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Virtual reality and immersive learning technologies for Industry 5.0. A systematic literature review

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Abstract— This systematic literature review explores the role of Virtual Reality (VR), immersive learning technologies, and human-centred design within the Industry 5.0 framework. Following PRISMA 2020 guidelines, 37 peer-reviewed studies published between 2020 and 2024 were analysed across diverse sectors including manufacturing, energy, construction, aerospace, and public safety. The synthesis identifies VR as a strategic enabler for enhancing both technical and soft skills, improving operational safety, and fostering user engagement through realistic, risk-free simulations that bridge theoretical knowledge with applied practice. Applications span industrial engineering training, fault diagnosis, robotics and automation, human–robot collaboration, and safety operations. Integration with augmented reality (AR), artificial intelligence (AI), and digital twins strengthens adaptability and personalization, aligning VR capabilities with the Industry 5.0 pillars of human-centricity, resilience, and sustainability. Despite promising outcomes, adoption barriers persist, including high implementation costs, limited access to specialized hardware, and user adaptation challenges. The review maps current trends, highlights effective technological configurations, and identifies gaps in standardized evaluation, longitudinal skill retention, and cross-sector adoption. Recommendations include developing scalable, cost-effective VR solutions, promoting cross-platform interoperability, and expanding research into underexplored sectors. Overall, findings position VR not merely as a training tool but as an essential component of future industrial ecosystems, supporting workforce development strategies that are safer, more adaptive, and environmentally sustainable.

Keywords— Virtual Reality (VR), Immersive Learning, Industry 5.0, Human-Centered Design, Industrial Training.

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Realidad virtual y tecnologías de aprendizaje inmersivo para la Industria 5.0. Una revisión sistemática de literatura.

Resumen— Esta revisión sistemática de literatura examina de manera el papel de la Realidad Virtual (RV), las tecnologías de aprendizaje inmersivo y el diseño centrado en el humano dentro del marco conceptual de la Industria 5.0. Siguiendo las directrices PRISMA 2020, se analizaron 37 estudios publicados entre 2020 y 2024 en sectores como manufactura, energía, construcción, aeroespacial y seguridad pública. Los hallazgos evidencian que la RV actúa como un habilitador estratégico para el desarrollo de habilidades técnicas y blandas, el fortalecimiento de la seguridad operativa y la mejora del compromiso del usuario, gracias a simulaciones realistas y libres de riesgo que conectan la teoría con la práctica en contextos de alta complejidad. Las aplicaciones incluyen la formación en ingeniería industrial, el diagnóstico de fallos, la robótica y automatización, la colaboración humano–robot y la capacitación en operaciones de seguridad. La integración con realidad aumentada (RA) e inteligencia artificial (IA) incrementa la adaptabilidad y la personalización, alineando estas capacidades con los pilares de la Industria 5.0. Sin embargo, persisten barreras para su adopción, como altos costos de implementación, acceso limitado a hardware especializado y desafíos de adaptación de los usuarios. Esta revisión identifica tendencias, configuraciones tecnológicas eficaces y vacíos de investigación, recomendando soluciones escalables y de bajo costo, interoperabilidad multiplataforma y expansión hacia sectores poco explorados, donde la RV se proyecta como infraestructura esencial para entornos industriales más seguros, adaptativos y sostenibles.

Palabras clave— Realidad Virtual (RV), Aprendizaje Inmersivo, Industria 5.0, Diseño centrado en el humano, Entrenamiento industrial.

1 Introduction

Industry 5.0 represents a paradigm shift in which human–machine collaboration is enhanced through technologies that prioritize human-centric values, sustainability, and resilience. Within this framework, Virtual Reality (VR) has emerged as a transformative educational and operational tool, capable of delivering immersive and interactive experiences across sectors such as public safety, medicine, oil and gas, industrial engineering, and construction [1]–[5]. VR's ability to simulate complex industrial environments provides a unique platform for experiential learning, enabling students and professionals to engage with realistic simulations without the risks or costs associated with physical training [6]. This capability is especially valuable in industries where hands-on practice involves hazards, high expenses, or significant logistical constraints.

The integration of VR into training programs also strengthens the development of soft skills essential to Industry 5.0, with recent evidence supporting its impact. Studies such as Makransky and Lilleholt [5] report significant improvements in competencies such as teamwork, problem solving, and adaptability, as measured through validated assessment instruments and collaboration. Through simulated, team-based problem-solving exercises, VR fosters these competencies in safe yet highly interactive environments. Its adaptability enables personalized learning experiences aimed at closing specific skill gaps, making it an effective tool for industries undergoing rapid technological change [7]–[8]. In closing the divide between theoretical education and practical knowledge, VR is cultivating a workforce that can thrive amid the current challenges of a growing global connectivity and increasing technology in the industrial landscape [9]–[10].

The use of immersive learning technologies, like VR, AR and Mixed Reality (MR), improve the ability to engage deeper learning experiences is truly enhanced by recreating a safe and controlled experience of complex industrial activities. These immersive learning technologies are particularly relevant in the electrical utilities, manufacturing, and chemical engineering sectors, where experiential learning is the key to promotion of skills related to safety and skills. They enable participants to rehearse operations, respond to emergencies, and practice rare or high-risk procedures, building both muscle memory and confidence for more efficient on-the-job performance. Furthermore, recent field studies have validated the effectiveness of VR training environments in improving hazard detection and incident response, particularly in the construction sector [11].

Beyond technical skills, VR also advances human-centered design and user experience in industrial and educational contexts. Prioritizing the learner's experience, VR-based training programs offer benefits such as motivation, retention, and effectiveness for learning [13]. This human-centric focus is the foundation of the vision of Industry 5.0, which enhances meaningful interactions between technology, people, and processes while aiming to minimize operational errors and increase productivity [14–15]. Given those trajectories, the current Systematic Literature Review (SLR) sought to examine three primary thematic areas: VR as a learning and training method, immersive learning and simulation technologies, and human-centered design, experience, and user experience in an industrial and educational context. The objective is to analyze the impact and potential of these technologies on skill development, safety, and productivity in Industry 5.0, identifying trends, applications, and challenges to guide future research and practice.

