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Simulation–adventure virtual worlds in the metaverse for engineering education and training: A domain-stratified narrative review

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Abstract: This study employs a narrative review methodology to analyze the integration of Virtual Worlds, specifically Simulation Worlds and Adventure Worlds, in engineering education, aiming to enhance conceptual understanding, technical competence, and 21st-century skills. The study synthesizes 23 peer-reviewed articles selected from the Scopus database using stringent inclusion criteria. Simulation-based learning models focus on procedural accuracy and conceptual mastery, while adventure-based models emphasize transversal skills like creativity, collaboration, and problem-solving. Hybrid models combining both approaches are identified as the most effective, fostering technical expertise and soft skills simultaneously. Despite challenges such as high infrastructure costs and potential cognitive overload, immersive virtual environments offer significant opportunities for scalable and adaptable remote learning. Thematic analysis is employed to synthesize findings and provide recommendations for future implementation. This review highlights the importance of integrating these technologies in engineering education and suggests exploring their long-term impact on engineering careers. Additionally, it underscores the need for further research on the application of immersive technologies across diverse engineering disciplines, focusing on overcoming existing challenges and maximizing their educational potential.

Keywords: metaverse; virtual worlds; engineering education; immersive learning; narrative review

1. Introduction

The landscape of engineering education is undergoing a profound transformation, driven by the accelerating integration of advanced digital technologies. These technologies fundamentally reshape how knowledge is delivered, applied, and internalized in academic settings (Azofeifa et al., 2024; Pacher et al., 2024; Roy & Roy, 2021). While traditional classroom-based pedagogies have long been adequate for imparting foundational technical skills, they are increasingly seen as insufficient to meet the rapidly evolving demands of the workforce, which is influenced by fast technological advancements, increasing interdisciplinarity, and growing complexity in modern engineering challenges (Huang et al., 2022; S. M. Lee & Wu, 2024; Zou et al., 2025). As such, there is an urgent need to evolve pedagogical approaches to better align with the dynamic, fast-paced demands of today's engineering environments. Innovative instructional paradigms are emerging in response to these challenges, emphasizing learner-centered, interactive, and experiential methods. One of the most promising of these innovations is the metaverse, a vast, immersive, and

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interconnected digital space that combines elements of virtual reality (VR), augmented reality (AR), artificial intelligence (AI), blockchain, and user-generated content (UGC), along with a strong focus on social interaction, interoperability, and 3D environments (Aiordachioae & Vatavu, 2024; Criollo-C et al., 2024; Muskhir et al., 2024; Samala et al., 2023). As illustrated in Figure 1, the metaverse serves as a rich, multidimensional environment, offering unprecedented opportunities for immersive learning experiences previously unattainable in traditional settings.

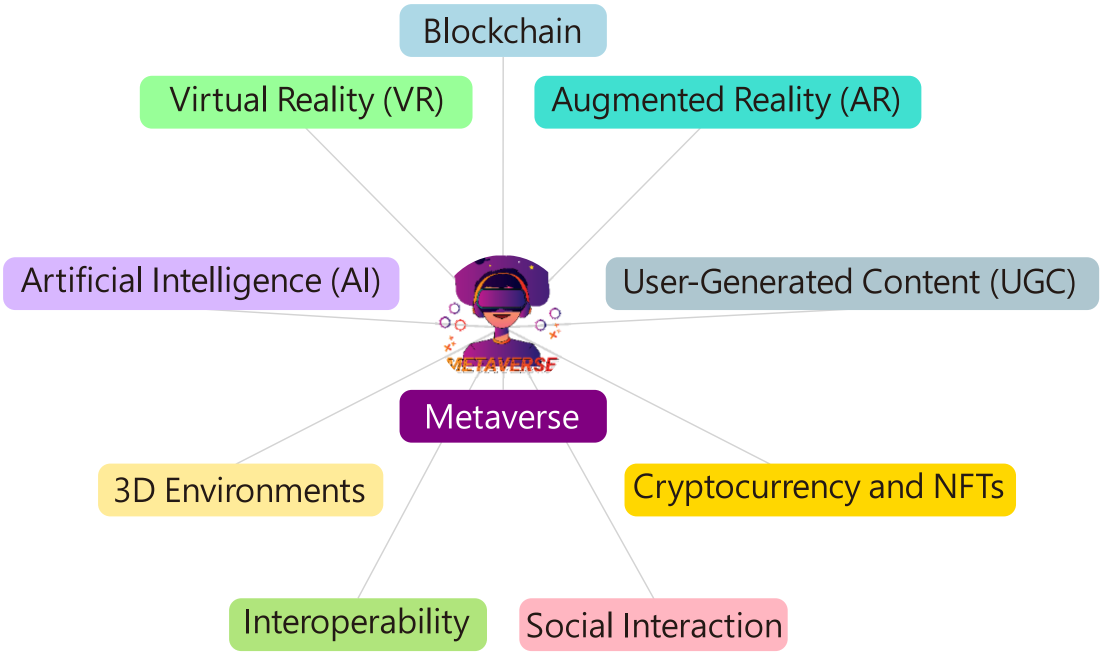

Figure 1. Components of the metaverse

Among the key components of the metaverse, the integration of Virtual Worlds stands out as a transformative approach to advancing engineering training (Chen et al., 2023; Yeganeh et al., 2025). These digitally simulated environments allow students to interact with virtual systems, tools, and peers in real-time, providing opportunities for engagement and collaboration that extend far beyond what is possible in conventional classrooms. Integrating Virtual Worlds, particularly Simulation Worlds and Adventure Worlds, holds significant potential in supporting immersive and contextualized engineering instruction (Filippone et al., 2025; Muzata et al., 2024; Negahban, 2024). These immersive environments allow students to engage in risk-free, real-world scenarios to develop technical expertise, apply engineering principles, engage in problem-solving activities, and practice critical decision-making skills (Chasokela, 2025; Reis et al., 2025). The interaction within these worlds can closely mimic real-world engineering challenges, effectively bridging the gap between theoretical knowledge and practical application.

Simulation Worlds and Adventure Worlds facilitate highly interactive, context-based learning by incorporating storytelling, simulated equipment operation, and scenario-based challenges (Jiménez-valverde, 2025; Loia et al., 2025). Through this interactive immersion, students gain a deeper understanding of engineering concepts, as they can visualize and experience real-life applications in a controlled yet dynamic environment. This hands-on approach significantly enriches the learning process by making abstract concepts tangible and fostering a more holistic understanding of technical systems (H. Y. Lee et al., 2024; May et al., 2023; Suarez et al., 2023). In addition to addressing technological trends within education, integrating Virtual Worlds into engineering education represents a pedagogical shift toward nurturing essential 21st-century skills such as critical thinking, creativity, collaboration, and communication, alongside traditional technical expertise. Immersive virtual environments promote digital fluency, cognitive flexibility, and professional soft skills, vital for engineers to succeed in an increasingly digital world. By leveraging collaborative missions and problem-based learning tasks, students hone their technical abilities and enhance their interpersonal skills, making them more adept at working in diverse, multidisciplinary teams. This shift in learning emphasizes adaptability, innovation, and professional readiness, key traits for modern engineers.

Despite the growing interest in integrating Virtual Worlds, a significant gap remains in the literature regarding how these environments function as effective pedagogical ecosystems. There is an urgent need to explore how its implementation can be optimized to achieve educational outcomes. This narrative review aims to address this gap by synthesizing theory-informed insights into integrating Simulation Worlds and Adventure Worlds within engineering education, particularly within the broader context of the metaverse. The review investigates how Virtual Worlds can support conceptual mastery, skill development, and real-world competencies, offering a comprehensive framework to evaluate these immersive environments. The central research question for this review is: How do immersive Virtual Worlds and the Metaverse enhance engineering training by improving conceptual understanding, technical competence, and 21st-century skills? To address this overarching question, the following research questions (RQ) are explored:

RQ1. How can Simulation and Adventure Worlds be integrated as immersive learning environments in engineering education and training?
RQ2. What features and design elements of virtual worlds enhance conceptual understanding and hands-on skill development within engineering education and training?
RQ3. In what ways do virtual worlds in the metaverse foster critical 21st-century skills, such as creativity, critical thinking, communication, and collaboration?
RQ4. What are the challenges, opportunities, and best practices for implementing immersive virtual environments in the context of general education and training?

This review seeks to provide educators, instructional designers, and policymakers a structured foundation to rethink and innovate engineering pedagogy in a digitally immersive context. By synthesizing insights from current literature and theoretical models, the study offers a holistic perspective on integrating Virtual Worlds and the Metaverse into engineering education, emphasizing technical learning outcomes and the development of transversal competencies essential for modern engineers.

