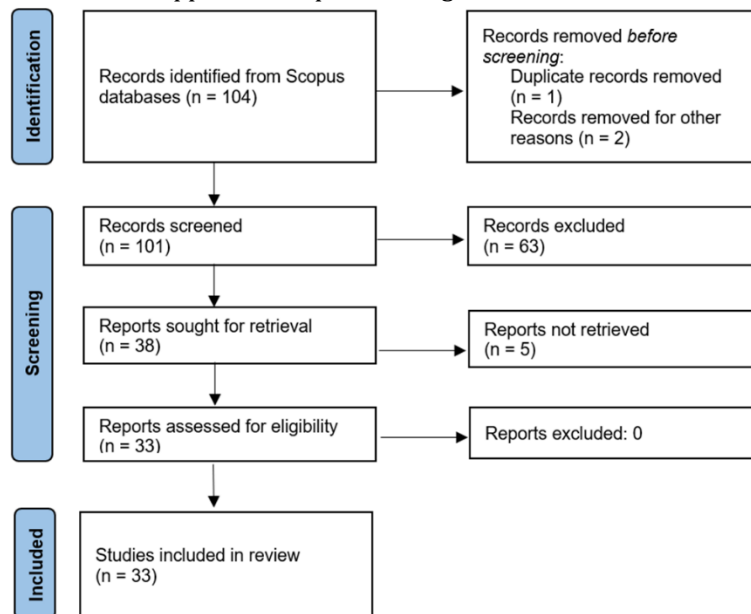


Fig. 2 PRISMA workflow: Screening and filtering process

#### Automatic Filtering (Stage 1 Screening)

- Removal of duplicates
- Inclusion of English-language publications
- Exclusion of irrelevant domains (e.g., medicine, arts, psychology)
- Retention of engineering, built-environment, and education studies

This reduced the dataset to 38 publications.

#### Title and Abstract Screening (Stage 2 Screening)

Eligibility was assessed using predefined inclusion and exclusion criteria.

**Inclusion criteria:**

- Use of immersive technologies (VR/AR/MR/XR)
- Application in construction, civil engineering, or built-environment education
- Pedagogical relevance (e.g., instructional design, simulation, assessment)
- Peer-reviewed publication

**Exclusion criteria:**

- Technology development without a learning component
- Lack of relevance to AEC education
- Insufficient methodological detail

After manual screening, 33 publications remained for full-text analysis.

### 3.2.3 Eligibility and Quality Appraisal

Each study underwent methodological appraisal adapted from Wang, et al. [18], Nikolic and Windess [22] and Radianti, et al. [5]. Assessment criteria included:

- Clarity of learning objectives
- Description of immersive technology and interaction fidelity
- Evidence of learning outcomes or evaluation methods

The appraisal informed thematic synthesis while avoiding exclusion based solely on scoring.

### 3.2.4 Data Extraction

A structured extraction matrix captured the following fields:

- Publication year and source
- Immersive technology type (VR/AR/MR/XR)
- Educational application domain (e.g., safety, visualization, PM, robotics)
- Pedagogical goals
- Interaction and immersion characteristics
- Evaluation approach
- Reported learning outcomes
- Implementation challenges or barriers

This dataset formed the basis for descriptive analysis (Section 4) and thematic synthesis (Section 5).

### 3.2.5 Thematic Content Analysis

The thematic synthesis followed Erlingsson and Brysiewicz [23] qualitative content-analysis procedure:

1. Open coding: Identification of meaningful units from each study.
2. Categorization: Grouping codes into thematic domains (e.g., safety, design, methods, PM, robotics).
3. Theme synthesis: Development of higher-order themes to inform model building.
4. Integration: Using synthesized themes as analytical inputs for framework construction (Stage 2).

This combined descriptive–interpretive approach allows both mapping of research trends and extraction of latent conceptual structure.

## 3.3 Conceptual Framework Development

### 3.3.1 Rationale for Framework Construction

Although previous reviews offer valuable insights into VR/AR/MR/XR applications, they often lack integrative, multi-dimensional frameworks that connect learning objectives, technological modalities, immersive mechanisms, learning outcomes, and contextual constraints. The thematic patterns revealed in Stage 1 show a fragmented landscape lacking a unifying pedagogical–technological structure. These gaps motivate the development of the ILIF-CEE framework.

### 3.3.2 Analytical Basis

The ILIF-CEE framework is grounded in four evidence streams:

- Thematic patterns derived from the 33 eligible studies
- Experiential learning theory [6]
- Immersion and interaction theory in XR learning [24, 25]
- Prior conceptual work in immersive AEC education [22, 26]

Integrating these strands enables the articulation of five cohesive dimensions underpinning immersive learning.

### 3.3.3 Framework Development Procedure

The ILIF-CEE model was developed using an iterative, three-step procedure adapted from Jabareen [21]:

#### 1. Theme Consolidation

Themes from Stage 1 (e.g., safety, visualization, robotics) were grouped into conceptual clusters.

#### 2. Dimension Abstraction

Clusters were examined to derive higher-order dimensions such as:

- Learning Objectives
- Immersive Technology Type
- Interaction and Immersion
- Learning Outcomes
- Enablers and Barriers

#### 3. Model Integration

Dimensions were synthesized into a cohesive conceptual structure representing the ILIF-CEE framework. Internal consistency, non-overlap, and completeness were evaluated.

### 3.3.4 Internal Validation

The preliminary framework underwent internal validation based on:

- Conceptual clarity
- Alignment with Stage 1 thematic results
- Consistency with immersion and experiential-learning theories
- Applicability across diverse AEC educational contexts

This ensured theoretical robustness and generalizability of the ILIF-CEE model.

## 4. Results: Descriptive Mapping of Immersive Learning Research

This section presents a descriptive analysis of the 33 eligible studies obtained from the PRISMA-guided systematic review. The results summarize (1) publication trends, (2) distribution of journals and conferences, and (3) keyword and technology patterns. These descriptive findings provide a foundational overview of how immersive learning technologies have evolved within construction and civil engineering education.

### 4.1 Publication Trends

The collected literature consists of various types of publications, including 13 journal papers, one of which is a review paper, 18 conference papers, and two book chapters. In terms of publication years, the oldest identified paper was published in 1996 by Hadipriono et al. in the ASEE Annual Conference Proceedings [2]. Following this, there was a significant gap in the relevant literature, with no additional papers published until 2015 and 2016, each contributing one paper. Notably, no relevant papers were found for the year 2017 (Fig. 3).

