

Virtual Reality in Engineering Education: A Survey of Applications, Trends, and Challenges

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Abstract

The use of Virtual Reality (VR) in education is rapidly increasing due to the immersive and interactive environments it provides that support the nature of engineering learning experiences that can be difficult, hazardous, or resource-intensive. However, this rapid growth of VR-based educational systems has produced a fragmented literature. This paper presents a scoping review of 32 peer-reviewed studies published between 2012 and 2025 that examine the use of VR in engineering education contexts. Using a structured extraction and descriptive synthesis approach, the review analyzes trends across engineering domains, learning objectives, VR modalities, instructional roles, learner populations, and evaluation methods. The results reveal a strong emphasis on procedural learning objectives, including laboratory skill rehearsal, equipment operation, and safety-oriented training. Despite this focus on procedural tasks, evaluation practices are frequently limited to short-term, perception-based measures, highlighting a structural misalignment between learning objectives and assessment methods. Furthermore, VR is most often deployed as a supplementary instructional tool rather than as a fully integrated component of course design.

Introduction

Virtual reality (VR) has become increasingly popular in engineering education as a tool to support learning experiences that are difficult, dangerous, or resource-intensive to reproduce in real life. Advances in immersive hardware and technologies have allowed educators to explore and employ VR for laboratory instruction, safety training, equipment operation, and visualization of complex systems. As a result, a growing body of research has emerged in all disciplines of engineering, proposing VR-based solutions to address existing challenges in hands-on engineering education [1] [2] [3].

Despite this growth, the literature on VR in engineering education remains fragmented. Studies vary widely in instructional goals, system design, deployment context, and evaluation methodology. VR is alternately framed as an experiential learning tool, a procedural simulator, a visualization aid, or an interface to analytical systems such as digital twins and computational simulations. At the same time, the evidence reported on educational impact is often inconsistent and difficult to compare across studies, limiting the development of the body of knowledge and best practices. Several prior reviews have examined the use of VR in education more broadly [2] [3] [4] [5]. However, many focus on general educational contexts, specific technologies, or isolated domains, without closely examining how VR is pedagogically positioned and evaluated within engineering education. In particular, less attention has been paid to the alignment between learning

objectives, instructional integration, and assessment strategies, an issue that is especially important given the procedural and safety-oriented nature of many engineering tasks [1] [4] [6]. To address these gaps, this paper presents a scoping review of VR applications in engineering education. Rather than assessing effectiveness or comparing learning outcomes, the review aims to map how VR is currently used, what types of learning objectives it supports, how systems are evaluated, and how these dimensions interact across engineering domains.

This paper makes the following contributions:

1. Providing a cross-domain synthesis of VR applications in engineering education, highlighting trends in learning objectives, system modalities, learner populations, and evaluation practices.
2. Identifying a recurring misalignment between the procedural goals of many VR systems and the predominantly perception-based methods used to evaluate them.
3. Offering an interpretive framework that characterizes common design archetypes and suggests the presence of a pedagogical ceiling.

These insights aim to inform future research and guide more pedagogically grounded and evaluative approaches to VR in engineering education.

The remainder of this paper is organized as follows. Related work is reviewed in Section 2, the methodology is described in Section 3, results are presented in Section 4, key findings are discussed in Section 5, and conclusions are provided in Section 6.

Related Work Virtual Reality in Education

Research on virtual reality (VR) in education has expanded rapidly over the past decade, driven by advances in immersive hardware and increased interest in experiential and interactive learning environments. Several comprehensive reviews and surveys have examined VR across broad educational contexts, including K–12 instruction, higher education, and professional training. These works commonly emphasize immersion, presence, and learner engagement as key affordances of VR-based instruction, often reporting positive effects on motivation and perceived learning [1] [9].

Despite these reported benefits, prior reviews also highlight considerable variability in learning outcomes. While engagement and affective responses are frequently improved, evidence regarding knowledge acquisition, skill transfer, and long-term retention remains mixed [1] [10]. Evaluation approaches in this literature are highly heterogeneous, with many studies relying on self-reported measures such as perceived learning, satisfaction, or

presence, rather than objective performance metrics or longitudinal assessment.

Because these reviews combine findings across diverse domains and learner populations, they provide limited insight into domain-specific instructional requirements. In particular, the procedural, safety-critical, and resource-intensive nature of many engineering learning tasks is often underrepresented, requiring closer examination within engineering education.

Virtual Reality in Engineering Education

Within engineering education, VR has been applied to support laboratory instruction, equipment operation, safety training, and visualization of complex or inaccessible systems. Engineering-focused reviews document applications across disciplines such as civil, mechanical, electrical, and construction engineering, frequently highlighting VR's ability to simulate hazardous or resource-intensive environments [1] [2] [3].