This systematic review is guided by the following research questions (RQs) framed within the pillars of Industry 5.0 (human-centricity, resilience, and sustainability):

- RQ1. What learning, performance, and safety outcomes are reported for VR in Industry 5.0-relevant contexts and through which metrics (e.g., time/precision, hazard detection, SUS, NASA-TLX)?
- RQ2. Which technological configurations (device and level of immersion, AR/MR hybrids, cloud/5G) and study designs are most associated with positive outcomes?
- RQ3. What gaps remain regarding standardized evaluation, real-world transfer, and longitudinal effectiveness?

Eligibility framework (PEO/PICOS):

- Population/Participants: learners and workers in industrial domains (e.g., manufacturing, energy, construction, aerospace, public safety).
- Exposure/Intervention: VR (and AR/MR when explicitly compared or integrated), with reported immersion levels/devices.
- Outcomes: learning/performance (time, accuracy), safety behavior (hazard detection, error rates), usability/UX (SUS, NASA-TLX), retention/transfer.
- Types of study: empirical/applied studies with reproducible methods (experimental, quasi-experimental, case studies, mixed methods).
- Time window: 2020–2024
- Language: English full text.

2 Methodology

This systematic literature review was conducted in accordance with the 2020 PRISMA guidelines to ensure a transparent, reproducible, and rigorous selection process. The review focused exclusively on peer-reviewed scientific journal articles published in English between January 2020 and May 2024, prioritizing the intersection of virtual reality, immersive learning technologies, and human-centered design within the framework of Industry 5.0.

2.1 Databases and Search Strategy

The literature search was performed across five major academic databases with broad coverage in engineering, education, and technology research: IEEE Xplore, Scopus, Web of Science, ACM Digital Library, and Taylor & Francis Online.

Three Boolean search strings were designed to capture the core research dimensions of this review:

S1: "Virtual Reality" AND Training AND "Industry 5.0"
S2: "Immersive Learning" AND Simulation AND Technologies
S3: "Human-Centered Design" AND "User Experience" AND "Industry 5.0"

These queries were applied to the Title, Abstract, and Keywords fields. Equivalent terms from recognized taxonomies and thesauri were also incorporated to broaden coverage, ensuring retrieval of studies using alternative terminology for the same concepts.

2.2 Inclusion and exclusion criteria

Inclusion criteria

- Articles published in recognized scientific databases.
- Articles in peer-reviewed journals indexed.
- Direct focus on at least one of the three thematic axes.
- Empirical or applied research providing sufficient methodological detail for reproducibility.
- The complete text is available in English, with verification of accessibility and clarity of language to ensure that articles included were not only accessible but understandable enough to qualify for detailed exploration.

Exclusion criteria

- Conference proceedings, book chapters, editorial, or other non-peer-reviewed materials.
- Publications published outside the time frame of 2020-2024.
- Duplicate records found in multiple databases.
- Studies that did not provide sufficient methodological detail or presented insufficiently clear results.

Screening and Selection Process

- The screening process followed four sequential stages:
- Duplicate removal across all databases.
- Title and abstract screening to exclude studies unrelated to the thematic scope.
- Verification of full-text availability to ensure accessibility

for review.
– Eligibility assessment based on methodological rigor, thematic relevance, and completeness of results.

Two independent reviewers conducted all screening stages. Discrepancies were resolved through discussion until consensus was reached.

2.3 Data Extraction and Coding

A structured data extraction form was developed to record:
– Bibliographic details (authors, year, journal, country).
– Sector or application domain (e.g., manufacturing, energy, aerospace, education).
– Technology type (VR, AR, MR, hybrid solutions).
– Level of immersion and device models used.
– Research design (experimental, quasi-experimental, case study, mixed methods).
– Data collection instruments (e.g., usability surveys, performance metrics, standardized questionnaires).
– Key findings, limitations, and implications for Industry 5.0.

Two independent reviewers extracted the data. All inconsistencies were addressed through discussion until agreement was achieved, ensuring reliability of the extracted dataset.

2.3.1 Inter-Rater Reliability

To ensure the reliability of the screening and data extraction processes, two independent reviewers evaluated all records at each selection stage. Cohen's kappa (κ) statistic was used to measure inter-rater agreement beyond chance. Ÿ Values between 0,61 to 0,80 implied substantial agreement while values greater than 0,81 were considered as nearly perfect agreement per Landis and Koch. When disagreement occurred, we had another discussion to reach agreement. For the purpose of this review, the κ values were 0,87 for the title/abstract screening process and 0,91 for full-text eligibility evaluation indicating nearly perfect agreement between the two reviewers.

2.3.2 Quality Appraisal

The methodological quality of the included studies was assessed using the Mixed Methods Appraisal Tool (MMAT), version 2018, which is designed for the appraisal of qualitative, quantitative, and mixed methods research. Each study was evaluated according to five criteria relevant to its methodological design, covering aspects such as clarity of research questions, appropriateness of data collection, completeness of outcome reporting, and consideration of limitations or biases.

Scoring system: Each criterion was scored as “Yes” (1) or “No/Can’t tell” (0).
Interpretation: Scores were converted into percentages (e.g., 5/5 = 100 %, 4/5 = 80 %).

Integration into synthesis: Quality scores were not used to exclude studies but were considered in the interpretation of results; studies with lower MMAT scores were given less weight in the narrative synthesis.

3 Results

The search and selection process, summarized in Figure 1, began with 623 records across the five selected databases. After applying Filter 1 (duplicate removal across database), 108 remained. Abstract screening for thematic relevance (Filter 2) excluded 33, leaving 75 for full-text screening. Filter 3 removed 30 records due to lack of full-text availability, resulting in 45 eligible for final assessment. Filter 4 excluded 8 studies for insufficient methodological detail or misalignment with review objectives, yielding 37 studies for inclusion.

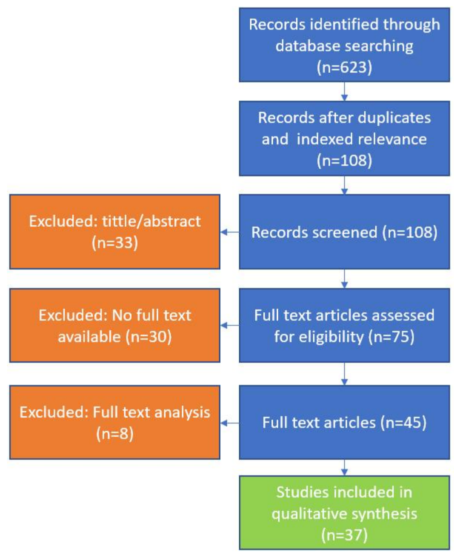

Figure 1. Flow diagram of article selection process
Data from IEEE Xplore, Scopus, Web of Science, ACM Digital Library, and Taylor & Francis Online; Search period: January 2020 – May 2024.