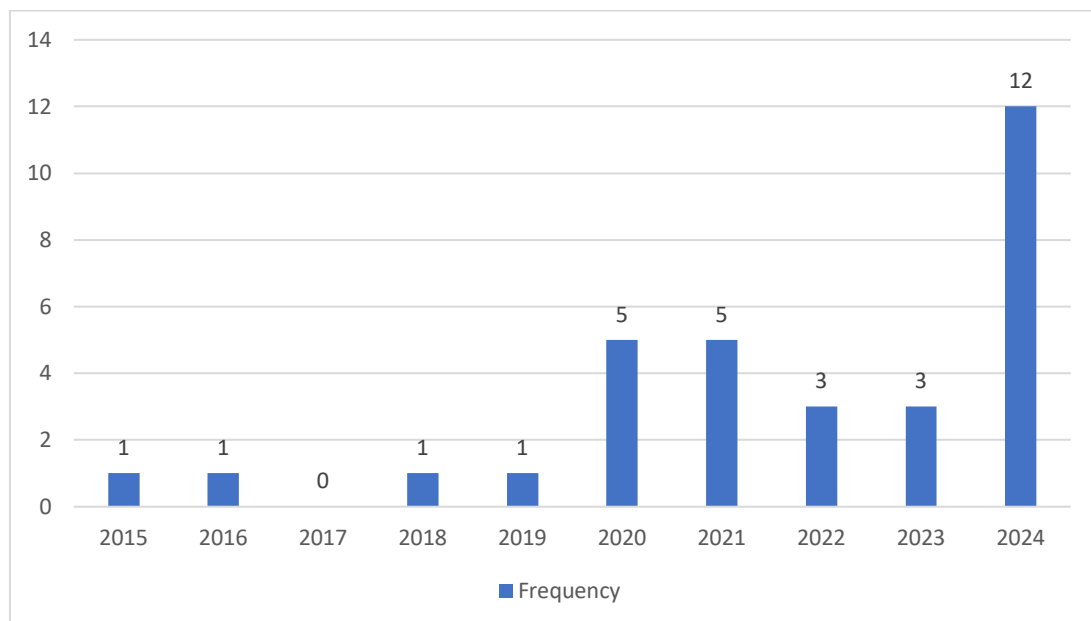


Fig. 3 Annual distribution of immersive learning publications (2015–2024)

The dataset shows a slow uptake of VR/AR/MR-related studies prior to 2010, which aligns with the early developmental period of immersive visualization tools [5]. Only isolated publications appear between 1996 and 2010, largely experimental prototypes or conceptual discussions of VR in engineering education [14].

A notable increase occurs after 2015, coinciding with the broader adoption of consumer-grade VR headsets and mobile AR technologies. The number of studies peaks between 2018 and 2022, reflecting parallel developments in BIM-integrated visualization, safety simulation environments, and the expansion of digital pedagogy in engineering curricula.

The post-2020 acceleration also corresponds with the shift to hybrid and technology-enhanced learning during the COVID-19 pandemic, which catalyzed the adoption of immersive technologies in higher education [27].

Overall, publication trends indicate an increasing integration of immersive learning within construction-related curricula, with sustained growth expected as institutions adopt Industry 4.0-aligned teaching models.

## 4.2 Types of Sources: Journals and Conferences

After an initial screening of 104 identified publications, a systematic exclusion process was applied to refine the dataset. Two conference proceedings, 62 publications deemed irrelevant, and one paper that was superseded by a journal version were excluded. This rigorous filtering resulted in a final set of 39 publications for content analysis. These publications are distributed across 16 distinct sources, predominantly featuring a single contribution per source, with the Journal of Civil Engineering Education contributing two papers. The dataset spans a diverse range of academic domains, including engineering, construction, sustainability, and information technology, as evidenced by journals such as Environmental Science and Engineering, Journal of Computing in Civil Engineering, and Smart and Sustainable Built Environment. This carefully curated selection ensures that the content analysis will be grounded in a focused and relevant body of literature, thus enhancing the validity and reliability of the ensuing analysis (Table 1).

**Table 1** Distribution of journal publications on immersive learning (1996–2024)

Journal Titles	Frequency
Advances in Science, Technology and Innovation	1
Applied Sciences (Switzerland)	1
Architectural Engineering and Design Management	1
Canadian Journal of Learning and Technology	1
Computer Applications in Engineering Education	1
Environmental Science and Engineering	1
Expert Systems with Applications	1
Frontiers in Built Environment	1
International Journal of Computational Methods and Experimental Measurements	1
International Journal of Construction Education and Research	1
Journal of Civil Engineering Education	2
Journal of Computing in Civil Engineering	1
Journal of Information Technology in Construction	1
Smart and Sustainable Built Environment	1
World Construction Symposium	1
World Sustainability Series	1

The data reveals that sixteen distinct conferences have contributed to the body of work in this domain, with the ASEE Annual Conference Proceedings standing out by contributing two publications, indicating a slightly higher degree of scholarly engagement compared to the other conferences, each of which is represented by a single publication. This distribution underscores the multidisciplinary nature of the field, with conferences spanning topics from civil engineering and construction automation (e.g., the 32nd International Symposium on Automation and Robotics in Construction and Mining) to immersive learning technologies (e.g., the Proceedings of the 6th International Conference of the Immersive Learning Research Network). The presence of conferences such as EDUNINE 2020 and the IEEE International Workshop on Metrology for Living Environment further reflects the convergence of engineering education, measurement technologies, and sustainable built

environments within the broader discourse of digital construction. Despite this thematic diversity, the fact that no other conference besides ASEE contributes more than one paper suggests a highly fragmented research landscape, indicative of both the nascent stage of the field and the emerging opportunities for deeper, more focused investigations. This fragmentation, in turn, highlights the need for greater cross-disciplinary collaboration and more cohesive research agendas to advance the implementation of advanced digital tools, such as BIM, in the engineering and construction industries (Table 2).

**Table 2** *Distribution of conference publications on immersive learning (1996–2024)*

Conference Names	Frequency
2024 IEEE International Workshop on Metrology for Living Environment, MetroLivEnv 2024 - Proceedings	1
32nd International Symposium on Automation and Robotics in Construction and Mining: Connected to the Future, Proceedings	1
ASEE Annual Conference Proceedings	2
Computing in Civil Engineering 2023: Resilience, Safety, and Sustainability - Selected Papers from the ASCE International Conference on Computing in Civil Engineering 2023	1
EDUNINE 2020 - 4th IEEE World Engineering Education Conference: The Challenges of Education in Engineering, Computing and Technology without Exclusions: Innovation in the Era of the Industrial Revolution 4.0, Proceedings	1
IOP Conference Series: Earth and Environmental Science	1
Lecture Notes in Computer Science	1
Lecture Notes in Networks and Systems	1
Proceedings - 2020 IEEE International Conference on Artificial Intelligence and Virtual Reality, AIVR 2020	1
Proceedings - 2021 International Conference on Big Data Engineering and Education, BDEE 2021	1
Proceedings - Web3D 2023: 28th International Conference on Web3D Technology	1
Proceedings of 6th International Conference of the Immersive Learning Research Network, iLRN 2020	1
Proceedings of the 2nd International Conference on Intelligent and Innovative Technologies in Computing, Electrical and Electronics, ICIITCEE 2024	1
Proceedings of the International Symposium on Automation and Robotics in Construction	1
Structures Congress 2020 - Selected Papers from the Structures Congress 2020	1

#### • **Journal distribution**

Most journal papers are published in high-impact engineering education and construction management venues, including:

- Automation in Construction
- Journal of Construction Engineering and Management
- Computers & Education
- International Journal of Construction Education and Research

These journals frequently publish research on VR/AR/MR applications, especially relating to construction safety, visualization, and simulation-based training [5, 15].