2. Methods

This study adopts a narrative review methodology well-suited for synthesizing diverse theoretical perspectives, conceptual models, and empirical findings across interdisciplinary domains (Ferrari, 2015; Greenhalgh et al., 2018). The aim is not to statistically aggregate data, as in systematic or meta-analytical reviews, but to critically examine, interpret, and contextualize how immersive Virtual Worlds, specifically Simulation Worlds and Adventure Worlds, are being integrated into engineering education and training within the evolving landscape of the Metaverse (Damaševičius & Sidekerskienė, 2024; Herath et al., 2024).

2.1 Research design and rationale

A narrative review approach was chosen for this study to enable a broad, theory-informed exploration of complex educational phenomena, particularly those emerging at the intersection of engineering education, immersive technologies, and digital pedagogy (Bankins et al., 2024). Narrative reviews are particularly valuable when the field is evolving rapidly, such as integrating the Metaverse and VR-based learning into educational contexts. As these technologies continuously reshape how learning experiences are designed and delivered, adopting a flexible approach that can synthesize diverse perspectives is crucial. Research on immersive learning is often fragmented across various disciplines such as engineering, educational psychology, and computer science. Integrating these disparate fields and concepts is critical to understanding the broader implications of immersive environments in education. Narrative

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reviews excel in this context as they focus on synthesizing theoretical frameworks and conceptual innovations, rather than merely aggregating data on effect sizes or intervention outcomes (Paparini et al., 2021; Schreiber & Cramer, 2024; Thomas & Gupta, 2022). This approach allows for interpretive flexibility, ensuring that the review maintains a broad, comprehensive scope while still being methodologically rigorous in its analysis (Sukhera, 2022).

2.2 Sources and search strategy

This study only includes peer-reviewed journal articles published in journals indexed in Scopus, one of the leading and reputable academic databases. The researchers selected scholarly articles and excluded conference proceedings and book chapters to ensure higher research quality and stronger relevance to the studied topic. Given the novelty of the Virtual Worlds and Metaverse, the researchers did not limit the search by publication year and included all relevant results, regardless of publication date. They included only articles published in English in this review to maintain consistency and clarity. The search strategy employed keywords and Boolean operators to expand and refine the search results. The keywords used in this search included:

- "Virtual World", "Simulation World", or "Adventure World"
- "Engineering Education", "Training", or "TVET"
- "Metaverse" or "Immersive Learning"
- "Digital Pedagogy" or "21st Century Skills"

This search was limited to final published articles, excluding those in press or under review. Only studies published in peer-reviewed scholarly journals indexed in Scopus were considered, as these databases are known for their high-quality standards. The search strategy is depicted in Figure 2.

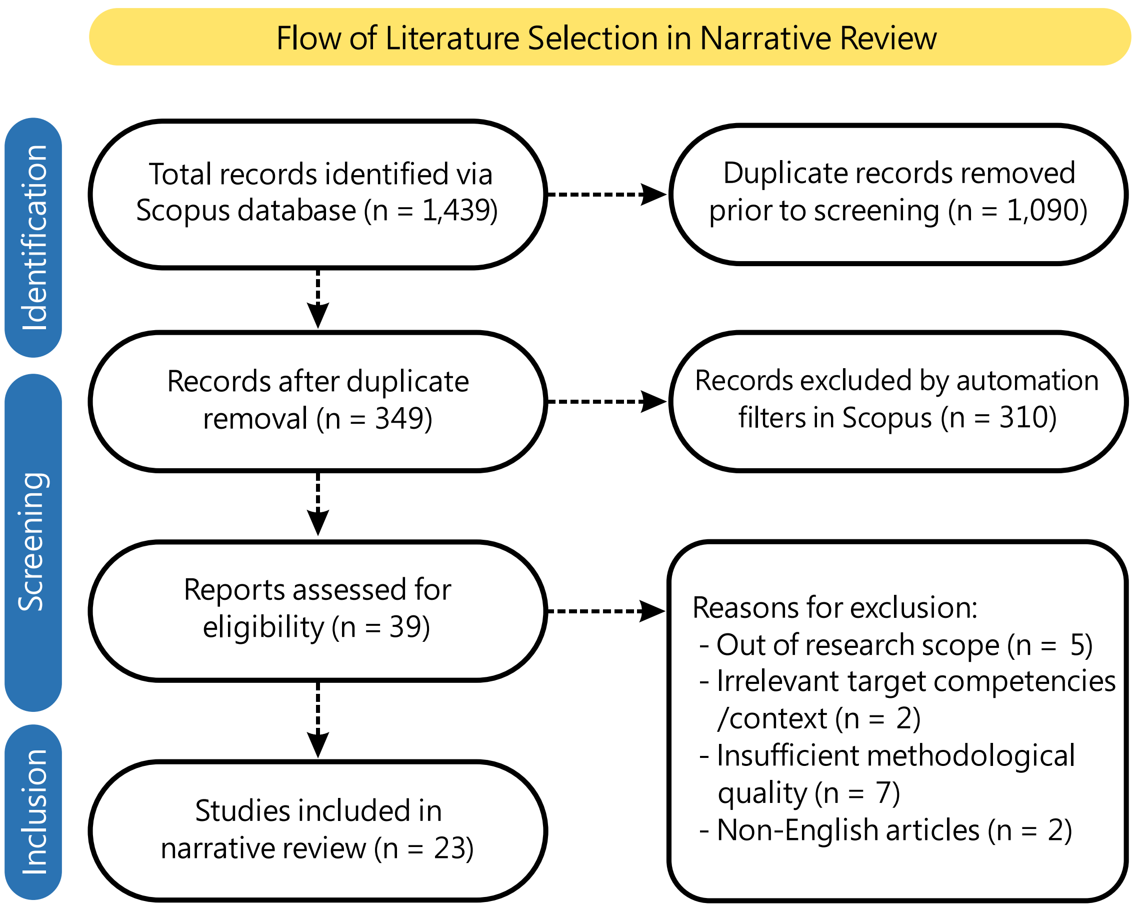

Figure 2. Flow of literature selection process for the narrative review

The flowchart outlines the process followed in Figure 2. It begins with the identification of 1,439 records from the Scopus database. After removing duplicates, 349 records remained for further evaluation. Additional screening excluded 310 records based on automation filters in Scopus. Following this, 39 reports were assessed for eligibility based on predefined criteria. Ultimately, 23 studies were selected for inclusion in the narrative review.

2.3 Eligibility, domain stratification, and evidence tiers

Maintaining methodological rigor is critical in any academic study to ensure the validity and reliability of the results. This research adopts a domain-stratified approach, which serves as a vital framework to enhance the transparency of the study and address the inherent heterogeneity of the reviewed literature (Kozak et al., 2008; Le et al., 2025; Øby, 2025). This methodological approach is articulated through two primary components: Domain Stratification and Evidence Tiers, which systematically categorize and assess the relevance of the studies reviewed in the context of engineering education and training.

(a) Domain Stratification:

- **E-Core:** Studies directly related to engineering education and training, focusing on practical and technical aspects such as equipment operation, industrial processes, safety, applied physics, and maintenance.
- **E-Adjacent:** Several studies originate from adjacent fields within engineering or TVET (Technical and Vocational Education and Training) but primarily assess transversal competencies (4Cs), including collaboration, critical thinking, communication, and creativity in engineering programs.
- **Non-E:** Studies from general education that are relevant to the engineering field but do not directly focus on engineering content or procedures.

(b) Evidence Tiers:

- **Tier A:** Empirical studies with robust data collection and analysis methods, such as pre-post assessments, experiments, quasi-experiments, rubrics, and telemetry logs.
- **Tier B:** Studies that are pilot projects, prototypes, or technical simulations, as well as those with expert validation.
- **Tier C:** Conceptual or framework studies that provide theoretical perspectives without empirical data or sample-based analysis, when these studies offer important insights in direct evidence of impact or effectiveness.

(c) Analysis Policy:

- RQ1 and RQ2 focus primarily on E-Core and E-Adjacent studies, with Tier A studies given priority and Tier B studies as secondary.
- RQ3 integrates E-Core and E-Adjacent studies (preferably Tier A/B/C) to investigate the development of 21st-century skills (4Cs), such as critical thinking, communication, creativity, and collaboration.
- RQ4 incorporates studies from all domains (E-Core, E-Adjacent, and Non-E) and all tiers (A/B/C) to map out the challenges, opportunities, and best practices for implementing immersive virtual environments in engineering and general education.

Differentiating studies into various tiers and domains plays a pivotal role in developing a nuanced understanding of the methods and approaches used in integrating virtual worlds into engineering education. This stratification facilitates a deeper interpretation of how transversal competencies, such as the 4Cs, are cultivated and how they influence the design of future engineering curricula and educational practices.