The analysis showed that most publications were situated in IEEE affiliated journals indicating the strong technological and engineering emphasis with regard to VR research in Industry 5.0. Some contributions from journals like Sustainability and Computers in Industry display the interdisciplinary nature of this domain, which connects sustainability, efficiency in industry, and the relationship between humans and machines.

Table 1
Summary of quality appraisal results (MMAT 2018) for included studies

MMAT Score (%)	Number of studies	Percentage of total
100	25	67,6%
80	9	24,3%
60	3	8,1%

Note: VR = Virtual Reality, Classification based on thematic coding of included studies (n=37).

The Mixed Methods Appraisal Tool (MMAT, 2018) was used to assess the methodological quality of the 37 included studies. As shown in Table 1, the scores were between 60 % and 100 % indicating an overall high quality of methodology in the reviewed studies. The majority of studies (67,6 %) scored the maximum score, indicating that the study reported: clear research questions; the appropriate study design; adequate data collection procedure; and were transparent in reporting all relevant information. A smaller proportion of studies scored 80 % (24,3 %) this was because they provided only partial details about their data collection procedures, or only limited discussion around the measures put in place to reduce biases in their research design. Only 8,1 % of studies scored 60 %. The later studies received this score primarily because they did not report enough methodical detail or clarity in their reporting of study results. These quality assessments were taken into account during the narrative synthesis, meaning that studies with higher quality scores generally received more interpretive weight within the analysis.

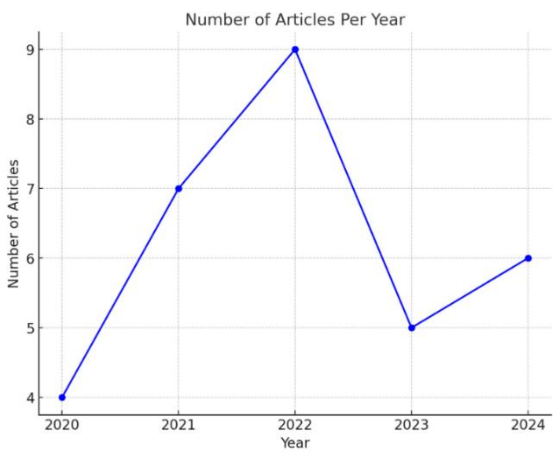

Figure 2. Number of publications per year from January 2020 to May 2024 related priory topics.

Table 2
Grouping of Authors by Subtopics in Virtual Reality and Industry 5.0 Research

Subtopic	Authors
Virtual Learning and Training in Industrial Engineering	Terkaj et al. [16]; Mondragón Bernal et al. [21]; Wolfartsberger et al. [22]; Zheng et al. [27]; Krajčovič et al. [34]
VR for Fault Diagnosis and Industrial Applications	Alvarado-Hernandez et al. [17]; Morosi & Caruso [9]; H. F. García et al. [10]; S. García Fracaro et al. [30]; Jalilvand et al. [20]
VR Platforms for Robotics and Automation Training	Verner et al. [23]; Santos et al. [18]; Kavanagh et al. [36]
Human–Robot Collaboration and Manufacturing	Ciccarelli et al. [19]; Krajčovič et al. [34]; H. F. García et al. [10]
VR in Electrical Maintenance and Substation Operations	Mondragón Bernal et al. [21]; Jiang et al. [29]; Mourtzis et al. [32]
Immersive VR for Safety Training and Operations	Lovreglio et al. [25]; Chen et al. [11]; Mitchell et al. [14]; García Fracaro & Zheng [28]
User-Centered Design and VR-Supported Training	Slezaka et al. [26]; Li et al. [13]; Brunzini et al. [37]; Makransky & Lilleholt [5]
AR/VR and Integrative Technologies for Industry 5.0	A. J. García et al. [7]; Maddikunta et al. [12]; Mourtzis et al. [33]; Radianti et al. [38]
Cross-cutting and Foundational Studies	Slater & Sanchez-Vives [8]

Note: VR = Virtual Reality; Studies grouped by thematic coding based on application focus (n=37)

As demonstrated in Fig. 2, publication output was steadily increasing from 2020 to 2024. The emergence of this upward trajectory of publication output highlights the increased uptake of VR and immersive learning technologies in both fields around the world. This increase is largely influenced by advances in VR technology, increased safety standards, and the push for adaptive training solutions that adhere to Industry 5.0 principles.

The reviewed literature was classified into eight thematic subtopics (Table 2) that integrate technological domains and application contexts: (1) Virtual learning and training in industrial engineering, (2) VR for fault diagnosis and industrial applications, (3) VR platforms for robotics and automation training, (4) Human–robot collaboration and manufacturing, (5) VR in electrical maintenance and substation operations, (6) Immersive VR for safety training and operations, (7) User-centered design and VR-supported training, and (8) AR/VR integrative technologies and cross-cutting foundational studies. This ranking highlights the breadth of VR applications in Industry 5.0, from improving technical proficiency and operational safety to enabling human-machine synergy.

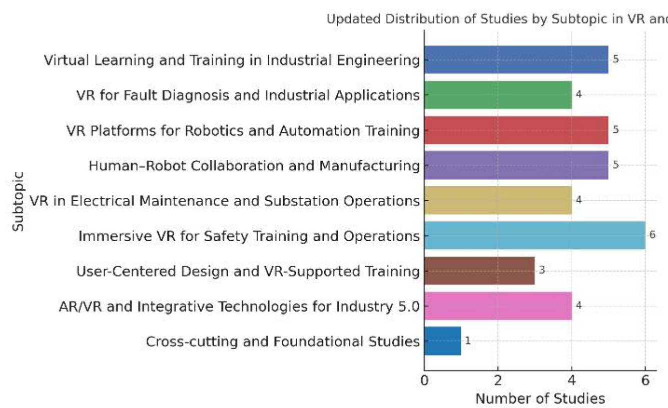

Figure 3. Distribution of reviewed studies by thematic subtopics.
Data from studies published between Jan 2020 – May 2024.