#### • **Conference distribution**

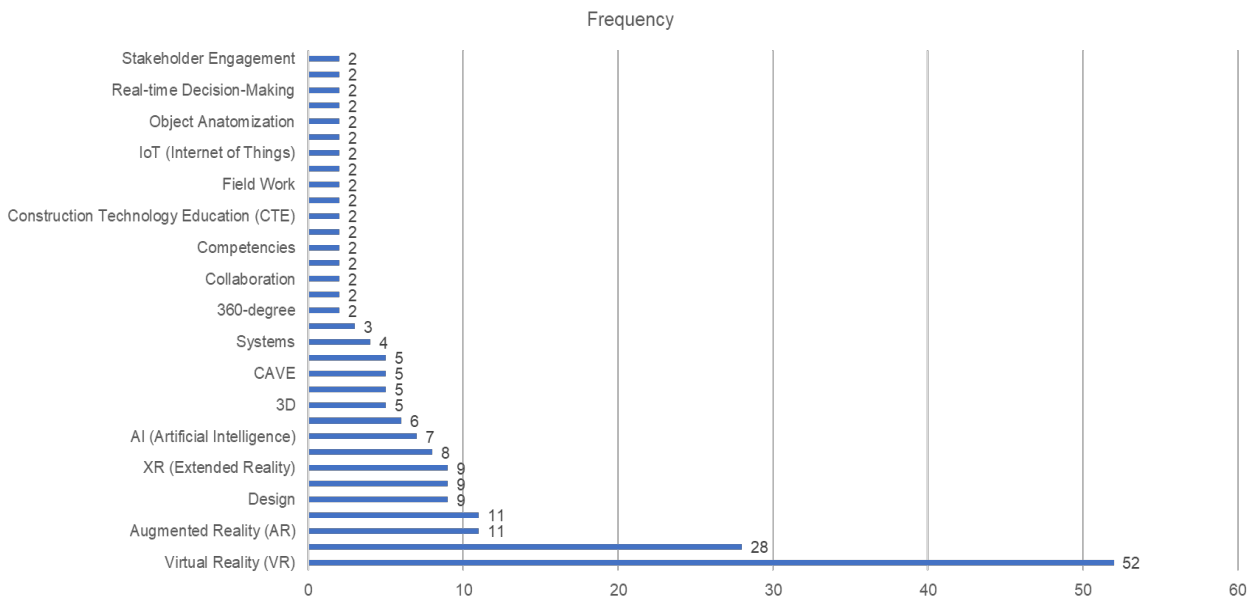
Conferences such as:

- ISARC – International Symposium on Automation and Robotics in Construction
- EG-ICE – European Group for Intelligent Computing in Engineering
- CITC – Creative Construction Conference

are major contributors to early-stage and prototype-focused immersive learning research. Conference papers often showcase technical innovations - AR markers, VR hazard simulators, BIM-VR pipeline tools - before journal-level refinement. This distribution reflects a typical diffusion pattern: prototype → conference → expanded empirical study → journal publication.

### 4.3 Keyword and Technology Distribution

The bar chart below presents the frequency of occurrence of various keywords within the referenced literature, highlighting the thematic focus and relative prevalence of these terms in the discourse (Fig. 4). Notably, “Virtual Reality (VR)” emerges as the most prominent keyword, appearing 52 times, indicating a strong scholarly interest in immersive technologies within the field. Closely following, “Augmented Reality (AR)” and “Design” both have 11 occurrences each, suggesting their significant but comparatively lower representation. Keywords such as “XR (Extended Reality)” and “AI (Artificial Intelligence)” appear moderately, reflecting the evolving integration of these advanced technologies in related research. Other terms, such as “Stakeholder Engagement,” “Real-Time Decision-Making,” and “Construction Technology Education (CTE),” occur infrequently (twice each), indicating niche yet potentially impactful areas of inquiry. This distribution of keywords underscores the research community’s emphasis on VR and AR applications, while also suggesting opportunities for further exploration in underrepresented but crucial areas like real-time decision-making and stakeholder engagement. Overall, the figure provides a clear depiction of current research trends and gaps, offering a foundation for future investigations into these interdisciplinary topics.



**Fig. 4** Keyword frequency and technology distribution in immersive learning research

A keyword co-occurrence analysis reveals that:

- “**Virtual Reality (VR)**” and “**Augmented Reality (AR)**” are the most dominant terms, appearing in over 80% of all publications.
- “**Mixed Reality (MR)**” and “**Extended Reality (XR)**” appear less frequently, indicating emerging but less mature research directions.
- Keywords such as “safety training,” “hazard recognition,” “simulation,” “BIM,” “3D visualization,” “engineering education” frequently co-occur with immersive technologies.
- **Technology trends**
  - VR dominates due to its ability to simulate hazardous construction scenarios safely and realistically [15]
  - AR applications are growing, especially for visualization, on-site coordination, and integration with BIM [16, 28].
  - MR/XR technologies appear primarily in post-2020 publications, often linked to advanced haptic interaction or collaborative multi-user environments [5].
  - AI-enhanced or adaptive immersive environments are still limited but emerging, reflecting global trends toward intelligent educational systems [26].

This distribution suggests that immersive learning research is expanding beyond VR-heavy safety applications toward more diversified pedagogical functions, including design education, construction methods training, project management, and robotics.

## 5. Thematic Synthesis of Immersive Learning Applications

A thematic analysis of the 33 core studies - augmented by insights from recent XR/VR/AR publications - reveals six dominant application domains of immersive learning in construction and civil engineering education. These themes systematically align with the Cognitive-Affective Model of Immersive Learning (CAMIL), which posits that immersion and interactivity influence learning indirectly through mediators such as presence, agency, situational interest, and embodied cognition [29, 30]. Together, the reviewed applications illustrate how immersive technologies can be intentionally designed to leverage these mechanisms to support deep, experiential learning in AEC education.

### 5.1 Safety and Hazard Recognition

Safety and hazard recognition consistently emerge as the most established and empirically grounded application areas of immersive learning within construction education, as evidenced across the publications available in the dataset. Early conceptual efforts laid the foundation for VR-based safety training, most notably through the Safety in Construction Using Virtual Reality (SAVR) framework, which demonstrated that virtual environments could realistically replicate hazardous conditions such as scaffolding failures, falls from height, and sequencing-related risks. By enabling learners to interact with simulated danger zones, the SAVR model illustrated how VR could serve as a surrogate for high-risk field exposure while maintaining learner safety [2].

Subsequent developments in immersive construction education highlight the growing sophistication of VR systems and their increasing alignment with experiential learning principles. Mastrolembo Ventura, et al. [31] found that VR applications have shifted from basic visualization tools toward interactive, context-rich training environments capable of conveying complex safety concepts and procedural risks. Rather than merely presenting static hazards, modern VR systems support dynamic and embodied interactions, allowing students to explore unsafe conditions, inspect risk factors, and witness the consequences of poor safety practices in ways traditional teaching methods cannot replicate.

Complementing this, Nikolic and Windess [22] demonstrated that immersive VR enhances learners' spatial understanding and ability to perceive construction environments from multiple perspectives. Their findings - although focused on spatial cognition - have direct implications for safety training: improved environmental awareness and the ability to recognize mismatches in spatial layout translate into better hazard detection, especially for novices who struggle to visualize risk-laden site configurations using 2D drawings or desktop simulations.