2.4 Study selection, extraction, and coding

The study selection process involved two independent reviewers who evaluated the titles, abstracts, and full studies texts. Any discrepancies were resolved through adjudication to maintain consistency and minimize bias. A standardized codebook was used to categorize key aspects of each study for data extraction. Studies were classified based on their Integration Pattern (Simulation-Dominant, Adventure-Dominant, or Hybrid), context (e.g., lab, capstone project, field simulation), and Domain/Level/Platform (e.g., engineering, undergraduate, VR). Other categories included Core Features (e.g., immersion, feedback, collaboration), Target Competencies (e.g., conceptual, procedural, 4C skills), and Assessments (e.g., tests, rubrics, surveys). The Outcome category recorded the impact on competencies (conceptual, procedural, or 4C). Lastly, studies were classified into Evidence Tiers (Tier A for empirical, Tier B for prototypes, Tier C for conceptual studies) to indicate the strength of their evidence. To ensure consistency, the initial coding was calibrated using a subset of studies, and the entire process was monitored through audit trails. This approach enhanced the reliability of the literature review and provided clear insights into the studies' contributions to engineering education in the metaverse.

2.5 Synthesis and evidence visualization

This study adopts a thematic synthesis approach to investigate the integration of immersive Virtual Worlds, specifically Simulation Worlds and Adventure Worlds, into engineering education and training within the metaverse. The synthesis process categorizes the reviewed studies based on integration patterns (Simulation-Dominant, Adventure-Dominant, Hybrid), core features (such as immersion, real-time feedback, and collaboration), and educational outcomes (including conceptual, procedural, and 21st-century competencies). To effectively visualize these relationships and insights, several key diagrams were utilized:

- The alluvial diagram illustrates the flow and connections between the integration patterns, core features, and educational outcomes.
- The heatmap is used to visualize the intensity of improvements in core features and outcomes. The X-axis represents core features (e.g., Artificial Intelligence, Immersion, Avatars, Game Role, Real-Time Feedback, Data/Simulation Tools, Process Modeling, Collaboration), while the Y-axis represents various educational outcomes (conceptual, procedural, and 21st-century competencies).
- The skill radar chart highlights the development of key competencies, including critical thinking, creativity, communication, and collaboration, across different integration patterns.
- A stacked bar chart is employed to visually represent the distribution of outcomes across integration patterns, showing how different features contribute to various competencies in a comparative format.

Several software tools supported data extraction, synthesis, and visualization. PlantUML was used to map the frameworks and relationships between the studies, offering a clear visual representation of how immersive technologies were integrated. Python-enabled data analysis and text mining, helping identify key themes, patterns, and trends across the literature, strengthening the synthesis process. Additionally, Microsoft Excel 2024 was used to track, organize, and categorize the studies, ensuring consistency in data management and providing an overview of the identified trends and patterns.

2.6 Quality appraisal and trustworthiness

To ensure the trustworthiness of this review, multiple independent reviewers assessed the relevance and quality of the studies based on the criteria outlined in the Data Sources and Search Strategy section. The Critical Appraisal Skills Programme (CASP) tool was employed to evaluate the quality of the studies (Long et al., 2020), ensuring that only methodologically sound articles were included. The CASP evaluation was crucial in maintaining consistency

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across reviews and providing a reliable framework for assessing the validity and rigor of the studies included in the review. We maintained an audit trail throughout the review process to further enhance transparency and accountability. This was achieved through a concise study table, a comprehensive codebook, and extraction files. The audit trail provided clear documentation of all decisions made during the data extraction process, ensuring traceability and easy verification of the review methodology. Any reviewer conflicts during the assessment were resolved through adjudication, ensuring that all studies were appropriately classified and no relevant study was overlooked. For studies where specific data was not reported, the term "n/r" (not reported) was used to indicate missing information. This practice contributed to maintaining the transparency and accuracy of the review process. Appendix 1 provides a detailed table that summarizes all the reviewed studies, including key data such as study ID, author(s), publication year, platform, core features, target competencies, assessments, and outcomes. This table offers a comprehensive overview of the studies evaluated, enhancing the clarity and structure of the review.

3. Results and discussion

3.1. General overview of the reviewed studies

This review synthesizes 23 peer-reviewed studies on integrating Virtual Worlds within the broader Metaverse ecosystem for engineering education and training. The corpus spans manufacturing, industrial processes, applied physics, automation, aircraft maintenance, and adjacent areas such as project management, digital learning communities, and social engineering. Learning contexts range from TVET to undergraduate, postgraduate, and professional programs, delivered on VR HMDs, desktop-3D, AR, and collaborative metaverse platforms. By domain, the distribution is E-Core 10 (43.5%), E-Adjacent 9 (39.1%), and Non-E 4 (17.4%). By evidence tier, Tier-A 9 (39.1%) and Tier-B 9 (39.1%) dominate, with Tier-C 5 (21.7%), indicating a generally solid empirical base despite modest samples and heterogeneous designs. Methodologically, studies combine concept tests, performance rubrics, project artifacts, telemetry/learning analytics, presence–UX questionnaires, and observations/viva.

Regarding integration patterns, Simulation-dominant designs prevail for low-risk, accuracy-critical training (e.g., equipment operation, process modeling, onboarding): adventure-dominant worlds foreground narrative, role-play, and open-ended problem solving, emphasizing team communication and cross-functional coordination. Many adopt a hybrid choreography simulation for procedural priming, then collaborate in mission-based scenarios to drive conceptual transfer and decision-making. Across adequate studies, recurring design levers include functional immersion/presence (avatars), real-time feedback, adaptive scaffolding, in-world collaboration, and authentic assessment. These features shift pedagogy from transmission toward experiential, interactive, learner-centered training. A study-by-study classification by domain stratum and evidence tier is provided in Table 1.

Table 1. Classification of reviewed studies based on domain strata and evidence tiers

No	Study (Author and Year)	Domain Strata	Evidence Tier	Brief Reason
1	(Rigou et al., 2025)	E-Adjacent	A	Soft/green skills training, strong evidence with mixed methods (n=27).
2	(Özsoy, 2025)	E-Adjacent	B	Project management simulations, qualitative interviews (n=32).
3	(Teichmann, 2025)	E-Core	B	Real-world process modeling, expert reviews, iterative testing.
4	(Hakim et al., 2025)	E-Core	A	VR-based learning in STEAM, validated with PLS-SEM (n=60).

No	Study (Author and Year)	Domain Strata	Evidence Tier	Brief Reason
5	(Areepong et al., 2025)	E-Adjacent	B	Metaverse-ILC model validated through expert feedback (n=40).
6	(Bobko et al., 2024)	Non-E	C	Conceptual Edu-Metaverse ecosystem, no empirical testing.
7	(Sim et al., 2024)	E-Core	B	Digital twin campus, small sample (n=8), initial trials.
8	(Yun et al., 2024)	E-Core	A	CPS/AI training, significant evidence (n=30).
9	(Wiangkham & Vongvit, 2024)	E-Adjacent	A	Adoption survey of metaverse for engineering education (n=365).
10	(Li et al., 2024)	E-Adjacent	A	Platform comparison (AltSpace, Gather, ZOOM), extensive survey (n=20).
11	(Singh & Singh, 2024)	E-Core	B	Quality of service simulation, no human participants.
12	(Sidhu et al., 2024)	E-Core	C	Metaverse constructivist framework, no empirical trial conducted.
13	(Gu et al., 2023)	E-Adjacent	B	Evacuation training with Metaverse simulation, no learners tested.
14	(Almeida et al., 2023)	E-Core	B	Industrial VR prototype, small sample testing (n=5).
15	(Onecha et al., 2023)	E-Core	A	AR for architecture, extensive survey (n=218).
16	(Thongprasit & Piriyasurawong, 2023)	E-Adjacent	B	Validation of Metaverse-MIAP model, expert evaluation (n=9).
17	(AbuKhousa et al., 2023)	Non-E	C	Conceptual model for career readiness, no empirical data.
18	(Mitra, 2023)	E-Adjacent	C	Conceptual framework for blended learning in the metaverse, no data.
19	(Jovanović & Milosavljević, 2022)	E-Adjacent	B	Prototype testing, small sample (n=24), post-demo survey.
20	(H. Lee et al., 2022)	E-Core	A	VR-based aircraft maintenance, pre-post tests (n=40).
21	(J. Lee, 2022)	Non-E	A	Survey of Metaverse adoption for non-STEM students (n=502).
22	(Wang et al., 2022)	Non-E	C	Conceptual framework for the Edu-Metaverse ecosystem, no empirical validation.
23	(Nunes et al., 2017)	E-Core	A	OpenSim programming experiment, controlled study (n=34).