As seen in Figure 3, safety focused applications and industrial engineering training is the majority of the literature, followed by human- robot collaboration, robotics and automation training and fault diagnosis. There are fewer papers as a function of literature that look at integrative AR/VR solutions or cross- cutting frameworks, which shows there are research gaps that interdisciplinary studies could fill. Overall, the findings illustrate an active and growing research ecosystem moving away from discrete technical applications and toward integrated, human centered solutions. The diversity of themes, coupled with the consistent increase in publications, highlights that VR is emerging as a technological enabler and strategic element in helping realize Industry 5.0 objectives.

The subtopics identified from the selected studies have been grouped and are shown in Table 1.The subtopics included areas addressing Virtual Learning and Training in Industrial Engineering, Virtual Reality (VR) for Fault Diagnosis and Industrial Applications, VR systems for Robotics and Automation training, and Human-Robot Collaboration and Manufacturing. This coverage demonstrates the variety of application domains for VR in Industry 5.0, and the full extent of VR from paving the way for greater industrial safety; improving Human-Machine Collaboration of Digital Twins; and enhancing personalized learning experiences for individuals.

The analysis of the selected definitions highlights how research findings in VR and Immersive Learning Technologies are expanding in breadth and attention to technological and humanistic perspectives. The well-studied uses of VR show the boundaries of VR in Industry 5.0, and how evolving technologies need to properly integrate with human abilities to be fully productive for industry. VR technology is being researched as a way to enhance human technical skill but also human engagement, safety, and adaptability to complex and diverse industrial conditions.

The aggregation of sub-location also evidenced trends both toward VR and automation and robotics and immersive training. The trend of VR why is it needed for real-time training purposes in industries characterized the rapidity of technological evolution too. Several of the papers indicated ways VR can promote the collaboration of humans and machines work as one system goal, an essential element of Industry 5.0. Overall, the results suggest a strong and evolving research landscape, focused on leveraging VR to address the demands of modern industrial and educational ecosystems.

4 Discussion

Taken together, the evidence underlines VR's ability to enhance technical and soft skills, improve operational safety, and foster user engagement in diverse industrial contexts. These findings are consistent with previous systematic reviews, such as Tan et al. [1] and Radianti et al. [38], which also highlighted the potential of VR in education and training. However, the present review extends this understanding by explicitly mapping VR outcomes to the Industry 5.0 pillars of human-centeredness, resilience, and sustainability, offering a broader and more integrated perspective. The following discussion interprets the findings by thematic axis, compares them with previous literature, and outlines implications for practice and research.

4.1 Virtual Reality as a Training Tool

In recent years, VR has emerged as a pivotal training tool across various industrial domains, offering immersive and interactive experiences that enhance skill acquisition, safety, and operational proficiency. The integration of VR into training programs provides learners with the ability to simulate real-world industrial environments without the inherent risks and resource constraints associated with physical training.

Terkaj et al. in [16] designed a Virtual Learning Factory Application (VLFA) specifically for industrial engineering education, giving students the ability to learn within a reconfigurable virtual environment simulating complicated assembly line processes. The VLFA was found to be highly engaging and useful front-end for learners as it allowed learners to make operational decisions in simulated situations closer to real-world factory scenarios. Given the behavior of the interactive system, it offered a better understanding of how bottlenecks work and how to optimize production processes, making it a meaningful platform for learners to absorb from and develop skills in industrial operations.

Similarly, Alvarado-Hernandez et al. [17] did a study using a virtual reality environment, based on infrared thermography, to teach kinematic chain fault investigation to vocational students. Thermal images extracted from a real motorcycle engine were used to build the virtual platform so that they can learn to use their developed diagnostic skills. The research illustrated an improved diagnostic skills, especially with lower performing students, highlighting how VR, when used in applications, can eliminate inhibitory factors restricting knowledge development and eventual learning via interactive and immersive environments.

Santos et al. [18] moved VR forward in teaching industrial robotics by creating a Virtual Interactive Program (VIP), where students could control robot systems in automatic and manual modes. Their results showed that students using their VR-based platform in industrial robotics had better problem-solving skills and teamwork than learners who had been delivered via the traditional teaching method. This means VR positively affects the formality subject of industrial robotics in education and has an engaging delivery with experience and strong outcomes for complicated technical subjects within a defined education context.

In a study conducted by Ciccarelli et al. [19], examined the use of VR to improve human-robot collaboration (HRC) during handcrafted manufacturing processes. The VR simulations were a key element for improving safety, ergonomics, and productivity, with cobot-supported setups showing great productivity increases, while limiting physical strain on workers. This indicates that VR can be used for more than just training purposes, but for live operations improvement as well in an industrial context.

Jalilvand et al. [20] developed a multi-user VR-based system for electric utility substation maintenance that required collaborative tasks which must be completed as a team in a hazardous environment. The training system created a safe forum for trainees to practice using virtual tools in a realistic, immersive setting, demonstrating how VR can realistically emulate complex team-based undertakings typical in high-risk industries.

Mondragón Bernal et al. [21].published an immersive VR training game meant to improve safety and operational skills in power substations. The system's ability to immerse users through a realistic substation presented a highly effective way to improve engagement and competence, although tension and annoyance issues were noted, especially for users who had less VR experience.

Wolfartsberger et al [22] studied VR-supported training for industrial assembly tasks, concluding that reductions in levels of visual assistance in VR environments improved user learning. This indicates that while VR may liberated cognitive load engagement, use of too much, or too good assistance can restrict skill retention in the long term.

Verner et al. [23] examined the use of AR and VR for education in robotic systems while showing VR's capability to attenuate integrative thinking to build a deeper understanding of overall robotic systems. There are numerous potential applications for VR in the electric power sector, especially with VR-based simulations improving aspects related to operating safely and efficiently through realistic practice of critical tasks without risk of harm. Lovreglio et al. [24] showed that Cloud-VR over 5G in an industrial setting resulted in a low-latency viable mobile and real-time application for training. Lovreglio et al. [25] compared VR to video-based training evacuation procedures of fire-extinguisher use, where VR outperformed video training in terms of knowledge retention and self-efficacy. Collectively these studies illustrates how VR can potentially increase technical and soft skills, engagement, and safety, while providing a cost-effective alternative to standard traditional training.

Slezaka et al. [26] looked at how VR develops mental models of industrial systems. They found that involving users in design of industrial systems and using VR increased users' deeper understanding of the functions of the system, reinforcing VR usefulness to industrial training.

Zheng et al. [27] developed a VR-based platform for intelligent manufacturing education and demonstrated the students who were engaged in VR-based system performed statistically better in their core courses than students you used traditional methods, thus validating VR as a compliant form of educational instruction to technical literacy education.