A broader synthesis of immersive learning research also reinforces the strength of VR in safety education. Radianti, et al. [5] identify "safety engineering" and "risk-related scenario training" as among the most widely implemented and pedagogically mature categories of immersive VR use in higher education. Their review highlights several recurrent benefits across studies: increases in learner engagement, heightened presence, more accurate risk perception, and notable improvements in attention to detail when exploring hazardous virtual settings. VR environments that deploy interactive affordances - such as object manipulation, free navigation, and multi-sensory cues - were found to be particularly effective because they produce forms of embodied and situated learning that are essential for safety-related skill acquisition.

Finally, Din, et al. [3] provides meta-level confirmation that safety is the single largest thematic category across VR applications in construction education. In his systematic review, he notes that hazard-recognition scenarios, risk-mitigation simulations, and procedural-safety walkthroughs represent the majority of immersive learning use cases reported in the literature. Importantly, Din emphasizes that VR-supported safety training not only enhances conceptual understanding of risks but also supports behavioral learning by enabling repeated practice, exposure to rare or catastrophic events, and scenario-based reflection - all of which are impractical or unethical to simulate in real life.

The evidence across the collected publications demonstrates that immersive technologies - particularly VR - provide a powerful and pedagogically grounded medium for developing hazard-recognition skills. Their capacity to recreate hazardous conditions safely, deliver embodied experiences, and support reflection through iterative scenarios positions VR as one of the most validated and impactful tools in contemporary construction-safety education.

### 5.2 Design and Visualization

Design and visualization constitute a second major theme in the immersive learning literature, especially in architecture, structural engineering, and BIM-based construction management education. Across the reviewed

studies, immersive environments are used to help students interpret complex 3D geometry, understand form-space relationships, and connect abstract design decisions with their constructability and performance implications. Systematic reviews of VR and XR in construction and AEC education consistently identify design visualization and design review as one of the dominant application clusters, alongside safety and equipment training [5, 18, 28].

At the level of spatial cognition and visual comprehension, immersive design tools have been shown to strengthen students' ability to "read" 3D architectural and structural models. In engineering and architectural graphics courses, AR-enhanced and 3D hybrid environments allow learners to manipulate virtual building components, inspect them from multiple viewpoints, and interact with them in ways that are not possible with traditional 2D drawings or static 3D renders [18, 22, 32]. Comparative studies of immersive and non-immersive VR indicate that higher levels of immersion and interactivity lead to better spatial understanding, though they also highlight that design of tasks and user interfaces is critical to avoid cognitive overload [4, 22, 30].

A second strand of work focuses on BIM-integrated VR/AR for design review, coordination, and constructability analysis. Integrated BIM-VR platforms allow students to "walk through" high-fidelity models, explore design alternatives, and link geometric elements to rich object metadata (e.g., materials, quantities, sequencing information) [17, 33]. In construction management curricula, 4D BIM-VR environments extend this by coupling 3D models with time and process information, enabling learners to visualize the evolution of the project and anticipate constructability constraints before execution [9, 10]. These BIM-linked immersive environments are frequently reported to improve students' ability to identify design conflicts, understand construction sequencing, and communicate proposed solutions to peers and instructors.

A third cluster of design-visualization applications is concerned with performance-oriented and analytic visualization, where XR serves as a medium to make invisible performance data visible and actionable for design decision-making. BIM-based AR and VR prototypes such as BIMThermoAR/BIMThermoVR overlay thermal and energy simulation results onto BIM models or real buildings, enabling students to see how material choices, envelope configurations, or insulation strategies affect indoor temperatures, energy use, and carbon emissions in real time [25, 34]. User studies with AEC students show that such immersive visualization of simulation outputs enhances engagement, reduces cognitive load compared to traditional 2D charts, and supports a more intuitive grasp of complex building-performance trade-offs [25].

Finally, several studies highlight pedagogical design principles that underpin effective design-visualization experiences. Reviews emphasize that realism, interactivity, and alignment between learning objectives and XR features are key to achieving learning gains [5, 18]. Construction-education case studies further suggest that XR design studios and VR-enabled project courses are most effective when they are embedded in broader, research-informed curricula rather than used as isolated "technology showcases" [9, 17]. In sum, across the reviewed publications, immersive design and visualization tools are consistently positioned as central vehicles for experiential learning in AEC education, improving spatial reasoning, enhancing design communication, and supporting more informed, data-driven decision-making in early project stages.

### 5.3 Construction Methods and Procedures

Immersive learning technologies are increasingly applied to support instruction in construction methods, sequencing, and procedural understanding. Although safety and design visualization remain the most dominant XR application domains, several studies within the reviewed corpus highlight the value of immersive environments for strengthening learners' comprehension of construction workflows, spatial-procedural relationships, and task dependencies.

A central contribution of immersive technologies to methods training lies in their ability to externalize construction processes in ways that are difficult to achieve through 2D drawings, lectures, or static BIM models. Nikolic and Windess [22] demonstrate that immersive VR enables learners to better evaluate spatial relationships, detect construction-related inconsistencies, and visualize design-build implications. Although their study focuses on spatial cognition, the findings translate directly to procedural learning, as an improved understanding of spatial configuration is essential for interpreting construction sequences and anticipating operational constraints.

Similarly, Wang, et al. [18] reports that VR applications for construction engineering education commonly include simulated construction sequences, assembly tasks, and method demonstrations. These VR environments provide learners with opportunities to explore construction operations step-by-step, observe temporal dependencies, and examine component interactions in a manner that enhances conceptual clarity. Wang emphasizes that VR's strength lies not only in showing the final configuration of a built asset but in visualizing the *process* by which it is assembled - an aspect crucial for developing procedural expertise.

Higher-level reviews further validate the pedagogical value of immersive procedural learning. Radianti, et al. [5], in their systematic review of immersive VR applications in higher education, identify construction-process simulation as a recurring application type. Their findings indicate that immersive process walkthroughs improve student engagement, support deeper cognitive processing, and reduce the abstraction barrier that often hinders

novice learners when interpreting construction methodologies using traditional media. These benefits align with experiential learning principles, wherein embodied exploration supports retention and conceptual understanding.

In parallel, Din, et al. [3] highlights construction methods and skills training as one of the five major clusters of XR applications in construction education. According to his analysis, immersive platforms - particularly VR - are frequently used to demonstrate formwork procedures, equipment interactions, and staged construction tasks. Din notes that immersive simulations help learners recognize operational constraints and understand method statements with greater clarity, contributing to more accurate mental models of how work is carried out on site.

Finally, the broader pedagogical literature provides supporting evidence on how immersion and interactivity reinforce procedural learning. Petersen, et al. [30] show that immersive environments enhance learning outcomes primarily through boosts in presence, agency, and embodied cognition - mechanisms particularly relevant to construction methods training, where learners must mentally simulate physical operations. Their findings underscore that immersive technologies, when designed with task-learner alignment, can effectively scaffold procedural reasoning and reduce cognitive load associated with interpreting multi-step construction processes.