3.2. RQ1 – Patterns of integration between simulation worlds × adventure worlds in engineering education and training

The synthesis of 23 reviewed studies reveals three dominant integration patterns between Simulation and Adventure Worlds in engineering training: simulation-dominant, adventure-dominant, and hybrid orchestration. These patterns embody distinct pedagogical logics and design rationales. Simulation-dominant models emphasize procedural accuracy and conceptual mastery, adventure-dominant models foster transversal competencies like collaboration, creativity, and problem-solving, and hybrid models combine the strengths of both. The findings, as detailed in Appendix 2, demonstrate how these integration patterns are strategically leveraged across engineering education and training contexts, while also aligning with domain strata (E-Core and E-Adjacent) in which Tier A competencies are prioritized, and Tier B competencies serve as complementary outcomes. Simulation-dominant environments focus on accuracy, safety rehearsal, and conceptual mastery by utilizing digital twins, parameterized sandboxes, and real-time feedback mechanisms. Studies by (Almeida et al., 2023; Hakim et al., 2025; H. Lee et al., 2022; Muzata et al., 2024; Sim et al., 2024; Yun et al., 2024) demonstrate that simulation pipelines effectively build "first-pass competence." For instance, (Hakim et al., 2025) integrated culturally grounded momentum-collision sandboxes to make physics learning more relevant, while (Almeida et al., 2023) showed how industrial equipment training in multi-user VR provided a safe yet realistic rehearsal of technical procedures. Similarly, (H. Lee et al., 2022) found that VR-based aircraft maintenance simulations significantly outperformed video-based training in retention and procedural knowledge, underscoring the value of simulations as a precursor to real-world practice.

In contrast, adventure-dominant environments leverage narratives, avatars, collaborative quests, and exploratory hubs to foster transversal skills and the 4Cs. A study by (Rigou et al., 2025) demonstrated how story-driven role-play scenarios enhanced communication and teamwork, where curriculum structure outweighed prior technological familiarity. Adventure-oriented models were also seen in (Onecha et al., 2023), where AR-based explorations of construction phases helped learners contextualize engineering systems, and (Gu et al., 2023), where DRL-driven evacuation adventures trained decision-making under pressure. Furthermore, (Nunes et al., 2017) showed that the integration of OpenSim and Sloodle with Moodle enhanced student interaction, engagement, and problem-solving skills, promoting critical thinking and algorithmic reasoning within simulation-based environments. Collectively, these studies highlight the effectiveness of adventure-dominant designs in sustaining engagement and equipping learners with soft skills essential for solving complex, ill-structured problems. Between these two extremes, the hybrid orchestration pattern emerges as the most balanced and scalable approach, integrating the precision of simulations with the collaborative richness of adventure missions. Research by (Teichmann, 2025) reduced learner friction by combining onboarding micro-simulations with exploratory foyer hubs, while (Thongprasit & Piriyasurawong, 2023) operationalized the MIAP cycle (Motivation Information Application Progress), ensuring that learners acquired technical competence through simulations and applied it in collaborative quests. Study by (Mitra, 2023), emphasized the potential of hybrid virtual-physical campuses to support inquiry-driven exploration. Even (Li et al., 2024) demonstrated that immersive avatar-mediated VR enhanced engagement and community and highlighted usability trade-offs that hybrid designs must negotiate.

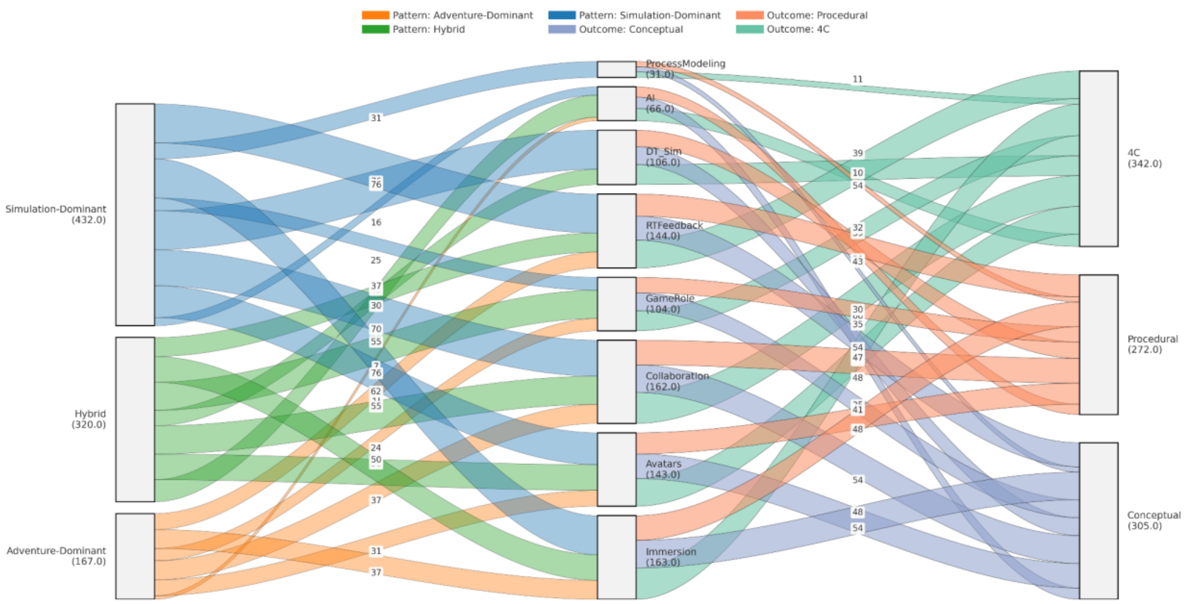

Figure 3. Alluvial diagram of simulation, adventure, and hybrid pipelines toward outcomes

As illustrated in Figure 3, the Alluvial Diagram reveals distinct integration patterns between simulation and adventure-based environments in engineering education and training. Simulation-dominant models, represented by the strong flows from Digital Twin Simulations and Real-Time Feedback, predominantly channel into conceptual and procedural outcomes, emphasizing the accuracy and mastery of technical skills. This is evident in studies like (Hakim et al., 2025; Sim et al., 2024), which showcase the effectiveness of simulation-based approaches for procedural training and conceptual understanding. Conversely, adventure-dominant patterns, driven by features like avatars and collaboration, flow robustly toward 4C outcomes, underscoring the importance of creativity, communication, and problem-solving in modern engineering practice. Studies such as (Onecha et al., 2023; Rigou et al., 2025) highlight how adventure-oriented environments can promote transversal competencies that complement technical expertise. The hybrid orchestration pattern, which distributes flows across all three outcome domains, offers the most balanced and scalable approach. It combines the precision of simulations with the collaborative, problem-solving opportunities adventure worlds provide. As seen in (Teichmann, 2025; Thongprasit & Piriyasurawong, 2023), hybrid models are well-suited to support the development of technical and soft skills in engineering students. This evidence aligns with broader scholarship: fidelity of simulations underpins safe procedural rehearsal and knowledge accuracy (Freitas & Veletsianos, 2010; Radianti et al., 2020), while adventure-like explorations sustain motivation and transfer through collaborative engagement (Hmoud et al., 2025; Johnson-Glenberg, 2018). The reviewed corpus suggests that future engineering education is best served by hybrid pipelines, leveraging simulation for accuracy and adventure for engagement, thereby uniting STEM knowledge with 21st-century skills.

3.3. RQ2 – Design features that enhance conceptual understanding and practical skills

The synthesis of multiple studies offers valuable insights into virtual worlds' key features and design elements (VWs) that enhance conceptual understanding and hands-on skill development within engineering education and training. These studies highlight the interaction between various design components, which, when effectively integrated, foster deep learning, mastery of skills, and the development of transversal competencies such as communication, collaboration, and creativity. As detailed in Appendix 3, these findings highlight how features of virtual worlds in the metaverse contribute to the development of both conceptual understanding and practical skills for students in the 21st century. These features align with the domain strata (E-Core and E-Adjacent), prioritizing Tier A competencies and Tier B competencies serving as complementary outcomes.

The most impactful design features identified for conceptual understanding are Digital Twin Simulations (DT_Sim) and Process Modeling. Studies by (Almeida et al., 2023; Mitra, 2023; Wang et al., 2022) highlight how Digital Twins allow learners to interact with real-time, dynamic representations of physical systems, helping them grasp complex engineering concepts. Digital Twin Simulations, combined with parameterized sandboxes, enable learners to visualize and manipulate system variables, thereby improving conceptual clarity (Özsoy, 2025; Sidhu et al., 2024; Sim et al., 2024; Singh & Singh, 2024). Additionally, studies (Sim et al., 2024; Teichmann, 2025) show that Process Modeling helps learners connect theoretical knowledge to real-world applications when integrated with real-time feedback. The combination of these features supports the development of conceptual mastery by providing immediate corrective feedback and deepening learners' understanding of how systems function.

In contrast, hands-on skill development is fostered through Real-Time Feedback (RT-Feedback) and Avatars. As seen in studies (Özsoy, 2025; Singh & Singh, 2024), real-time feedback mechanisms offer learners immediate validation or correction during skill practice. This feedback is crucial in refining technical skills and procedural accuracy, particularly in industrial equipment simulation and cybersecurity training, where learners must build precise procedural skills without risk. Avatars, on the other hand, enhance embodied presence in virtual worlds, promoting learner engagement and interaction. This embodiment allows learners to engage with systems and situations physically, fostering skill mastery through active practice. For example, studies (Areepong et al., 2025; Jovanović & Milosavljević, 2022; Nunes et al., 2017) found that role-play scenarios and collaborative environments effectively enhance problem-solving skills and teamwork. Another critical design element for skill development is mission-based tasks and quests. Research (Jovanović & Milosavljević, 2022; Rigou et al., 2025; Wiangkham & Vongvit, 2024) demonstrates how gamified tasks like quests simulate real-world challenges, allowing learners to apply knowledge dynamically. These tasks promote problem-solving and critical thinking, essential for hands-on skill development in engineering contexts.