Recent large-scale reviews and bibliometric analyses indicate substantial growth in VR research within engineering education, particularly since 2020, alongside increasing diversity in system design and application contexts [3]. However, these reviews also note that studies are commonly organized by discipline or technological features, such as immersion level, hardware type, or interaction modality, rather than by pedagogical role or instructional intent. Several authors have observed that, although many VR systems target procedural or skill-based learning objectives, their evaluation often relies on perception-based measures, short-term interventions, or small-sample laboratory studies [2] [4]. Meta-analytic evidence further suggests high heterogeneity across studies, making it difficult to draw generalizable conclusions about learning effectiveness, particularly for engineering-specific practical skills [5].

As a result, existing reviews provide limited guidance on how VR should be integrated into engineering curricula, how instructional objectives should shape system design, or how evaluation strategies should align with the procedural goals of engineering education.

Cross-Domain Perspectives on Immersive Learning Environments

Related challenges have been reported in other domains that employ immersive or experiential environments, including healthcare training, rehabilitation, and therapeutic design. Studies in these areas emphasize experiential qualities such as perceived safety, autonomy, comfort, and environmental control as important contributors to user engagement and satisfaction. However, links between these experiential factors and objective functional or performance outcomes are often indirect or inconsistently evaluated [8]. These cross-domain findings suggest that tensions between experiential design goals and outcome-focused evaluation may reflect broader characteristics of immersive systems rather than limitations unique to engineering education. In particular, they underscore the difficulty of translating rich experiential interactions into rigorous, comparable learning evidence, similar to challenges also observed in VR-based engineering education research.

Positioning of the Present Review

Building on this body of work, the present study adopts a scoping review approach to examine how VR is currently used in formal engineering education. Rather than assessing effectiveness or comparing learning gains, this review focuses on mapping patterns in learning objectives, instructional roles, system modalities, and evaluation practices across engineering domains. By synthesizing these dimensions, the study aims to clarify structural trends and identify misalignments that may constrain the pedagogical impact of VR in engineering education.

Methodology Review Design

This study adopts a scoping review methodology [3]. Scoping reviews are appropriate for emerging or heterogeneous research areas where the goal is to characterize patterns and identify gaps rather than to perform quantitative synthesis or meta-analysis. Accordingly, this review emphasizes breadth of coverage and descriptive analysis over exhaustive inclusion or effect-size estimation.

Search Strategy

An initial literature search was conducted across major academic databases commonly used in engineering and educational technology research, including IEEE Xplore, Web of Science, and Google Scholar. Search queries combined terms related to virtual reality (e.g., "virtual reality," "immersive VR," "HMD") with engineering education keywords. Because the term "engineering" is broad and often appears in unrelated domains (e.g., medical engineering, psychology in engineering departments), a single broad search string returned many irrelevant records. Therefore, the search strategy was structured into six domain-specific queries for distinct engineering subfields (i.e., civil, mechanical, electrical, manufacturing, mining, chemical engineering).

All searches were restricted to the title field using the operator intitle: to prioritize studies with a primary focus on VR in engineering education and to reduce retrieval of peripheral or tangential applications. Review articles, surveys, and systematic reviews were excluded by appending -review, -survey, and -"systematic review" to each query. Reference lists of relevant papers were also examined to identify additional studies.

The initial database search returned 679 records, which underwent title and abstract screening. Of these, 553 records were excluded due to lack of relevance to VR in engineering education or training. The remaining 126 articles were assessed for full-text eligibility, resulting in 94 exclusions, primarily because the VR systems were designed for industrial planning or system optimization without human learners or educational evaluation. This process yielded a final dataset of 32 studies.

Inclusion and Exclusion Criteria

Studies were included if they met the following criteria:

1. The study involved a virtual reality system used for instructional purposes.
2. The application context was engineering education, including undergraduate, graduate, or pre-professional learning environments.
3. The study was peer-reviewed and written in English.

4. The paper reported on system design, deployment, or evaluation in an educational context.

Studies were excluded if they:

- Focused exclusively on general workforce or industry-only training without an explicit educational framing,
- Addressed non-engineering domains (e.g., medical, military, or entertainment applications),
- Lacked sufficient methodological detail to support extraction of instructional or evaluation characteristics.

Data Extraction and Coding

Each included study was analyzed using a structured extraction checklist to ensure consistency across papers. Extracted fields included publication year, engineering domain, learning objective (procedural, conceptual/visualization, or collaborative), VR modality, interaction method, participant type, instructional role of VR, and evaluation approach. Learning objectives and instructional roles were coded based on the primary emphasis described by the authors. Evaluation methods were categorized into learning outcomes, performance-based metrics, and user experience measures.