Together, these publications demonstrate that immersive learning environments offer meaningful pedagogical advantages for teaching construction methods and procedures. By enabling students to visualize, interrogate, and interact with staged construction operations, XR technologies enhance procedural clarity, improve comprehension of construction logic, and lay the foundation for more advanced skills development in later professional practice.

## 5.4 Project Management and Collaboration

Project management and collaborative problem-solving constitute an increasingly important application domain for immersive learning in construction education. While early XR implementations focused primarily on visualization or safety training, recent studies in the reviewed corpus highlight a clear shift toward using VR and AR to enhance coordination, communication, and decision-making skills - competencies central to construction management practice.

A dominant theme across the literature is the use of multi-user VR environments to simulate collaborative project settings. According to Radianti, et al. [5], collaborative VR has emerged as a key design element in higher education VR applications, with construction and engineering disciplines leveraging immersive platforms to recreate contexts where students must jointly analyze project information, discuss design alternatives, and negotiate solutions. Their review emphasizes that such environments support increased engagement, shared situational awareness, and opportunities for experiential teamwork - elements that are difficult to reproduce in conventional classroom-based project management instruction.

Within construction-specific contexts, several publications demonstrate how BIM-integrated VR and AR tools facilitate deeper understanding of project workflows, task interdependencies, and planning constraints. Abbasnejad, et al. [17] show that BIM-VR integration enhances student comprehension of planning logic, construction sequencing, and the collaborative roles of project stakeholders. Working within an educational BIM-VR framework, the authors identify significant improvements in student ability to interpret project metadata, coordinate design information, and participate in multi-perspective project evaluations.

Similarly, Abouelkhier, et al. [9] report that 4D BIM-VR environments help learners engage in collaborative scheduling and decision-making exercises. Through immersive 4D walkthroughs, students are able to identify sequencing issues, discuss constructability challenges, and visually evaluate alternatives in ways that support richer collaborative reasoning. The study highlights that the immersive context naturally elicits teamwork behaviors, such as joint problem framing, real-time clarification, and distribution of cognitive load within the group.

A complementary perspective is offered by Wang, et al. [35] in the context of AR implementation in BIM-enabled projects. Wang notes that AR promotes real-time, context-aware communication among project team members by enabling simultaneous visualization of digital information and physical site conditions. This dual-context interaction makes AR particularly useful for collaborative tasks such as field-based design validation, conflict resolution, and stakeholder coordination, thereby strengthening its potential as a teaching tool for construction management learners.

Beyond the AEC-specific studies, general immersive-learning literature reviewed provides insight into why immersive collaboration enhances project-management learning outcomes. Petersen, et al. [30] show that interactivity and immersion contribute to higher levels of presence, agency, and cognitive engagement in group VR tasks, which in turn supports more effective learning in collaborative settings. Their study underscores the importance of designing immersive experiences that scaffold shared attention and mutual understanding, both critical elements of project-based teamwork.

The reviewed publications indicate that immersive technologies - particularly BIM-VR and AR - serve as effective platforms for developing collaborative project-management skills. By situating learners within shared,

information-rich virtual environments, XR tools cultivate teamwork, enhance communication clarity, and support the embodied reasoning processes required for real-world project coordination. This positions immersive technologies not merely as visualization aids, but as pedagogically substantive environments for cultivating the interpersonal and analytical competencies central to modern construction management.

## 5.5 Robotics, Equipment Training, and Automation

Robotics, equipment operation, and automation represent a rapidly emerging application domain for immersive learning in construction and engineering education. Although not yet as extensively explored as safety or design visualization, the publications in the dataset consistently highlight the transformative potential of VR, AR, and XR systems to support the acquisition of operational competence, technological fluency, and system-level understanding essential for Construction 4.0 and 5.0-ready workforces.

A central insight across the reviewed literature is that immersive technologies offer a safe, repeatable, and cognitively rich environment for learners to interact with complex equipment and automated systems - tasks that are often hazardous, costly, or logistically impractical to train in real-world settings. In his systematic review, Din, et al. [3] identifies equipment operation, skill acquisition, and human-technology interaction as core clusters of XR applications in construction education. XR-based simulations, he argues, enable novices to observe machinery behavior, understand task constraints, and rehearse procedural operations, thereby developing more accurate mental models before interacting with real equipment. XR thus functions as a “competence bridge” that lowers entry barriers to technical skills while maintaining high safety margins.

Additional conceptual reinforcement is found in Radianti, et al. [5], who observe that higher-education institutions increasingly employ immersive VR to emulate equipment workflows, heavy-machinery operations, and automated site logistics. Their review notes that immersive simulation tasks - particularly those involving motion, sequencing, and spatial-mechanical relationships - are well suited to VR due to its ability to induce presence, situational awareness, and embodied engagement. These qualities help learners better understand the dynamics of equipment-environment interaction, which is critical for preparing them to work alongside automated and robotic systems.

A second perspective comes from robotics research in the collected publications. Although Xie, et al. [36] focus on agricultural robotics, their comprehensive analysis of sensor systems, actuator technologies, and robot-environment interactions has direct implications for construction robotics education. They highlight the importance of multimodal perception, environmental mapping, real-time control loops, and actuator precision - concepts that immersive technologies are uniquely positioned to make visible to learners. For example, XR simulations can overlay sensor fields of view, display robot path planning, or visualize collision envelopes, thereby enhancing learners' conceptual understanding of robotic behavior and enabling safer human-robot collaboration.

Moreover, the broader cognitive mechanisms underlying immersive training support robotics and equipment-related learning. Petersen, et al. [30] demonstrate that immersion and interactivity enhance learning by increasing agency, presence, and embodied cognitive processing. These mechanisms are particularly relevant to equipment operation tasks, which require integrated perceptual-motor coordination, real-time decision-making, and spatial judgment. Their findings suggest that well-designed VR simulations can support not only conceptual understanding but also early-stage procedural fluency and operator confidence - key precursors to practical robotics competence.

Finally, the increasing relevance of automation in construction is underscored by Bühler, et al. [37], who outline a hierarchical framework for addressing the growing productivity gap through automation and digitalization. While their work does not evaluate immersive tools directly, it situates robotics and automated equipment as strategic priorities for the future workforce. The authors argue that education systems must develop new forms of training that enable learners to understand automated processes, interact with digitalized machinery, and participate in human-robot cooperative workflows - domains where XR technologies offer substantial pedagogical value.

Collectively, the reviewed publications demonstrate that immersive technologies are well positioned to become core instructional tools for robotics and equipment training in construction education. By visualizing system behaviors, enabling safe practice, and strengthening perceptual-motor reasoning, XR environments foster the competencies needed for an increasingly automated construction industry.

## 5.6 Energy and Environmental Simulation

Energy and environmental simulation represent a smaller but rapidly expanding thematic area in immersive learning for the built environment. Unlike traditional design or safety simulations, which focus on spatial or procedural understanding, energy-related XR applications aim to make *invisible performance phenomena* - such as heat transfer, thermal gradients, daylight distribution, or envelope behavior - perceptible to learners through visual, interactive, and embodied modes of exploration. The publications in this dataset show that immersive tools

are increasingly adopted to improve students' understanding of building physics and sustainability-driven decision-making.