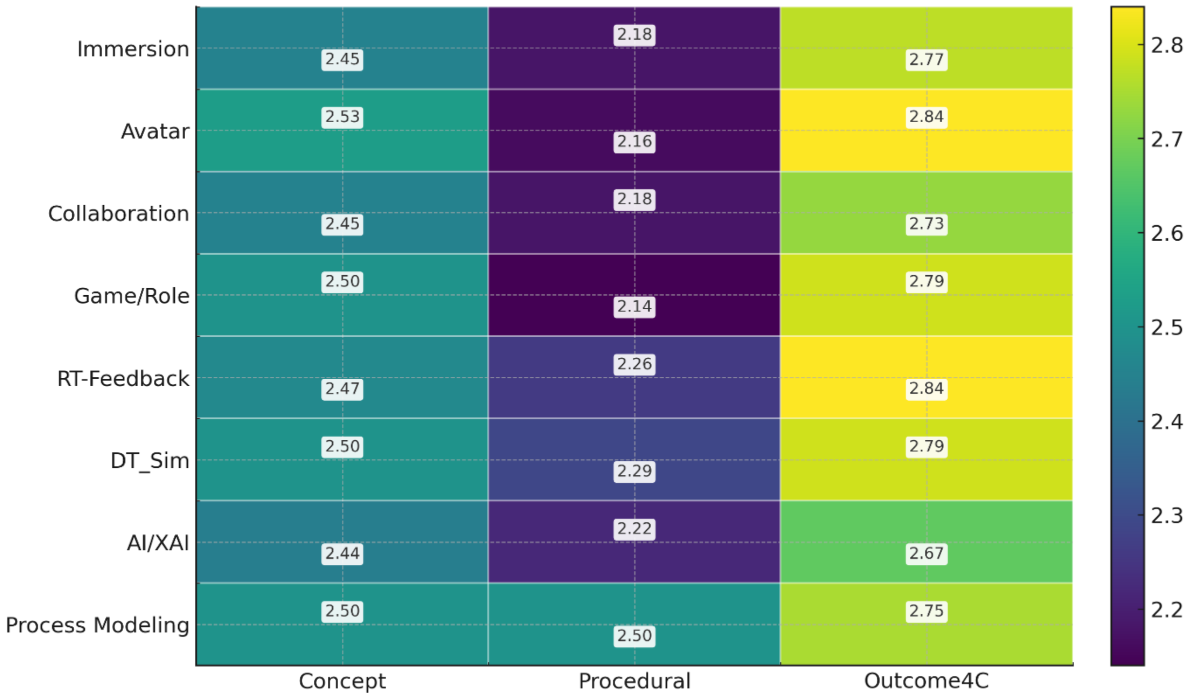

Figure 3. Heatmap of core features and outcomes

The heatmap in Figure 3 further strengthens these findings by visualizing how features correlate with specific learning outcomes, conceptual understanding, procedural accuracy, and 21st-century competencies (4C). For conceptual outcomes, the highest mean values were observed for Avatars (≈2.53), DT_Sim (≈2.50), and Process Modeling (≈2.50). These features are highly effective in enhancing learners' grasp of theoretical concepts. Avatars foster presence and identity, while DT_Sim and Process Modeling provide realistic, interactive simulations that deepen learners' understanding. In terms of procedural outcomes, Process Modeling (mean ≈2.50) is the top feature, followed by DT_Sim (mean ≈2.29) and RT-Feedback (mean ≈2.26). These features help learners refine their technical skills and procedural knowledge through interactive simulations and real-time feedback. Process Modeling allows learners to engage with actual systems and workflows, while DT_Sim provides a dynamic environment for testing theories in real-time. RT-Feedback is crucial for offering immediate, actionable feedback that enables learners to improve their performance during procedural tasks.

Regarding 4C competencies, creativity, communication, collaboration, and critical thinking, the highest correlations were found with Avatars and RT-Feedback (both mean ≈2.84), followed by Game/Role and DT_Sim (≈2.79), and immersion at ≈2.77. Avatars and RT-Feedback play crucial roles in fostering collaboration, critical thinking, and creativity. The embodiment facilitated by Avatars enhances learner engagement, while RT-Feedback encourages real-time reflection and problem-solving. Moreover, Game/Role scenarios and DT_Sim further promote creativity and collaboration by requiring learners to work together on complex tasks. The heatmap data confirms that the most effective virtual worlds for engineering education integrate simulation and adventure-based elements, providing learners with a well-rounded experience. Hybrid designs, such as those in the studies by (Bobko et al., 2024; Teichmann, 2025; Thongprasit & Piriyasurawong, 2023), combine the technical precision of simulations with the collaborative nature of mission-based exploration, ensuring that learners acquire both technical skills and transversal competencies like teamwork and creativity. These hybrid models align with the growing need for 21st-century skills in engineering education, where technical expertise and soft skills must coexist. In conclusion, hybrid models that combine simulation-based precision with the collaborative richness of adventure-based tasks offer the most promising approach to engineering education. By integrating features such as DT_Sim, Process Modeling, Avatars, and RT-Feedback, these virtual worlds provide a balanced learning environment that fosters both conceptual understanding and hands-on skill development, preparing students for the complexities of modern engineering challenges.

3.4. RQ3 – Development of 21st-century skills in virtual worlds

Integrating virtual worlds in the metaverse provides an innovative approach to developing critical 21st-century skills such as creativity, critical thinking, communication, and collaboration. This section synthesizes the role these virtual worlds play in fostering essential skills by analyzing 23 studies across various virtual-world environments, including immersive simulations, game-based adventures, and hybrid learning spaces. The findings, represented through a 4C Skill Radar (Figure 4), offer a comprehensive analysis of how different design patterns in the metaverse contribute to these competencies. The data is derived from coding rules used in evaluating these environments on an intensity scale, as shown in Appendix 4, where each skill, Critical Thinking, Creativity, Communication, and Collaboration, was scored based on empirical evidence, expert validation, or pilot studies. Additionally, these features align with E-Core and E-Adjacent studies, where Tier A competencies are prioritized, Tier B competencies serve as complementary outcomes, and Tier C focuses on conceptual or framework studies that offer valuable theoretical insights, enriching the learning experience**.**

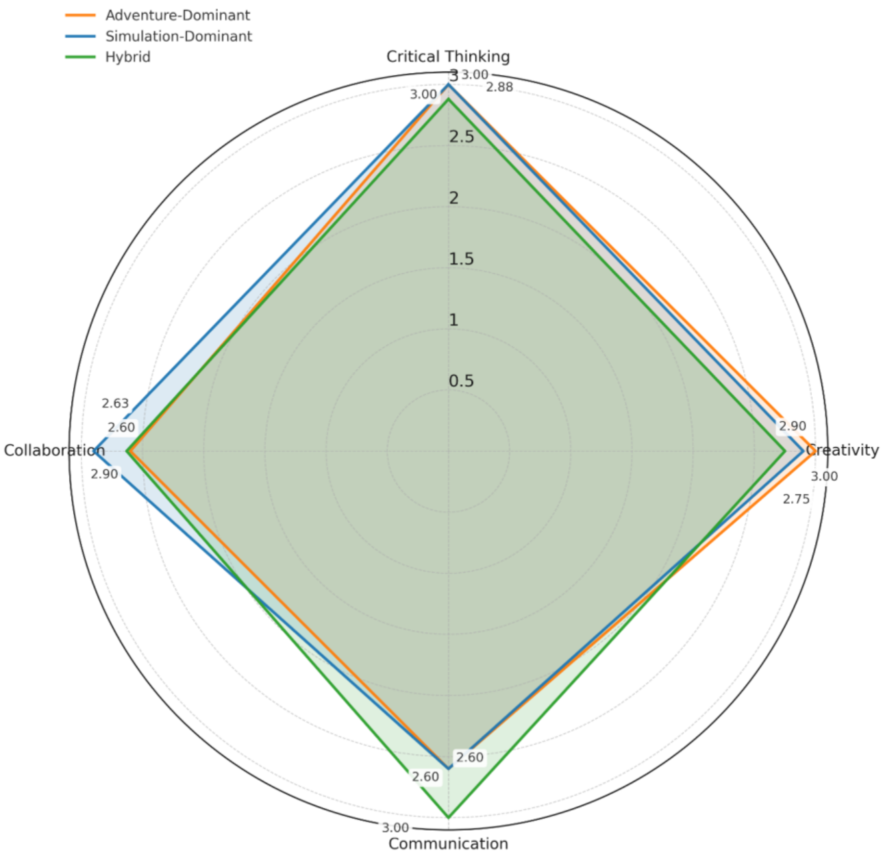

Figure 4. Skill radar 4c (per integration pattern)

3.4.1 Critical thinking

Critical thinking was consistently developed across all three virtual-world patterns, Adventure, Simulation, and Hybrid, with both Adventure and Simulation environments demonstrating high scores (≈3.0). These environments provided learners with time-pressured decisions and consequence-rich scenarios that encouraged reflective thinking, allowing learners to compare various options and outcomes. As observed in studies by (Areepong et al., 2025; Gu et al., 2023; Özsoy, 2025; Teichmann, 2025), branching scenarios and real-time feedback were used to deepen reasoning skills by requiring participants to justify their choices. Although Hybrid environments scored slightly lower (≈2.88), they still supported critical thinking. These environments integrate simulation accuracy with exploratory learning, offering learners reflective opportunities, though less intense than Adventure or Simulation. Nonetheless, critical thinking was effectively nurtured across all models, suggesting that virtual worlds, regardless of the design pattern, can foster critical reasoning through dynamic problem-solving scenarios.