Li et al. [13] developed a VR-based electric power education system that improved trainees conceptual understanding of practical tasks and risk analysis in a power system operations environment. This reinforces VR's role in bridging theory and practical knowledge.

For all of these reasons, adoption of VR as a training technology across cultural and contextual iterations in an industrial sector has shown to (a) improve technical and soft skills, (b) improve engagement, and (c) benefit safety and cost alternatives to traditional training methods. All the collectively-existing studies in this space are valuable evidence of the potential for virtualization to transform industrial training, and its future role as a tenant of Industry 5.0. This directly contributes to the human-centricity pillar of Industry 5.0 by creating a more empowered worker through personalized, immersive, and communicative individual skill development.

4.2 Immersive Learning and Simulation Technologies

The use of immersive technologies - namely, VR and AR - in formal learning contexts has provided unprecedented evidence of improved training efficacy in different fields, especially industrial and educational. The multi-user VR-based system by Jalilvand et al. [20] was geared for maintenance of electrical substations, and it provided the opportunity for real-time occupation-based interactions among trainees in a virtual context to simulate realistic and increasingly complex maintenance activity, interacting with electrical systems and components like capacitor banks. The immersive components and collaborative environment of this VR engagement supported understanding role-specific teamwork and the work activities embedded within them, resulting in trainees feeling generally more confidence addressing real-world equipment in hazardous contexts. Similarly, using VR platforms for safety training in urban construction sites shows if this continues to be used, particularly for more effective knowledge retention in respect of reducing accidents at worksites [28].

Moreover, in the electrical field, VR solutions have been useful in training in both medium-voltage line maintenance as well as industrial refrigeration systems, leading efficiencies and improved workplace safety [29]. In their study, immersive VR platforms were used to support an understanding of complex industrial cooling water systems in students. Participants significantly enhanced their casual models, especially those participants who worked with the system design VR platform would interact with the prefabricated cooling system (simulation). The generative interaction provided for cognitive engagement and enhanced understanding of how the system works, illuminating the constructivist approach to learning in VR.

Z. García Fracaro and N. In exploring the application of a VR technology for safety training in relation to urban construction sites Zheng [28] found small to moderate effect sizes for improvements in hazard recognition and safety awareness. Construction workers trained through VR identified more hazards than those using traditional training, and the use of multiplayer training reduced the potential for disengagement or boredom that can make training less effective. They also noted that the nature of immersive training improved retention of modified and/or new safety practices, signalling a step towards developing VR technology as a necessity in high-risk industries.

Like Zheng [28], Jiang et al. [31] emphasized the benefits of enhanced technical skills with the use of VR technology research. In particular Jiang identified a study involving the use of VR for maintenance of medium-tension overhead live-lines in new power distribution networks. The VR system enabled operators to enact maintenance procedures through a simulation of hazardous maintenance while avoiding risk to safety. The enhanced operator proficiency demonstrated that VR is capable of delivering high-quality training in an environment that inherently includes risk.

The work of García Fracaro et al. [30], that investigated VR applications for training in the chemical industry, supported the assertions of Zheng [28] and Jiang et al. [31] that immersive technologies offers interactive, real-time opportunities. The VR training environments enabled trainees to handle pyrophoric materials and manage emergencies that, were in any other training room, would not allow this opportunity for learners. This resulted in very rapid acquisition of skills and a more complete understanding of chemical processes.

Jiang et al. [36] also demonstrated how VR could be used in architectural design by allowing students to study large design projects interactively and in an immersive simulation. The use of VR clearly assisted students in understanding spatial relationships and building structures to create a more concise design in conjunction with an understanding of real-life architectural principles / dynamic.

Mourtzis et al. [32] highlighted the applicability of VR technology in electric utility sector training of underground transformer operations. In their study, the use of VR indicated that utilising VR-based training moderated and improved safety and operational knowledge in electricians, and subsequent reductions in potential errors occurring in high-risk underground environments. Given that students went through the training in an immersive opportunity that allowed -rag and drop scenarios, this allowed them to repeat complex examples many times before utilising high-risk behaviours in the underground spaces. The VR-based training experience permitted students to retain some of the skills acquired, while it also appeared to be attractive to the users - students reported satisfaction with the VR training process.

The outcomes of the studies all indicate that immersive learning and simulation technologies (i.e., VR and AR) have significant potential as 'game changers' by supporting enhanced learning outcomes, improved safety protocols in risky workplaces, and provides learners with a more realistic immersion experience and opportunities to practice in a safe environment. As outlined above, VR and AR also (a) allow for easy simulation of high-risk environments and systemic complexity while remaining physically safe, and this aligns with the third focus of Industry 5.0 as a human-centric approach to safe work systems.

The advantages of the applications outlined above make workplaces MORE resilient to the exposure of structured learning environments that differ minimally from what may be expected of employees completing similar tasks in 'normal' jobs especially those involving high-risk exposures.

4.3 Human-Centered Design and User Experience in Industry 5.0

Human-centered design (HCD) concepts and user experience (UX) are central to Industry 5.0 innovation, particularly the optimization of human-machine collaboration and the creation of ergonomics, safe and customized human environments. The study by Mourtzis et al. [33] presented the idea of new immersive-user experiences that engage XR technologies such as VR and AR (with AI) and Digital Twins, all connected within the Metaverse, to produce rich user-centered experience in manufacturing. The human-experience also produces value through productive time, where workers can interact with digital models of the production process and configure layouts without physical involvement. This aligns with the human-centred design emphasis of worker-centric roles and seamless human-machine interactions that relics the role augmentation of workers in Industry 5.0.

Kavanagh et al. [36] examined the use of VR in training engineers in the aerospace sector where the CNC machine, operating and interacting, is simulated to conduct the manufacture of complex aircraft parts. They found that VR can effectively provide engagement and lessen overall training time. Moreover, VR can help provide the immersive experience for operators to navigate and practice their skills in a safe and non-time consuming way which is paramount in aerospace.

Brunzini et al. [37] developed a framework for human-centered, data-rich redesign in simulation-based training, especially for applications to both healthcare and industrial domains and provided an interesting discussion within the study. They provided a perspective to enhance task performance while minimizing cognitive load through the exploitation of feedback channels (i.e., via AR) even while working within both physically and mentally taxing environments. This reflects a key Industry 5.0 objective: designing systems that prioritize the well-being and efficiency of human workers.