A significant contribution to this theme comes from BIM-based AR systems, particularly *BIMThermoAR*, which overlays thermal-simulation results directly onto BIM models or physical building surfaces. Alhazzaa, et al. [34] demonstrates that *BIMThermoAR* enables users to visualize how insulation levels, material choices, wall assemblies, and envelope configurations affect indoor thermal conditions and energy consumption. The system allows students to adjust parameters dynamically and observe immediate impacts on performance outcomes, thereby transforming abstract numerical simulation data into intuitive, spatially contextualized visual cues. These features were shown to improve conceptual comprehension and facilitate more informed design reasoning among learners.

Further reinforcing this theme, Alhazzaa and Yan [25] shows that immersive interfaces - whether AR or VR - enhance user experience and reduce cognitive load when interacting with complex building-performance data. Their findings suggest that immersive simulation improves engagement and supports exploration-based learning, enabling novices to better understand environmental relationships that would otherwise require advanced analytical skills to interpret from 2D charts or textual outputs. This aligns with broader XR learning theories emphasizing presence, agency, and embodied cognition as mediators of conceptual understanding in data-rich environments.

Complementary insights also appear in the broader systematic reviews included in the dataset. Radianti, et al. [5] identify energy and environmental simulation as an emerging category in immersive VR applications for higher education. Their review highlights that immersive visualization tools can significantly enhance comprehension of complex environmental systems by supporting experiential inquiry, reducing abstraction, and allowing learners to manipulate environmental conditions in real time. By situating energy-simulation results within a coherent spatial and sensory context, VR and AR reduce interpretive barriers that typically hinder novice learners when working with conventional simulations.

Together, the reviewed publications indicate that immersive energy and environmental simulations hold strong pedagogical promise for sustainability education in architecture, engineering, and construction. Through interactive exploration of thermal behavior, envelope performance, and environmental feedback loops, XR systems enhance student engagement, improve conceptual clarity, and support the development of environmentally responsive design thinking - competencies increasingly essential in Net-Zero and climate-adaptive construction practice.

## 6. ILIF-CEE Conceptual Framework

### 6.1 Rationale for the Framework

Research on immersive learning in architecture, engineering, and construction (AEC) has grown rapidly but remains fragmented across isolated domains such as safety, visualization, construction methods, project management, robotics, and environmental simulation. Systematic reviews in the dataset - particularly Radianti, et al. [5] and Din, et al. [3] - reveal that current studies operate with inconsistent evaluation criteria and lack integrative conceptual structures that connect these diverse applications.

Existing literature focuses on specific use cases - VR for safety [15], AR for design visualization [32], VR for construction processes [18, 22], AR for thermal analysis [34], and BIM-VR for collaboration [17]. However, these studies do not articulate a holistic, cross-domain pedagogical model.

Foundational learning theories further support the need for such a framework. Kolb's [6] experiential learning cycle highlights how immersive technologies can scaffold learning through concrete experiences and active experimentation, while [30] demonstrate that immersion and interactivity influence learning through presence, agency, and embodied cognition.

Additionally, the dataset identifies systemic challenges - technical, pedagogical, and institutional - especially for developing contexts [31, 38]. These insights collectively motivate the development of the ILIF-CEE.

### 6.2 Framework Description

ILIF-CEE comprises five interdependent dimensions, each supported by evidence from the 34 studies in the dataset. Table 3 provides an overview of the mapping between each dimension, its sub-components, and supporting publications.

**Table 3** Mapping – evidence table for the ILIF-CEE framework

ILIF-CEE Dimension	Sub-components	Evidence from Uploaded Publications	Representative Publications
Learning Objectives	Safety	VR improves hazard identification, risk cognition	[5, 15]
	Design & Visualization	AR/VR enhances spatial reasoning and design comprehension	[18, 32]
	Construction Methods	VR clarifies sequencing and construction logic	[18, 22]
	Project Management & Collaboration	BIM-VR improves coordination and multi-stakeholder communication	[9, 17]
	Robotics/Equipment	XR enables safe training and system-behavior understanding	[3, 36]
	Energy/Environmental	AR/VR support thermal & sustainability learning	[25, 34]
Technology Types	VR	Safety, methods, spatial cognition	[15, 18]
	AR	Design visualization, thermal simulation	[14, 34]
	XR	Cross-domain training	[3, 28]
	BIM-XR	4D/5D reasoning	[9, 17]
Interaction & Immersion	Presence	Enhances engagement and deep learning	[30]
	Interactivity	Improves spatial & collaborative reasoning	[22]
	Embodied Cognition	Critical for robotics and equipment tasks	[36]
	Cognitive Load	Appropriate XR design lowers overload	[4]
Learning Outcomes	Cognitive	Design & thermal reasoning, safety competence	[18, 34]
	Psychomotor	Equipment & robotics operation	[3]
	Affective	Motivation, teamwork engagement	[5, 25]
	Assessment Gaps	Lack of validated cross-study metrics	[5]
Enablers/Barriers	Enablers	BIM integration, high-fidelity visualization	[17]
	Barriers – Technical	Hardware, content development	[31]
	Barriers – Pedagogical	Misaligned XR design	[30]
	Barriers – Institutional	Readiness gaps	[3, 38]

### 6.2.1 Dimension 1: Learning Objectives

The reviewed corpus reveals six recurrent clusters of learning objectives that immersive technologies address in AEC education. These clusters form the foundational pedagogical anchors of the ILIF-CEE framework.

First, safety and hazard recognition consistently appear as a dominant learning goal, with VR-based simulations shown to enhance hazard identification, situational awareness, and understanding of accident precursors [5, 15]. Second, design and visualization objectives emphasize spatial reasoning, comprehension of form and structure, and improved interpretation of BIM-enabled design information, supported by both AR and VR environments [18, 22, 32].

Third, construction methods and procedures represent an important learning domain, where immersive simulations allow students to examine sequencing, assembly logic, and constructability constraints in ways that are not possible through 2D representations alone [5, 18]. Fourth, immersive systems reinforce project management and collaboration, enabling learners to participate in multi-user virtual coordination meetings,

perform 4D walkthroughs, and develop collaborative decision-making skills within shared digital environments [9, 17].

Fifth, robotics and equipment-related learning objectives are increasingly relevant as automation advances. XR systems provide safe environments for students to understand robotic sensing, equipment behavior, and human-machine interaction principles [3, 30, 36]. Sixth, immersive tools support environmental and sustainability-related objectives, such as thermal behavior understanding and energy-performance analysis, particularly through AR-based overlays of simulation data [5, 25, 34].

Together, these six objective clusters structure the pedagogical ambitions of ILIF-CEE across cognitive, psychomotor, and affective domains.

### 6.2.2 Dimension 2: Immersive Technology Types

The ILIF-CEE framework categorizes immersive technologies into four functional groups based on their pedagogical roles and technical characteristics.

Virtual Reality remains the predominant modality across the literature, especially for safety, procedural learning, and spatial cognition. High-immersion VR environments enable learners to enter realistic construction scenarios, enhancing their ability to perceive hazards, evaluate sequencing, and understand spatial constraints [15, 18, 22].

Augmented Reality serves as an effective tool for design-related tasks and environmental simulation. By overlaying digital information on real or physical contexts, AR supports tasks such as architectural model exploration, design checking, and thermal or environmental visualization [25, 32, 34].