3.4.2 Creativity

Creativity was most strongly developed in Adventure-based environments, with a score of 3.0, highlighting these worlds' open-ended, exploratory nature. The immersive experience, such as role-playing and mission-based environments (Bobko et al., 2024; Sidhu et al., 2024; Singh & Singh, 2024), allows learners to explore, prototype, and iterate ideas. These environments allow for creative autonomy and innovation, which are critical components for fostering divergent thinking and problem generation. Features like avatars, game-based challenges, and sandbox tools contribute to an environment that promotes creative flow and continuous ideation. Although simulation (mean ≈2.90) and Hybrid environments (mean ≈2.75) also foster creativity, they do not achieve the same level of engagement in open-ended tasks. These designs often focus more on procedural accuracy and technical mastery, with creativity being a secondary focus. Simulation environments frequently prioritize the realistic modeling of functions and processes, whereas Hybrid environments combine elements of both structure and exploration, making them less conducive to creativity in its pure form.

3.4.3 Communication

Hybrid virtual worlds excelled in fostering communication skills, earning a top score of 3.0. These environments integrate features such as avatars, real-time feedback, and social presence to facilitate dynamic communication among learners. As highlighted by (J. Lee, 2022; Li et al., 2024; Wang et al., 2022), these spaces allow learners to collaborate, share knowledge, and engage in problem-solving tasks, which are essential for refining communication strategies. The emphasis on multi-stage communication, particularly in collaborative activities, allows learners to practice clear and concise expression, active listening, and real-time feedback exchanges. On the other hand, Adventure environments (mean ≈2.90) support communication in a less structured manner, typically through individual decision-making or shared quests. While Simulation environments (mean ≈2.60) support communication through team-based procedural tasks, they focus more on collaboration and coordination of roles within the team rather than on fostering detailed interpersonal communication.

3.4.4 Collaboration

Simulation environments slightly outperform Adventure and Hybrid environments in fostering collaboration, with a mean score of 2.90. These environments emphasize team-based tasks where learners are required to coordinate roles, communicate effectively, and solve problems together (Almeida et al., 2023; Hakim et al., 2025; Wang et al., 2022). This structured collaboration, often in a high-stakes context, strengthens teamwork dynamics, making it highly suitable for skill development in cooperative problem-solving. Adventure environments (mean ≈2.60), which are more centered on individual exploration, show lower scores in collaboration, although they still promote teamwork through shared quests and challenges. Hybrid environments (mean ≈2.63), which balance individual and group tasks, also encourage collaboration but to a lesser degree than Simulation environments. The combination of independent exploration and collaborative problem-solving makes hybrid environments suitable for promoting balanced collaboration, although the results are slightly behind those of simulation.

3.4.5 Synthesis and implications

The Skill Radar 4C clearly demonstrates the differentiated strengths of each virtual-world model in developing specific 21st-century skills (AbuKhousa et al., 2023; Bobko et al., 2024). Adventure environments best suit creativity, encouraging exploration and innovation through role-play and open-ended tasks. On the other hand, hybrid environments excel in communication, providing structured spaces for real-time interaction, collaboration, and feedback. Simulation environments lead in collaboration, where teamwork and procedural coordination are integral to success. They also foster critical thinking, as learners engage in consequence-driven scenarios requiring analysis and decision-making. These findings suggest that integrating Hybrid models, which combine simulation accuracy and exploratory learning elements, offers a comprehensive approach to fostering all four skills. By incorporating avatars, real-time feedback, and dynamic problem-solving tasks, Hybrid environments provide an optimal learning framework for creativity, critical thinking, communication, and collaboration. Overall, the metaverse provides diverse virtual environments that contribute significantly to developing 21st-century skills. Whether through exploratory creativity in adventure, collaborative communication in Hybrid, or team-based problem-solving in simulation, these virtual worlds offer powerful, immersive experiences. However, the successful development of these skills depends on careful design considerations, including integrating appropriate affordances, well-structured tasks, and adequate facilitator support.

3.5. RQ4 – Implementation challenges, opportunities, and best practices

Integrating immersive virtual environments (IVEs) in general education and training offers substantial opportunities but presents significant challenges that must be addressed for successful implementation. This synthesis of 23 studies highlights these dimensions, identifying recurring themes across diverse applications of IVEs, ranging from engineering education to general instructional design, as detailed in Appendix 5. It focuses on the challenges faced, the potential opportunities unlocked, and the best practices that can maximize effectiveness.

Figure 5, a stacked frequency chart, visually demonstrates these challenges, opportunities, best practices, and risks across various themes. The themes examined include Digital Twin Assets, Safety & Risk-Free Simulation, Collaboration, Usability & Ergonomics, and Privacy & Ethics. These categories are represented by color-coded bars: Challenges (orange), Opportunities (blue), Best Practices (green), and Risks (yellow). Each theme is assessed in terms of the frequency of responses in each category, providing a comprehensive overview of the key concerns and successes identified in the literature, as shown in Appendix 5. A prominent challenge in implementing IVEs is the high hardware and technical infrastructure cost, particularly for Virtual Reality (VR) headsets and related technologies. Numerous studies (Almeida et al., 2023; H. Lee et al., 2022; Li et al., 2024) emphasize that the cost of VR devices and the need for advanced technical infrastructure create barriers to the widespread adoption of these immersive environments. This challenge is compounded by device and platform heterogeneity, leading to issues of compatibility and access equity (AbuKhousa et al., 2023; Bobko et al., 2024; J. Lee, 2022). Moreover, concerns such as motion sickness (Hakim et al., 2025; Mitra, 2023) and cognitive overload (Nunes et al., 2017) remain significant challenges in ensuring learners can engage effectively with the virtual environment without detracting from their learning experience.

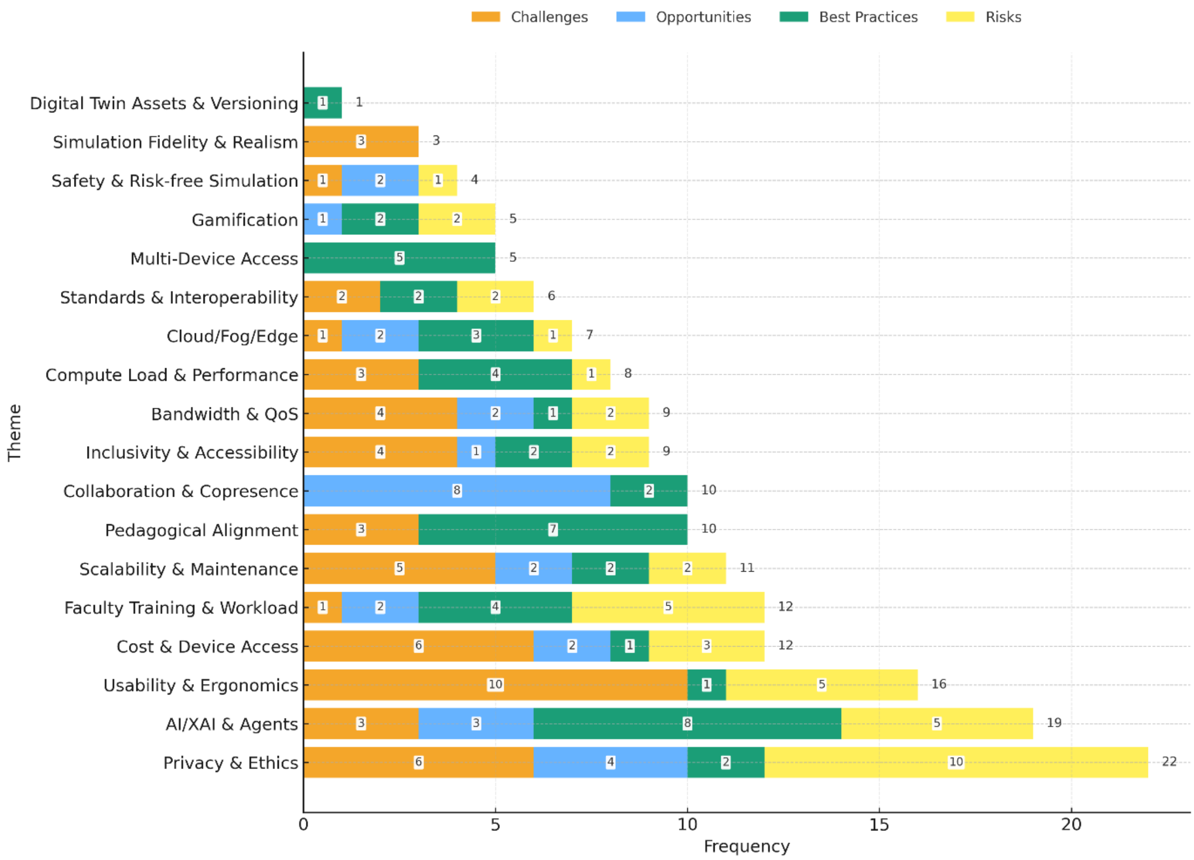

Figure 5. Stacked frequency by theme (challenges, opportunities, best practices, and risks)