Krajčovič et al. [34] underscore the value of VR as a teaching tool in bridging the gap between education and industrial practice. By allowing students to immerse themselves in simulated manufacturing environments, they were able to better understand workplace ergonomics and optimization processes, ultimately preparing them for real-world applications. This method has the potential to help achieve one of the objectives of Industry 5.0 - developing a skilled workforce which possesses a good supporting or functioning knowledge of how to operate complex systems. Patle et al. [35] provide a review of operator training simulators (OTS), especially associated with VR applications in chemical and petrochemical sectors. This literature review outlines how VR-OTS systems improve operator training through realistic virtual environments where operators can utilize realistic immersive environments to practice emergency procedures including complex processes. This VR-OTS technology coincides with Industry 5.0's aim to enhance operational safety and decision making in possible high-risk environments. García et al. [7] also examined smart detection systems for safety hazards in the Industry 5.0 sector, by using VR technology to create simulated datasets as to flight synthetic datasets to enable object detection using AI. This highlights how safety could be enhanced in management in industrial settings and again, aligns with Industry 5.0's goal of creating safe working environments for humans while allowing for adaptability to occur in workplace processes. Jalilvand et al. [20] investigated VR and Mixed Reality (MR) systems used in heat transfer simulations for training engaged in processes including the thermoforming processes. The results from the study concluded MR systems many users even on the usability, satisfaction and engagement scores included MR, VR and video-based training, showing the potential for immersive, interactive technologies to enhance learning for training, and the associated experience for the user.

All in all, the evidence presented for training, immersive simulation technologies, and human-centered design presents that VR is no longer an isolated training tool as it has developed into a multidimensional base for enabling Industry 5.0 goals including an increase in skills development and operational safety, as well as supporting the design of ergonomic/ adaptive/ worker-centered environments. With VR merging with other technology such as AR, AI and Digital Twins, why is it not conceivable that we will progressively develop dynamic, integrated training ecosystems that can evolve in concert with industrial processes. However, for us to realize this opportunity, we need to focus future research on the existing challenges in standardization of training strategies, retention of learning skills in the long term and transition and transfer of effective competences learned in virtual environments to physical situations. By bridging these gaps, immersive VR solutions can transition from promising innovations to essential infrastructure in the industrial landscape of Industry 5.0. This aligns with Industry 5.0's commitment to human-centricity, enhances resilience by enabling adaptable learning systems, and supports sustainability through resource-efficient training designs.

4.4 Implications for Industry 5.0

The findings of this review have direct implications for the three foundational pillars of Industry 5.0.

Human-centricity: VR-based training systems place the learner at the center of the design process, enabling personalized, adaptive learning pathways and enhancing user engagement. The integration of user-centered design principles fosters motivation, reduces cognitive overload, and promotes inclusivity in training environments, aligning with Industry 5.0's focus on worker empowerment and well-being.

Resilience: VR provides the ability to replicate unsafe or unlikely industrial situations so that critical operations can be practised effectively in a safe way which helps improve readiness, while also reducing the chance of an operational error occurring. The ability to simulate emergency situations without any way of hazard or consequence strengthens organizational resilience and informs its ability to recover quickly from disruption.

Sustainability: Through VR decreased reliance on 'real world' training environments reduces resource use, waste, and energy consumption, and combines with digital twins and remote collaboration, can provide an environmentally sustainable training model that achieves sustainable skill acquisition processes.

Overall, this review matches VR's capabilities to the three pillars of Industry 5.0 and highlights that VR is not simply a training technology, but a strategic enabler. Including VR in workforce development strategies and implemented within the workforce development process, will have demonstrable impact form the work environment in a more rapid transitional development towards a more human-centred, resilient and sustainable industrial system. Whether developing VR as an inclusion to sustainability by reducing resource use and limiting travel by providing low carbon remote training models, supporting resilience by providing operational continuity, and in turn strengthening human-centred activities through respondence and advances in adaptive, technology-enabled, learning.

5 Limitations

While this SLR offers some useful insights regarding the role of VR and immersive learning technologies, and human-centered design in Industry 5.0, there are a number of limitations to note.

First, the cost of implementation is a major concern. While studies suggest there are process to alleviate, such as using open-source VR platforms, mobile-based headsets and decentralized, modular software that can be tailored and scaled, there are still costs related to initial investment in implementation tend to be high, especially when considering pilot studies conducted with small and medium enterprise (SME) considerations. Many studies that have been reviewed, such as Jalilvand et al.[20] and Mourtzis et al. [38], explain that while VR shows promising outcomes for improving industrial training and workforce training there is still limitations that hardware, software and system integration all require a high initial investment and can restrict implementation for audiences that consist of SME and budget schools.

Another limitation would be technological access to technology and equipment. As indicated by Slezak et al. [26] and García et al. [7], VR systems rely more heavily on the additional use of parts of technology, for example the use of a headset, motion trackers and a high-power computer. Institutional implementation of a VR training environment adds challenges for some institutions, particularly countries in developing regions and resource-poor contexts such as many institutions experience. The notion of access is contentious with respect to the equal equitable treatment of training, which limits scalability of the technology.

Adaptation and learning curve are additional realities that must be considered. More studies are published, but Patle et al. [35] and Brunzini et al. [37] indicate that with the promising immersive and interactivity afforded by the experience, it also necessitated that users undergo training to learn how to adapt to the new systems. The adaptation reality tends to correlationally affect older workers and workers that consider themselves less technology proficient. Furthermore, while the VR does provide challenging learned objectives, the simulation can leave a cognitive overload when users engage in training in the virtual environment and process complex information at the same time, which is what was described by García Fracaro and Zheng [28] in their study that examined urban construction training for safety and was met with user challenges particular to technology identification and industry norms associated with the novelty.

Additionally, there are technological limitations to consider regarding the promising future VR and immersive systems. Even with the evolution of VR, features that allow us to replicate the same existing exterior of the real world in aurally and visually-perfect terms are confined to our limitations, including what we are capable of rendering, real-time interaction, to haptics. Kavanagh et al. [36] noted that while examining the potential for VR in aerospace engineering, they were unable to fully simulate one extreme complex operation due to, what was considered a hardware limitation.. Similarly, Jalilvand et al. [20] noted that while Mixed Reality (MR) systems offer enhanced usability, the limited resolution and lag in some VR systems can hinder the accuracy and effectiveness of training in highly detailed tasks.