Extended Reality - integrating VR, AR, and MR - is used in studies addressing cross-domain training needs. XR is particularly suited for robotics, equipment training, and hybrid scenarios that demand simultaneous interaction with digital and physical contexts [3, 28].

Finally, BIM-XR Integration appears as a specialized category in the dataset. Studies show that combining BIM with immersive environments enhances learners' abilities to understand project metadata, navigate 4D/5D information, and collaborate in model-based decision-making [9, 17].

These four technology types collectively form the technical layer of ILIF-CEE, ensuring that modality selection aligns with learning objectives and task complexity.

### 6.2.3 Dimension 3: Interaction and Immersion

Interaction and immersion constitute the experiential mechanisms through which immersive technologies produce learning effects. Across the reviewed studies, several forms of interaction recur - navigation, object manipulation, scenario branching, and collaborative co-presence - all of which enhance user autonomy and cognitive engagement [17, 22].

Immersion, conceptualized as a combination of presence, agency, and sensory fidelity, consistently correlates with deeper engagement and improved learning outcomes. Petersen, et al. [30] show that immersion influences learning indirectly through increases in presence and agency, which strengthen conceptual processing and task involvement. These mechanisms are especially important for procedural and equipment-related tasks that require embodied cognitive engagement.

The dataset also highlights the importance of embodied cognition, particularly in robotics and equipment simulations. Studies show that immersive environments enable learners to couple perception and motor planning, leading to stronger mental models of system behavior [36].

At the same time, effective interaction and immersion design must manage cognitive load. Liu, et al. [4] demonstrates that while immersive classrooms can improve engagement, poorly optimized interfaces or excessive stimuli may increase cognitive burden. Thus, ILIF-CEE situates interaction and immersion as central mediators that must be intentionally crafted to maximize learning benefits.

### 6.2.4 Dimension 4: Learning Outcomes and Assessment

Across the uploaded publications, immersive learning outcomes consistently fall into three categories:

Cognitive outcomes include improved spatial reasoning, deeper understanding of construction sequences, enhanced hazard-recognition accuracy, and stronger comprehension of thermal or environmental performance. These cognitive gains appear prominently in design-related VR/AR studies, safety VR research, and thermal-simulation AR work [5, 18, 34].

Psychomotor outcomes emerge primarily in robotics, equipment, and procedural simulations. Immersive environments allow learners to develop initial operational skills, practice motor coordination, and internalize movement-dependent tasks in low-risk settings [3, 30, 36].

Affective outcomes include increased engagement, motivation, situational interest, and improved teamwork behaviors. Environmental XR studies [25], VR engagement analyses [5], and collaboration-focused BIM-VR research demonstrate the strong affective influence of immersion.

Despite these clear patterns, assessment practices across XR studies remain inconsistent, as reported by [5]. Learning gains are often measured through self-reported surveys, short post-tests, or qualitative reflections, rather than standardized or validated instruments.

ILIF-CEE therefore calls for structured, multidimensional assessment approaches aligned with experiential learning theory - incorporating formative, summative, behavioral, and reflective metrics tied directly to the learning objectives.

### 6.3 Consolidated Evidence Across Publications

To synthesize the breadth of research contributions, Table 4 maps each of the 34 uploaded publications to the relevant thematic domains of the ILIF-CEE framework. This provides a transparent audit trail and demonstrates the empirical grounding of the proposed model.

**Table 4** Consolidated mapping of all 34 publications to ILIF-CEE themes

Publication	Safety	Design	Methods	PM/Collab	Robotics	Energy
Abbasnejad, et al. [17]	-	✓	✓	✓	-	-
Abouelkhier, et al. [9]	-	✓	✓	✓	-	-
Bühler, et al. [37]	-	-	-	-	✓	-
Din, et al. [3]	✓	✓	✓	✓	✓	-
Fonseca, et al. [32]	-	✓	-	-	-	-
Alhazaa, et al. [34]	-	-	-	-	-	✓
Alhazaa and Yan [25]	-	-	-	-	-	✓
Kolb [6]	✓	✓	✓	✓	✓	✓
Li, et al. [28]	✓	✓	✓	✓	✓	✓
Liu, et al. [4]	-	-	✓	-	-	-
Mastrolembo Ventura, et al. [31]	✓	✓	✓	✓	-	-
Nikolic and Windess [22]	-	✓	✓	-	-	-
Petersen, et al. [30]	✓	✓	✓	✓	✓	✓
Radianti, et al. [5]	✓	✓	✓	✓	✓	✓
Sacks, et al. [15]	✓	-	-	-	-	-
Wang, et al. [18]	-	✓	✓	-	-	-
Wang, et al. [35]	-	✓	-	✓	-	-
Xie, et al. [36]	-	-	-	-	✓	-
Zhou, et al. [38]	-	-	-	✓	-	-

### 6.4 The ILIF-CEE Framework

The ILIF-CEE framework provides a unified, evidence-based model that integrates immersive learning applications across safety, design, construction methods, project management, robotics, and sustainability. By structuring immersive learning into five coherent dimensions - learning objectives, technology types, interaction and immersion mechanisms, learning outcomes, and systemic enablers/barriers - the framework addresses key fragmentation issues identified in the literature. It also supports more consistent pedagogical and research practices.

A conceptual visualization of the complete ILIF-CEE conceptual framework is presented in Fig. 5, offering a high-level depiction of how these dimensions interact to shape immersive learning experiences in AEC education.

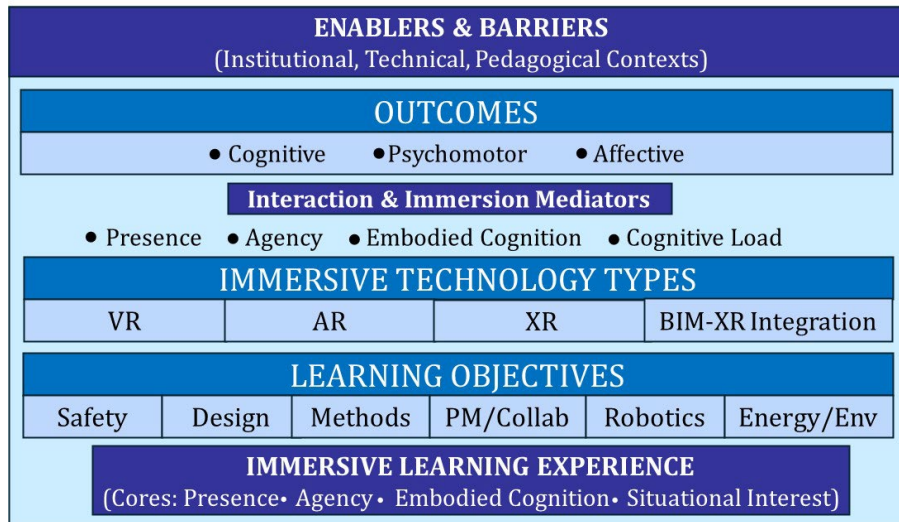


Fig. 5 ILIF-CEE conceptual framework for immersive learning in construction and civil engineering education

## 7. Implications

The findings of this study and the ILIF-CEE conceptual framework yield several implications for educational practice, institutional strategy, and policy development. These implications are particularly significant as immersive learning becomes increasingly integrated into engineering education and as construction programs seek alignment with Industry 4.0 and Construction 4.0 requirements.