Privacy and security concerns are recurring challenges, particularly when dealing with sensitive learner data in virtual worlds. As (Wiangkham & Vongvit, 2024) highlight, collecting and managing personal data in IVEs pose risks related to privacy breaches, requiring stringent data protection measures. Additionally, the lack of standardized processes, such as those seen in Digital Twin Assets & Versioning, further complicates the implementation of virtual environments. Studies by (Gu et al., 2023; Yun et al., 2024) note the technical hurdles in creating reliable simulations and ensuring that platforms are compatible across various devices and standards. Despite these challenges, IVEs offer significant opportunities for transforming education and training. Studies consistently point to immersive virtual environments' scalability and remote reach, which can democratize access to education and training, especially in underserved or geographically isolated regions. As noted by (Bobko et al., 2024; Wang et al., 2022), the ability to provide remote access to immersive labs allows learners from various locations to participate in educational experiences that would otherwise be unavailable to them.

Another key opportunity is the personalization and adaptive learning capabilities offered by IVEs. Numerous studies (Khalil et al., 2024; Li et al., 2024; Wu et al., 2024) highlight how AI-driven simulations and real-time feedback systems can tailor learning experiences to individual needs, fostering self-paced learning and self-regulation. This personalization enables learners to progress at their own pace and receive corrective feedback as needed, making these systems particularly valuable for diverse learning populations. Additionally, integrating collaborative features such as multi-user environments and virtual teamwork enhances communication and collaboration skills, which are increasingly important in the modern workforce. In addition, (Almeida et al., 2023; Jovanović & Milosavljević, 2022) demonstrate how features like avatars, spatial audio, and real-time collaboration tools create dynamic, engaging environments for communication and problem-solving. To maximize the potential of IVEs, several best practices have been identified across the studies reviewed. A standard recommendation is hybrid models, combining simulation-based learning with adventure-based tasks (Teichmann, 2025; Thongprasit & Piriyasurawong, 2023). This dual approach allows learners to master technical skills through simulations and develop soft skills through interactive, collaborative quests and role-playing. Pedagogical alignment is also crucial, with many studies (Özsoy, 2025; Rigou et al., 2025) emphasizing the importance of starting with clear learning outcomes and designing the immersive experience to support these goals directly. Backward design, as suggested by (Rigou et al., 2025), ensures that virtual environments are aligned with specific educational objectives, making the learning process more focused and relevant.

Furthermore, it is recommended to prioritize multi-device compatibility and open standards for assets and platforms to mitigate technical difficulties and device limitations. This approach prevents the platform lock-in that could hinder innovation (Sim et al., 2024). Additionally, scaffolding the learning process is essential, as highlighted in studies by (Onecha et al., 2023; Sidhu et al., 2024). Providing learners with clear guidance, such as structured prompts and feedback loops, helps reduce cognitive overload and ensures meaningful engagement with the content. As suggested by (Bobko et al., 2024), pilot testing and iterative refinement are also critical to ensuring the effectiveness and usability of virtual environments before scaling them to larger audiences. In conclusion, implementing IVEs in education and training presents substantial challenges and promising opportunities. The key challenges lie in the high hardware cost, technical infrastructure, privacy and security concerns, and device compatibility. Nevertheless, the opportunities provided by IVEs, such as scalable access, personalized learning, and enhanced collaboration, offer transformative potential for education and training. To successfully implement these environments, educators should employ best practices such as hybrid learning models, pedagogical alignment, multi-device compatibility, and scaffolding the learning process. By addressing the challenges proactively and capitalizing on the opportunities, the integration of IVEs can significantly enhance educational outcomes, preparing learners for the demands of the 21st century.

3.6. Conceptual model: Mechanisms of virtual worlds' impact on engineering learning outcomes

The conceptual framework illustrated in Figure 6 demonstrates the intricate relationships between the design features of virtual worlds, the cognitive and affective processes they trigger, and the resulting learning outcomes in engineering education and training. This model provides a clear and structured understanding of how immersive virtual environments (IVEs) influence learning, aligning closely with the findings from the studies reviewed in this narrative. As seen in Figure 6, the model links design features with learning mechanics, mediators, behaviors, and outcomes, creating a comprehensive framework for understanding how virtual worlds impact the engineering and education context.

The model begins with critical Design Features and Learning Mechanics, including Authentic Assessment, Interactivity & Feedback, Presence, Adaptive Scaffolding, and Narrative & Role-play. These features, such as immersion, feedback, collaboration, agency, and authenticity, lay the foundation for the Learning Mechanics of virtual worlds. These elements are central to enhancing student engagement and fostering deeper learning by creating a virtual environment that feels connected to real-world applications. Studies such as (Bobko et al., 2024; Teichmann, 2025) have shown that elements like avatars, real-time feedback, and collaborative tasks in virtual worlds significantly enhance learners' immersion, providing a more hands-on, interactive experience central to effective learning. Once these learning mechanics are established, they interact with key Mediators' presence, motivation/self-efficacy, cognitive load balance, affective processes, and shared understanding. These mediators ensure students remain engaged, focused, and motivated throughout their learning journey. For instance, presence in the virtual environment, critical for ensuring learners feel "there," enhances engagement (Almeida et al., 2023; Dunmoye et al., 2024; Lasekan et al., 2024). Similarly, motivation/self-efficacy (Li et al., 2024) is crucial for helping students believe in their ability to succeed within the virtual world, strengthening their commitment to the tasks. The cognitive load balance (Singh & Singh, 2024) ensures that students are appropriately challenged, without becoming overwhelmed. Shared understanding (Jovanović & Milosavljević, 2022) promotes collaboration, enabling learners to work together to solve complex problems, which is especially vital in engineering contexts where teamwork is critical. According to (AbuKhousa et al., 2023), embedding curriculum-aligned missions within high-fidelity digital twins can further close Kolb's experiential learning cycle, reinforcing learning outcomes.