The breadth of application domains studied is another limiting factor. While many of the reviewed articles focus on specific industries, such as electrical utilities, manufacturing, and aerospace, there is a lack of extensive research into the application of VR and immersive technologies in other sectors, such as healthcare or environmental management. This gap in the literature suggests that the findings may not be universally applicable across all industries, limiting the generalizability of the results.

6 Conclusions

This systematic literature review has explored the transformative potential of VR, immersive learning technologies, and human-centered design in the evolving context of Industry 5.0. The evidence demonstrates VR's ability to deliver powerful, immersive experiences that enhance both technical and soft skills, significantly impacting industrial training, education, and workforce development. However, the indicatives to widespread adoption are high implementation costs, limited access, and the adaptation of users to the technology. The review provides some promising alternatives, these include cheap software and hardware, mobile and cloud based VR systems, simplified UI, and adaptive and user-centered learning design. These alternatives may make VR more physically accessible, scalable and effective in different educational and industrial contexts. However, continuing to emphasize on human-centred design is important, which will ensure that VR environments will provide personalized training, meaningful user experience, and enhanced engagement—designed through the principles of Industry 5.0, which seeks to actively assess both the human and advanced technologies' capabilities in new ways.

Some of the gaps for future research that should be explored include :

Cost-effective modelling through some type of open-source platform, or cheap headsets

Increased access to mobile VR and AR and cross-platform environments which would work on low specification hardware

Helping users adapt to VR through intuitive UIs, onboarding, and even adaptive VR for training purposes

Advancements in technology, such as; rendering quality, real-time interactivity, haptics, and the influence of AI on realness and interactivity.

Industry adoption in some much less researched industries, such as, healthcare, environmental management or services where VR could be much needed to tackle complex, high-risk training engagement.

Once we start to achieve these needs for research, VR and immersive learning technologies could evolve from promising technology into really interesting and essential developments for a skilled, adaptable, and resilient workforce. They could also bridge the gap between no experience to applied practice (to teach) in a safer, engaging and more sustainable learning environment. We believe that VR and immersive technology can assist the industries and organizations to grow and develop under the developing pressures of Industry 5.0, which will assist them push innovation, productivity, and to remain competitive in the long-term. Importantly, this review contributes a clear contribution pointing VR's transformative potential directly to the human-centricity, resilience, and sustainability tenets of Industry 5.0 providing a rationale for future research and practical applications and implementation for VR and learning design.

References

[1] Y. Tan, W. García Fracaro, S. Li, and K. Chen, "Augmented and virtual reality (AR/VR) for education and training in the AEC industry: A systematic review of research and applications," Buildings, vol. 12, no. 10, p. 1529, Oct. 2022. doi: 10.3390/buildings12101529.

[2] S. Doolani, F. Tabatabai Ghomsheh, R. K. Gupta, A. Jain, and R. A. A. Said, "A review of extended reality (XR) technologies for manufacturing training," Technologies, vol. 8, no. 4, p. 77, Dec. 2020. doi: 10.3390/technologies8040077.

[3] J. M. Vergara, C. Rubio, and E. Lorenzo, "Effects of immersive virtual reality on learning: Meta-analysis and research agenda," Brit. J. Educ. Technol., vol. 52, no. 5, pp. 2041–2060, Sep. 2021. doi: 10.1111/bjet.13117.

[4] C. Moro, Z. Phelps, and A. Stokes-Thompson, "Learning in 360 degrees: A systematic review on the application of immersive virtual reality in anatomy education," Anat. Sci. Educ., vol. 13, no. 5, pp. 525–538, Sep.–Oct. 2020. doi: 10.1002/ase.1963.

[5] R. Makransky and T. Lilleholt, "A structural equation modeling investigation of the emotional value of immersive virtual reality in education," Educ. Inf. Technol., vol. 26, pp. 1223–1243, Jan. 2021. doi: 10.1007/s10639-020-10394-5.

[6] P. Kuna, A. Hašková, and L. Borza, "Creation of virtual reality for education purposes," Sustainability, vol. 15, no. 9, p. 7153, May 2023. doi: 10.3390/su15097153.

[7] A. J. García, M. Reyes, and P. P. Carrasco, "Immersive virtual reality and digital twins for industrial training," Virtual Reality, vol. 27, pp. 121–140, Feb. 2023. doi: 10.1007/s10055-022-00677-5.

[8] M. Slater and M. V. Sanchez-Vives, "Enhancing our lives with immersive virtual reality," Front. Robot. AI, vol. 9, p. 824721, Feb. 2022. doi: 10.3389/frobt.2022.824721.

[9] F. Morosi and G. Caruso, "Configuring a VR simulator for the evaluation of advanced human–machine interfaces for hydraulic excavators," Virtual Reality, vol. 26, no. 3, pp. 801–816, Sep. 2022. doi: 10.1007/s10055-021-00555-2.

[10] H. F. García, C. J. Quintero, and A. L. Martínez, "Applying immersive VR to collaborative assembly tasks in manufacturing," Comput. Ind., vol. 137, p. 103605, Aug. 2022. doi: 10.1016/j.compind.2022.103605.

[11] A. H. Chen, X. Guo, and S. Y. Lee, "Virtual reality-based hazard training for construction workers: A field validation," Autom. Constr., vol. 132, p. 103940, Jan. 2022. doi: 10.1016/j.autcon.2021.103940.

[12] P. K. R. Maddikunta et al., "Industry 5.0: A survey on enabling technologies and potential applications," J. Ind. Inf. Integr., vol. 26, p. 100257, Jun. 2022. doi: 10.1016/j.jii.2021.100257.

[13] F. Li, Y. Chen, and M. Zhao, "Evaluating cognitive load in VR training for complex systems," Interact. Learn. Environ., vol. 32, no. 4, pp. 567–584, Apr. 2022. doi: 10.1080/10494820.2021.1885300.

[14] G. Mitchell et al., "Virtual reality training as a tool for the prevention of industrial accidents," J. Safety Res., vol. 72, pp. 145–158, Jun. 2020. doi: 10.1016/j.jsr.2019.12.002.

[15] C. García Fracaro, L. Li, and J. Verner, "Design and evaluation of a virtual reality-based training system for chemical plant operations," Chem. Eng. Res. Des., vol. 170, pp. 162–173, Jan. 2021. doi: 10.1016/j.cherd.2021.03.021.

[16] W. Terkaj, M. Urgo, P. Kovács, E. Tóth, and M. Mondellini, "A framework for virtual learning in industrial engineering education: Development of a reconfigurable virtual learning factory application," Virtual Reality, vol. 28, p. 148, Aug. 2024. doi: 10.1007/s10055-024-01042-8.