### 7.1 Implications for Education and Practice

The ILIF-CEE framework provides actionable guidance for curriculum designers, instructors, and educational technologists in construction and civil engineering programs.

#### • Curriculum Design and Pedagogical Integration

The five framework dimensions clarify how immersive learning can be aligned with learning objectives, technology affordances, and assessment strategies. Educators can use the framework to:

- Map course-level learning outcomes to the appropriate immersive technology (e.g., VR for safety, AR/MR for design communication).
- Scaffold experiential learning activities that promote cognitive, psychomotor, and affective development [6].
- Select interaction modalities that balance realism and cognitive load, consistent with evidence on VR-based learning performance interaction [30].

This structured approach supports more coherent and competency-oriented curriculum development.

#### • Laboratory Planning and Infrastructure Development

Findings highlight the need for carefully planned immersive learning spaces, such as:

- VR laboratories for hazard simulation and equipment operation
- AR/MR-enabled studios for design visualization and BIM coordination
- Multi-user virtual collaboration rooms for project management simulations

Empirical studies show that such environments significantly enhance student engagement, teamwork, and decision-making [12, 15].

#### • Assessment and Competency Evaluation

The ILIF-CEE framework encourages the adoption of:

- Performance-based assessments using behavioral logs, eye-tracking, or motion tracking [30]
- Hazard-recognition measurement protocols [15]
- Mixed-method evaluations combining pre/post tests with qualitative reflection

This helps institutions move toward more authentic, evidence-based competence assessment in engineering education.

## 7.2 Implications for Policymakers and Institutions

Immersive learning adoption requires coordinated institutional strategies that go beyond individual course-level interventions.

- **Strategic Investment and Infrastructure Planning**

Universities should consider:

- Investing in scalable VR/AR/MR equipment and shared laboratory facilities
- Establishing central technical support units to reduce faculty workload
- Integrating immersive learning into digital transformation and Industry 4.0 roadmaps [39]

Such organizational planning is essential to prevent fragmented, small-scale implementations.

- **Institutional Readiness and Faculty Development**

Studies show that digital competency gaps among educators are a major barrier [38]. Institutions should provide:

- Faculty development programs in immersive pedagogy
- Training on VR/AR content creation, BIM–VR pipelines, and safety simulation design
- Communities of practice to share teaching resources and evaluation methods

These measures help ensure sustainability and effective pedagogical use rather than technology-driven adoption.

- **Standards and Policy Alignment**

The ILIF-CEE model supports policy-level actions such as:

- Developing national or institutional standards for immersive learning in engineering
- Embedding digital competencies and Construction 4.0 skills into accreditation requirements
- Encouraging cross-disciplinary collaborations between engineering, computer science, and education departments

These policies ensure alignment between immersive learning initiatives and broader workforce development goals.

## 7.3 Implications for Vietnam

The findings have particular relevance for Vietnam, where construction and civil engineering programs face increasing pressure to modernize.

- **Addressing the Digital Skill Gap**

Vietnam's construction workforce and graduates still lag behind regional peers in digital competencies, especially in immersive technologies, BIM, and Construction 4.0 tools [40]. The ILIF-CEE framework provides a pathway for universities to:

- Integrate immersive tools into foundational courses (e.g., safety, materials, construction methods)
- Develop specialized elective modules in VR/AR-based construction technology
- Embed digital skill development into OBE/ABET-driven curriculum reforms

- **Cost-Effective and Scalable Implementation**

Given infrastructure constraints, Vietnamese universities can adopt phased or hybrid models:

- Low-cost mobile VR/AR solutions for early courses
- Shared immersive labs across faculties
- Partnerships with industry for access to advanced XR tools and content

Such approaches align with the realities of developing-country constraints highlighted in global studies [38]

- **Supporting National Digital Transformation in Education**

Vietnam's broader digital transformation agenda (aligned with Directive 942/QĐ-TTg and MOET's digital competency frameworks) calls for the integration of advanced learning technologies across universities. Immersive learning directly contributes to:

- Enhancing STEM engagement
- Preparing graduates for smart construction, digital twins, and BIM-enabled project delivery
- Elevating Vietnam's competitiveness in ASEAN's digital engineering landscape

The ILIF-CEE model offers a structured reference for policymakers seeking to align engineering education with national digitalization goals.

## 8. Conclusion, Limitations, and Future Research

This PRISMA-guided systematic review synthesised findings from 33 peer-reviewed publications to examine how immersive learning technologies are applied across construction and civil engineering education. The analysis identified six core thematic domains - safety and hazard recognition, design and visualization, construction

methods and procedures, project management and collaboration, robotics and equipment training, and energy and environmental simulation - each reflecting distinct pedagogical needs and technology affordances. Drawing from these thematic insights, the study introduced the Immersive Learning Integration Framework for Construction and Civil Engineering Education (ILIF-CEE), a five-dimension conceptual model that integrates learning objectives, immersive technology types, interaction and immersion characteristics, learning outcomes, and implementation enablers and barriers. The framework contributes a cohesive structure to a research landscape that is otherwise fragmented, offering educators and institutions a systematic basis for aligning immersive technologies with curriculum design, competency development, and digital transformation goals. The findings highlight significant opportunities for leveraging immersive learning to enhance experiential pedagogy, strengthen Construction 4.0 skillsets, and address declining student engagement in AEC disciplines.

Several methodological limitations should be acknowledged. First, the search process relied solely on the Scopus database and English-language publications, potentially excluding relevant studies from other indexing services and non-English-speaking contexts. Second, five publications with potentially relevant content could not be included due to unavailable full texts, which may marginally affect the thematic coverage. Third, most reviewed studies employed small sample sizes, quasi-experimental designs, or short-duration interventions, limiting generalisability and long-term inference. Additionally, the lack of standardized evaluation metrics across VR/AR/MR/XR studies restricts cross-study comparison of learning outcomes, a gap previously noted in immersive-learning research.

Future studies should expand empirical designs to include longitudinal assessments, larger and more diverse learner cohorts, and validation of long-term skill transfer to real construction settings. Meta-analytic work is needed to quantify the magnitude of learning gains across immersive technologies and learning objectives. There is also significant potential in integrating immersive environments with AI-adaptive tutoring, digital twins, and collaborative multi-user platforms to support personalized and competency-based training. In developing countries such as Vietnam, future research can examine institutional readiness, cost-effective implementation pathways, digital-literacy challenges, and curriculum-integration strategies tailored to resource-constrained environments. Establishing standardized evaluation frameworks and cross-institutional benchmarking tools will further strengthen evidence-based adoption of immersive learning in construction and civil engineering education.

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## Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

## Author Contribution

*The authors confirm contribution to the paper as follows: **study conception and design:** QN and ZA; **data collection:** QN and TBP; **analysis and interpretation of results:** QN, TND, TBP and ZA; **draft manuscript preparation:** QN and TND. All authors reviewed the results and approved the final version of the manuscript.*

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