Synthesis Approach

Extracted data were synthesized using descriptive aggregation and thematic grouping rather than statistical analysis. Results are presented through summary tables to highlight dominant patterns, while qualitative synthesis is used to contextualize observed gaps and limitations.

Results

Overview of Included Studies

32 peer-reviewed studies published between 2012 and 2025 were included in the final dataset, spanning a range of engineering domains including civil and construction engineering, mechanical and manufacturing engineering, electrical and power systems, chemical engineering, and mining. Table 1 summarizes the distribution of studies by engineering domain, primary learning objective, VR modality, and participant type.

Learning Objectives and Instructional Roles

Procedural learning objectives were the most common and included applications such as laboratory skill rehearsal, process execution, equipment operation, and safety-oriented training (Table 1). Some studies included conceptual and visualization-focused applications, particularly in studies addressing abstract processes or spatial understanding. Collaborative or multi-user VR was rarely treated as a primary instructional objective. Most studies employed VR as a practice or rehearsal environment to enable learners to repeatedly engage with procedures or scenarios. A smaller number of studies used VR as a pre-training or pre-laboratory preparation tool, while others used VR as an assessment or decision-support environment rather than as the sole instructional medium (Table 2).

Procedural VR Subtypes Across Engineering Domains

Table 3 shows variations observed in the type of instructional focus. Safety and hazard recognition were prominent in civil, con-

struction, and electrical engineering contexts, while equipment operation and process execution were more common in mechanical, manufacturing, and chemical engineering studies. Decision-making and management-oriented procedural VR appeared primarily in studies integrating VR with higher-level systems such as building information models or digital twins.

Learner Populations

The majority of included studies targeted undergraduate engineering students, with fewer studies involving graduate students, professional engineers, or domain experts. Studies involving professional or expert participants were mostly associated with procedural, safety-oriented, or decision-support applications. Mixed or public participant groups appeared infrequently and were generally limited to exploratory or framework-oriented studies.

Evaluation Practices and Rigor

Evaluation approaches varied widely across the reviewed studies (Table 4). Many studies relied on self-reported measures such as perceived learning, engagement, or usability. Knowledge-based assessments and task performance metrics were less consistently applied, and objective behavioral data or expert-based evaluations were relatively rare. Procedural and safety-focused applications were more likely to include performance-based or expert-driven evaluations than conceptual visualization studies.

Discussion

This review highlights many consistent patterns in the use of virtual reality in engineering education. VR has been most frequently applied to procedural learning objectives across engineering domains, such as laboratory skill rehearsal, process execution, equipment operation, and safety-oriented training. This emphasis is likely to show the alignment between immersive, interactive environments and the procedural nature of many engineering tasks, in which repeated practice, spatial understanding, and risk-free exploration are valuable. Our review also indicates that few studies position VR as a standalone instructional medium. Instead, VR is most commonly applied as a supplementary tool, such as a practice or rehearsal environment, a pre-laboratory preparation activity, or a decision-support interface. This suggests that VR is currently viewed as an enhancement to existing methods rather than a replacement for traditional instructional methods. This could potentially be due to pedagogical and institutional limitations rather than technological, and reflect challenges related to curriculum design, instructional alignment, and assessment strategies.

A prominent finding across the reviewed studies is the imbalance in evaluation practices. Although VR is often deployed for procedural and safety-critical tasks, where accuracy, reliability, and transfer are essential, evaluation practices are frequently limited to short-term, perception-based measures such as self-reported engagement or usability. Objective assessments of performance, skill acquisition, or transfer to real-world contexts are applied less consistently. This suggests that current evaluation approaches may not capture the educational effectiveness of VR.

Collectively, the reviewed studies cluster into distinct design paradigms, including experiential add-ons emphasizing engagement, procedural simulators supporting task rehearsal, and ana-

Table 1. Overview of virtual reality applications in engineering education included in the scoping review (n = 32), [11–42]

Dimension	Category	Count	Percentage
Learning Objective	Procedural (incl. safety)	22	~69%
	Conceptual / visualization	9	~28%
	Collaborative (primary)	1	~3%
VR Modality	Immersive HMD	21	~66%
	Desktop / Web-based VR	4	~13%
	Hybrid (HMD + desktop/web)	3	~9%
	Mobile VR	3	~9%
	CAVE	1	~3%
	Engineering Domain	Mechanical / manufacturing	9
	Civil / construction	8	~25%
	Chemical / bio	6	~19%
	Electrical / power	5	~16%
	Mining	2	~6%
	Other	2	~6%
Participant Type	Undergraduate students	19	~59%
	Graduate students	5	~16%
	Professionals / experts*	8	~25%
Evaluation Type	UX / self-report	18	~56%
	Learning outcomes (tests)	14	~44%
	Performance metrics	15	~47%

Table 2. Role of VR in the Engineering Learning Pipeline (n = 32)