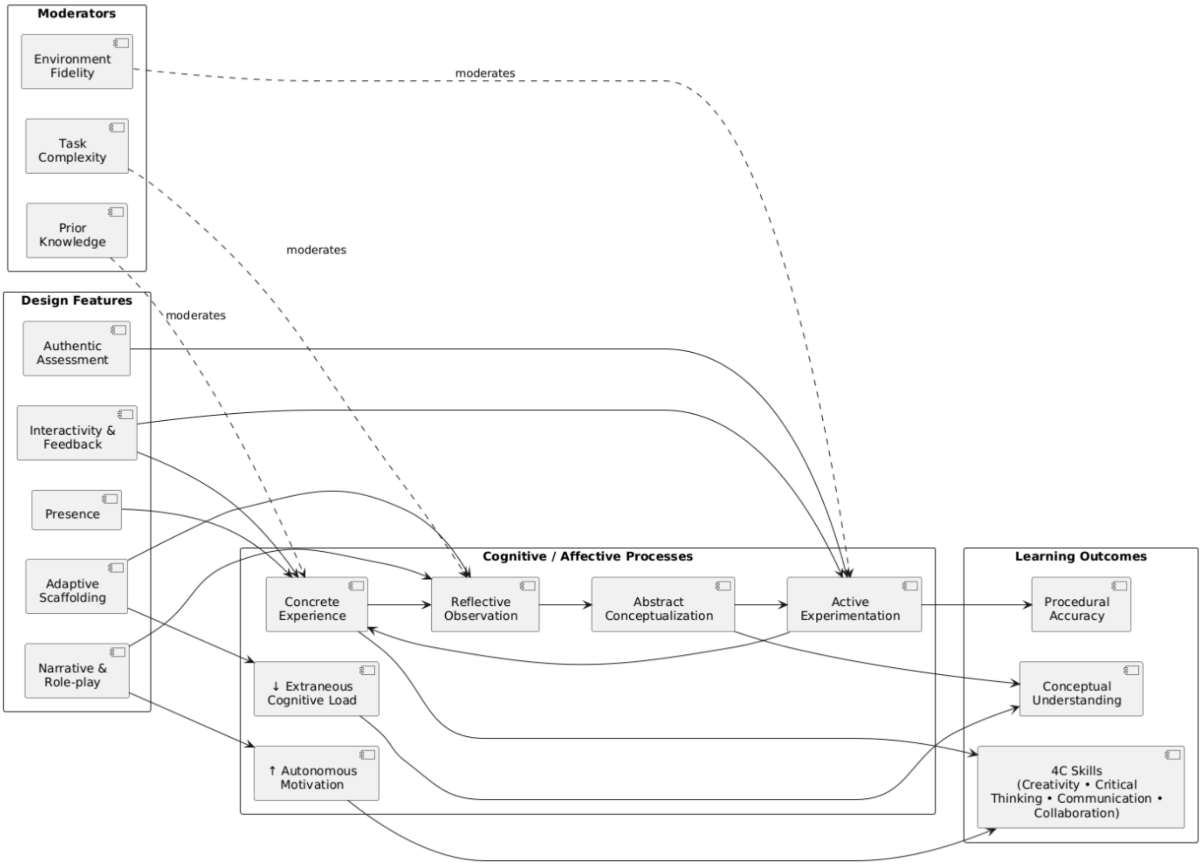

Figure 6. Conceptual framework of virtual world design, cognitive/affective processes, and learning outcomes

The interaction between design features and mediators drives Behaviors such as guided practice, problem-solving, co-construction of knowledge, and reflective learning. These behaviors are essential for deep engagement with the content and achieving meaningful learning outcomes. For instance, guided practice in virtual worlds (H. Lee et al., 2022) allows learners to practice engineering tasks safely and receive immediate feedback. Problem-solving tasks (Gu et al., 2023) help students apply concepts to realistic scenarios, further reinforcing their learning. Co-construction of knowledge, as demonstrated in collaborative missions (Campanella et al., 2022; S. M. Lee & Ahn, 2024; Nleya & Velempini, 2024), fosters teamwork and communication skills, while reflection on tasks, supported by in-world feedback mechanisms (Park & Kim, 2025; Singh & Singh, 2024; Zhang & Juvrud, 2024), enables learners to internalize their experiences and deepen their understanding of complex systems.

These behaviors ultimately lead to key Outcomes such as Conceptual Understanding, Procedural Accuracy, and the development of 4C Skills (creativity, critical thinking, communication, and collaboration). As observed in studies by (Bobko et al., 2024; Teichmann, 2025), integrating real-time feedback, avatars, and problem-solving tasks directly enhances students' conceptual understanding and procedural accuracy. Additionally, virtual worlds' immersive and interactive nature plays a crucial role in fostering the development of 21st-century competencies, equipping students with essential skills such as creative problem-solving, effective communication, and collaborative decision-making.

The model also accounts for Moderators such as domain stratum, Tier of evidence, platform fidelity, prior knowledge, and exposure time, which influence how design features and cognitive processes contribute to learning outcomes. For instance, domain stratum (E-Core vs. E-Adjacent) dictates the depth and complexity of the content being taught, while exposure time (the duration learners engage with the virtual environment) can affect the extent to which learning outcomes are achieved. Platform fidelity, as noted by (Sim et al., 2024), impacts the realism and effectiveness of the immersive experience, ensuring that simulations remain accurate and applicable to real-world contexts. In conclusion, the conceptual model in Figure 6 shows how immersive virtual worlds positively impact engineering education. By combining key features like feedback, collaboration, and support, IVEs encourage behaviors such as problem-solving and reflection. These lead to better learning outcomes in technical skills and essential 21st-century skills like creativity, critical thinking, communication, and collaboration. Although factors like platform quality and exposure time affect learning, hybrid models that mix simulations and adventure-based tasks are the most effective approach. This integrated learning helps students build technical expertise and essential soft skills, preparing them for future challenges in the engineering field.

3.7. Limitations of the review and future research direction

Despite the valuable insights provided by this review, several limitations must be addressed to improve the applicability and comprehensiveness of the findings. First, the studies reviewed primarily focus on specific domains within engineering education, such as manufacturing, industrial processes, and maintenance. This narrow focus may not fully capture the broader application of immersive virtual worlds across all engineering disciplines, including emerging fields like renewable energy, biotechnology, and robotics. As these areas become more prominent in modern engineering, it is crucial to explore how immersive virtual worlds can be integrated into these evolving fields to support specialized skill development and knowledge application. Second, the review predominantly draws on studies from Tier A and Tier B evidence, with fewer studies from Tier C. This reliance on empirical studies and pilot projects may limit the breadth of conceptual frameworks and theoretical perspectives, which could be important for a more nuanced understanding of the pedagogical effectiveness of immersive virtual worlds. Although the review offers a robust analysis of design features, it is necessary to explore how different virtual platforms and technologies, such as virtual reality (VR), augmented reality (AR), and hybrid systems, affect learning outcomes. The diversity in platform technologies requires additional exploration to understand how these environments influence learner engagement, knowledge retention, and skill development across various engineering contexts.

Moreover, while hybrid models combining simulation and adventure-based learning show promise, their implementation often requires high-quality hardware, infrastructure, and specialized teacher training. These resources may not be universally accessible, particularly for institutions with limited funding. Integrating immersive virtual environments also poses challenges related to cost-effectiveness, as the infrastructure needed to support such environments, such as VR headsets and high-performance computers, can be prohibitively expensive. Additionally, challenges such as cognitive overload and motion sickness, as identified in several studies, remain significant barriers to successfully adopting these technologies. These issues could detract from the immersive learning experience and hinder students' ability to engage with the content thoroughly.

Future research should broaden its scope to include more engineering disciplines and educational contexts, particularly focusing on vocational and professional training programs. These programs are vital for developing hands-on skills in the engineering workforce, and it is essential to explore how immersive virtual worlds can enhance these skills. Additionally, conducting longitudinal studies that track the long-term impact of immersive learning on the careers of engineering graduates could offer valuable insights into how these technologies continue to benefit students beyond the classroom. Moreover, research on the cost-effectiveness of immersive technologies in education is needed to evaluate their feasibility in resource-rich and resource-constrained settings. Understanding the economic implications will help assess scalability. User experience (UX) studies are also crucial to optimizing the design and usability of virtual environments, identifying factors that enhance or hinder engagement. Finally, examining the role of platform fidelity, exposure time, and prior knowledge on learning outcomes will allow educators to refine immersive experiences, ensuring they meet the specific needs of learners and enhance engineering education and training.

4. Conclusion

This review emphasizes immersive virtual worlds, specifically simulation and adventure worlds, that are revolutionizing engineering education within the metaverse. Immersive environments help bridge the gap between theoretical learning and real-world application, enabling students to gain technical proficiency and essential 21st-century skills such as critical thinking, creativity, collaboration, and communication. The study highlights that Simulation-dominant environments foster procedural accuracy and conceptual understanding, while Adventure-dominant environments enhance creativity and transversal competencies. Hybrid models, combining both approaches, offer the most balanced and effective pedagogical framework, allowing students to develop technical expertise and soft skills through interactive learning. While immersive virtual environments provide substantial benefits in experiential learning and digital fluency, challenges such as high infrastructure costs, technical limitations, and potential cognitive overload remain. Despite these barriers, the opportunities for scalable, remote learning and personalized education make immersive environments a promising tool for future engineering training. The review concludes that hybrid learning models are the optimal approach for integrating technical and soft skill development, and future research should focus on expanding these models across various engineering disciplines, addressing economic and technical challenges, and exploring the long-term impact of immersive learning on engineering careers.

Author's Declaration

Author contribution

Aprilla Fortuna: Conceptualization, Data Curation, Methodology, Investigation, Data Curation, Writing–Original Draft, Writing–Review & Editing, Visualization, Supervision. **Muhammad Raihan**: Methodology, Investigation, Data Curation, Formal Analysis, Writing–Original Draft, Writing–Review & Editing, Visualization. **Dimas Aulia Saputra**: Investigation, Resources, Data Curation, Formal Analysis, Writing–Review & Editing. **Juan Luis Cabanillas García**: Investigation, Resources, Data Curation, Formal Analysis, Writing–Review & Editing. **Firas Tayseer Ayasrah**: Conceptualization, Methodology, Investigation, Software, Validation, Writing–Original Draft, Writing–Review & Editing, Visualization, Supervision, Project Administration.

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Competing interest

The authors declare that there are no competing interests related to the research or publication of this article.

Ethical clearance

Not Applicable

Data availability

No applicable

AI statement

This research is written entirely in original form without any data generated by generative AI. However, the study utilized Grammarly to enhance readability and clarity of the research.

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