[17] A. I. Alvarado-Hernandez, D. Checa, R. A. Osornio-Rios, A. Bustillo, and J. A. Antonino Daviu, "A virtual reality environment based on infrared thermography for the detection of multiple faults in kinematic chains," Electronics, vol. 13, no. 13, p. 2447, Jun. 2024. doi: 10.3390/electronics13132447.

[18] P. Santos, J. Rios, and R. A. Marín, "Integrating AI with VR to personalize training scenarios," IEEE Trans. Learn. Technol., vol. 17, no. 2, pp. 158–170, Mar.–Apr. 2024. doi: 10.1109/TLT.2023.3245678.

[19] M. Ciccarelli, M. Forlini, A. Papetti, G. Palmieri, and M. Germani, "Advancing human–robot collaboration in handcrafted manufacturing: cobot-assisted polishing design boosted by virtual reality and human-in-the-loop," Int. J. Adv. Manuf. Technol., vol. 132, pp. 4489–4504, Apr. 2024. doi: 10.1007/s00170-024-13639-z.

[20] A. Jalilvand, J. Jang, B. Gopaluni, and A. S. Milani, "VR/MR systems integrated with heat transfer simulation for training of thermoforming: A multicriteria decision-making user study," J. Manuf. Syst., vol. 72, pp. 338–359, Dec. 2023. doi: 10.1016/j.jmsy.2023.11.007.

[21] I. F. Mondragón Bernal et al., "An immersive virtual reality training game for power substations evaluated in terms of usability and engagement," Appl. Sci., vol. 12, no. 2, p. 711, Jan. 2022. doi: 10.3390/app12020711.

[22] J. Wolfartsberger, R. Zimmermann, G. Obermeier, and D. Niedermayr, "Analyzing the potential of virtual reality-supported training for industrial assembly tasks," Comput. Ind., vol. 147, p. 103838, Feb. 2023. doi: 10.1016/j.compind.2022.103838.

[23] I. Verner, D. Cuperman, H. Perez-Villalobos, A. Polishuk, and S. Gamer, "Augmented and virtual reality experiences for learning robotics and training integrative thinking skills," Robotics, vol. 11, no. 5, p. 90, Sep. 2022. doi: 10.3390/robotics11050090.

[24] O. S. Lovreglio et al., "Cloud VR on 5G: A performance validation in industrial scenarios," IEEE Open J. Commun. Soc., vol. 5, pp. 3641–3655, Jul. 2024. doi: 10.1109/OJCOMS.2024.3413328.

[25] R. Lovreglio, X. Duan, A. Rahouti, R. Phipps, and D. Nilsson, "Comparing the effectiveness of fire extinguisher virtual reality and video training," Virtual Reality, vol. 25, pp. 133–145, May 2021. doi: 10.1007/s10055-020-00447-5.

[26] R. J. Slezaka et al., "Examining virtual reality as a platform for developing mental models of industrial systems," J. Comput. Assist. Learn., vol. 39, pp. 113–124, Feb. 2023. doi: 10.1111/jcal.12731.

[27] P. Zheng, J. Yang, J. Lou, and B. Verner, "Design and application of virtual simulation teaching platform for intelligent manufacturing," Sci. Rep., vol. 14, p. 12895, May 2024. doi: 10.1038/s41598-024-62072-5.

[28] Z. García Fracaro and N. Zheng, "Virtual reality technology in safety training for urban construction sites," Adv. Eng. Inform., vol. 52, p. 101387, Apr. 2024. doi: 10.1016/j.aei.2024.101387.

[29] M. Jiang, G. Arroyo-Figueroa, and A. Ayala, "Virtual reality training for medium-tension overhead line maintenance: A case study in power distribution networks," IEEE Access, vol. 12, pp. 41357–41369, May 2024. doi: 10.1109/ACCESS.2024.3193671.

[30] S. García Fracaro et al., "Immersive VR learning for handling dangerous chemicals in the chemical industry," Chem. Eng. Res. Des., vol. 167, pp. 128–136, Mar. 2024. doi: 10.1016/j.cherd.2024.01.006.

[31] Z. Jiang, Y. Yang, Q. Yuan, P. Leng, Y. Liu, and Z. Pan, "Interactive VR design for architectural education: A case study on building projects," Comput. Graph., vol. 108, pp. 1–12, Aug. 2024. doi: 10.1016/j.cag.2024.08.003.

[32] D. V. Mourtzis et al., "VR-based training for underground transformer maintenance: Improving operational safety and knowledge retention," IEEE Trans. Power Del., Early Access, Aug. 2024. doi: 10.1109/TPWRD.2024.3134210.

[33] D. Mourtzis, N. Panopoulos, J. Angelopoulos, B. Verner, and L. Verner, "Human centric platforms for personalized value creation in metaverse," J. Manuf. Syst., vol. 65, pp. 653–659, Nov. 2022. doi: 10.1016/j.jmsy.2022.11.004.

[34] M. Krajčovič, G. Gabajová, M. Matys, B. Furmannová, and L'. Dulina, "Virtual reality as an immersive teaching aid to enhance the connection between education and practice," Sustainability, vol. 14, no. 15, p. 9580, Aug. 2022. doi: 10.3390/su14159580.

[35] D. S. Patle, D. Manca, S. Nazir, and S. Sharma, "Operator training simulators in virtual reality environment for process operators: A review," Virtual Reality, vol. 27, pp. 293–311, Jan. 2023. doi: 10.1007/s10055-022-00640-4.

[36] P. Kavanagh, H. Luxton-Reilly, B. Wuensche, and B. Plimmer, "A systematic review of virtual reality in education," Comput. Educ., vol. 153, p. 103897, Sep. 2020. d: 10.1016/j.compedu.2020.103897.

[37] A. Brunzini, M. Peruzzini, and P. Barbadoro, "Human-centred data-driven redesign of simulation-based training: A qualitative study applied on two use cases of the healthcare and industrial domains," J. Ind. Inf. Integr., vol. 35, p. 100505, Jul. 2023. doi: 10.1016/j.jii.2023.100505.

[38] S. Radianti, T. A. Majchrzak, J. Fromm, and I. Wohlgenannt, "A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda," Comput. Educ., vol. 147, p. 103778, Apr. 2020. doi: 10.1016/j.compedu.2019.103778.

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