Role of VR in Instruction	Description	Count	%
Pre-training / Pre-lab preparation	Familiarization with equipment, procedures, and hazards prior to real-world exposure	6	~19%
Practice & rehearsal environment	Repeated execution of procedures or safety-critical scenarios	13	~41%
Core instructional medium	Primary delivery mechanism for instructional content	4	~13%
Assessment / evaluation tool	Hazard identification, performance scoring, and expert-based evaluation	5	~16%
Decision-support / systems reasoning	Management, planning, sustainability analysis, and digital twin interaction	4	~13%

lytical interfaces integrating VR with computational or decision-support systems. These reflect fundamentally different assumptions about the educational role of VR, yet are rarely compared or evaluated using appropriate principles. These observations suggest that the current limitations of VR-based engineering education come from fragmentation in educational models and evaluation frameworks rather than hardware capabilities. Advances in instructional design and assessment have not occurred at the same pace as VR systems improves in technical terms and suggests further improvements in system fidelity alone are unlikely to yield proportional educational benefits without clearer alignment between learning objectives, instructional integration, and evaluation methodology.

Limitations and Scope Considerations

Several limitations should be considered when interpreting these findings. First, as a scoping review, this study prioritizes breadth over exhaustive coverage, and inclusion criteria were intentionally defined to focus on engineering education rather than general workforce training. Therefore, some VR applications involving professional practitioners or industry-only training contexts were excluded. Second, dissimilarity in study designs, evaluation metrics, and reporting practices limits direct comparison across studies. Finally, publication bias toward positive findings and short-term evaluations may over represent favorable outcomes associated with VR-based learning.

Implications and Future Directions

The findings of this review suggest several opportunities for future research. Greater emphasis on standardized, performance-based, and longitudinal evaluation methods would strengthen the evidence base for VR in engineering education. Additionally, deeper integration of VR into curricula, beyond stand-alone modules, may enable more meaningful assessment of its educational impact. Future work may also benefit from bridging educational and professional training literatures to better understand how insights from workforce-focused VR systems can inform formal engineering education. These directions will be explored further in an extended journal version of this work.

Conclusion

This paper presented a scoping review of virtual reality applications in formal engineering education, synthesizing evidence from 32 peer-reviewed studies published between 2012 and 2025. Rather than evaluating effectiveness or comparing learning outcomes, the review focused on identifying patterns in instructional objectives, system design, deployment context, and evaluation practices across engineering domains.

The synthesis revealed that VR in engineering education is most commonly positioned as a procedural or safety-oriented learning tool, particularly in laboratory preparation, equipment operation, and hazard recognition tasks. Evaluation practices

Table 3. Distribution of Procedural VR Subtypes Across Engineering Domains

Procedural VR Subtype	Civil / Construction	Mechanical / Manufacturing	Electrical / Power	Chemical / Bio	Other	Total
Safety & hazard recognition	4	2	3	1	1	11
Equipment / lab operation	1	4	2	2	0	9
Process execution	2	3	1	3	0	9
Decision-making & management	2	2	0	2	1	7
Compliance & organizational readiness	1	1	1	0	1	4

Table 4. Evaluation Levels and Metrics Used in VR-Based Instructional Studies

Evaluation Level	Description	Count	%
Self-report only	Perceived learning, engagement, and satisfaction	12	~38%
Knowledge pre/post testing	Conceptual or factual assessments	9	~28%
Task performance metrics	Accuracy, completion time, and hazard detection	11	~34%
Behavioral logs / telemetry	In-VR action tracking	4	~13%
Expert judgment	Structured expert evaluation	6	~19%
Multi-criteria decision methods	AHP or comparable formal decision-making frameworks	2	~6%

remain largely perception-based, with limited use of objective performance measures, longitudinal assessment, or evidence of transfer to real-world practice. This recurring misalignment between instructional goals and comparatively lightweight evaluation approaches represents a central challenge for the field. The findings suggest that continued advances in VR technology alone are unlikely to yield proportional educational impact unless accompanied by clearer pedagogical integration and more rigorous, outcome-aligned evaluation methods.

This review is subject to some limitations. The scope was intentionally constrained to formal engineering education and student-focused contexts, excluding workforce-only training and non-engineering applications. Additionally, as a scoping review, the study does not claim exhaustive coverage of all VR-based engineering education research. Future work may extend this analysis through a larger systematic review, domain-specific deep dives, or empirical studies that directly examine instructional alignment and learning transfer.

Overall, this work contributes a structured synthesis of current VR practices in engineering education and offers a foundation for more pedagogically grounded and evaluative research. By clarifying how VR is currently used, and where gaps persist, the review aims to support more intentional design, deployment, and assessment of immersive technologies in engineering learning environments.

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