# A Review on Enabling Technologies of Industrial Virtual Training Systems

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## ABSTRACT

Industrial training increasingly uses computer technologies to boost efficiency, effectiveness, and safety. Virtual reality (VR), augmented reality (AR), and e-learning platforms have transformed traditional training methods. This review examines these technologies and highlights their applications in various sectors. The review addresses adoption challenges, including high costs, technical complexity, user acceptance, learning curves, simulation realism, and health concerns. It proposes strategies to mitigate these issues, such as cost-effective solutions, improved usability, enhanced realism, and robust assessment mechanisms. By analyzing multiple studies, the paper provides insights into the current state and future directions of technology-enabled industrial training, emphasizing ongoing innovation and adaptation to maximize these advanced tools' potential.

## KEYWORDS

Virtual Reality (VR), Augmented Reality (AR), Industrial Training, Gamification, Adaptive Learning, Simulation Training, Training Systems, Industrial Education

## INTRODUCTION

Workforce training is necessary to ensure workers are skilled, safe, and productive in the fast-changing world of industrial operations. Traditional training methods typically require the trainee and trainer to be physically present and involve hands-on practice with actual work environments and objects. These methods face challenges in terms of scalability, cost, and adaptability to the diverse learning needs of trainees. New technologies have been adopted and developed to address these issues, fundamentally transforming how industrial training is delivered and experienced.

Virtual Reality (VR) and Augmented Reality (AR) lead this technological change, offering immersive and interactive training environments that closely mimic real-world tasks. These technologies allow trainees to practice complex tasks in a safe, controlled setting, reducing the risk of accidents and permitting repeated practice without wearing or wasting actual equipment and parts. The immersive nature of VR creates a highly engaging learning experience, making it particularly effective for training in hazardous or high-risk environments. AR, on the other hand, overlays digital information onto the physical world, providing real-time instructions and visual aids that enhance task performance and reduce cognitive load.

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Beyond VR and AR, digital learning platforms and adaptive learning tools offer flexible, scalable, and personalized training experiences that cater to the varied needs of today's industrial workforce. E-learning and web-based training platforms are crucial for industrial training, providing the flexibility of remote learning and allowing employees to access training materials at their convenience. These platforms often use multimedia elements such as videos, interactive modules, and quizzes to enhance engagement and retention. However, while these methods increase training scalability and reduce costs, they may lack the immersive content necessary for complex industrial training.

Despite the promising potential of these advanced technologies, their adoption is not without challenges. High initial costs, technical complexities, user acceptance, and health concerns are significant barriers. The initial investment for developing and implementing VR, AR, and MR systems can be substantial, deterring many organizations from adopting these technologies. Technical complexity requires specialized knowledge and skills for effective use, posing an entry barrier for some users. User acceptance is another critical factor, as the effectiveness of these training tools depends mainly on the willingness and ability of trainees to engage with them. Health concerns, such as motion sickness and visual strain from prolonged use of VR headsets, also need addressing.

Researchers have proposed various strategies to mitigate these limitations. Implementing cost-effective solutions, such as utilizing low-cost VR setups and leveraging existing technologies, can significantly reduce the financial burden of adopting these systems. Improved usability through intuitive interfaces and user-friendly designs can enhance user acceptance and engagement. Enhancing simulation realism through high-quality 3D rendering, haptic feedback, and immersive theater setups can provide a more authentic and effective training experience. Robust assessment mechanisms, including standardized evaluation methods and comprehensive feedback systems, are essential for measuring these training tools' effectiveness and identifying improvement areas.

This review paper aims to provide a thorough overview of the enabling technologies behind industrial virtual training systems, including VR, AR, and conventional virtual training methods like e-learning and training platforms. The paper explores how these technologies are used in industrial settings and their impact on training outcomes. The paper examines the limitations and challenges of these technologies and offers methodologies to address these issues. By analyzing findings from multiple studies, this paper aims to be a valuable resource for researchers, practitioners, and decision-makers looking to leverage technology-enabled industrial training.

## THEORETICAL BACKGROUND

The following sections provide detailed explanations of the core technologies that form the foundation of industrial virtual training. These include the definitions and applications of AR, VR, MR, e-learning, digital learning platforms, gamification, and adaptive learning tools. Understanding these concepts is crucial for comprehending the broader discussion on the applications, challenges, and mitigation strategies of virtual training in industrial settings.

### Definition of Virtual Training

Virtual training uses computer-based technologies to deliver educational content and training exercises. This approach allows the trainee to consume training materials, practice, and be evaluated by the evaluator remotely. Virtual training encompasses a wide range of technologies, including augmented reality (AR), virtual reality (VR), mixed reality (MR), and e-learning.

### Augmented Reality (AR)

Augmented Reality (AR) overlays multimedia information such as images, videos, instruction, or 3D models onto the physical space through smartphones, tablets, or AR glasses. In industrial training, AR can provide real-time instructions and visual aids to workers, helping them perform tasks more accurately and efficiently by augmenting their physical environment with relevant digital content.

AR technology has improved learning outcomes of procedural tasks and task performance in various industrial applications (Liu et al., 2020; Oliveira et al., 2007).

### Virtual Reality (VR)

Virtual Reality (VR) creates an immersive environment and completely isolates users from the physical world. Users interact with this environment through VR headsets and controllers, which track their movements and allow them to interact with virtual objects. VR is widely used in industrial training to introduce trainees to complex tasks, hazardous environments, or actual work scenarios. VR training has proven effective in enhancing skills and reducing the risk of accidents in industrial settings (Hoedt et al., 2017; Radhakrishnan, Koumaditis, et al., 2021).

### Mixed Reality (MR)

Mixed Reality (MR) combines the characteristics and elements of both AR and VR. It blends the physical and digital worlds to create an interactive environment where real and virtual objects coexist. MR devices enable users to manipulate digital objects within their physical space, making them particularly useful for collaborative industrial training and simulation of complex tasks. MR technology facilitates enhanced interaction and collaboration in training environments (Reyes et al., 2020).

### E-Learning

E-learning uses digital media and technologies to deliver educational content. It typically involves web-based platforms that provide access to courses, tutorials, videos, and interactive modules. E-learning allows learners to study at their own pace and convenience, making it a flexible and scalable option for industrial training. This method often includes multimedia elements to enhance engagement and retention, and it has been widely adopted for its cost-effectiveness and accessibility (Illyefalvi-Vitez et al., 2006; Martinetti et al., 2020).

### Digital Learning Platforms

Digital learning platforms are comprehensive systems that support the delivery, management, and tracking of outcomes of training programs. These platforms often integrate various technologies, including e-learning, VR, and AR, to provide a cohesive training solution. The platform generally comprises content libraries, interactive modules, learning assessments, and analytics to monitor learner progress. Such platforms significantly improve training programs' scalability and efficiency (Costa et al., 2014; Radhakrishnan, Chinello, et al., 2021).

### Gamification

Gamification is a methodology that involves incorporating game design elements, such as points, badges, leaderboards, and challenges, into training programs to increase engagement and motivation. In industrial training, gamification can make learning more interactive and enjoyable, encouraging trainees to complete tasks and achieve learning objectives (Bohne et al., 2023; Uletika et al., 2020).

### Adaptive Learning Tools

Adaptive learning tools use algorithms and data analytics to personalize the learning experience based on each learner's needs and performance. It automatically adjusts the training modules' content, pace, and difficulty, ensuring learners receive the proper challenge and support to optimize learning outcomes. Doing so increases training programs' efficiency and effectiveness (Martinetti et al., 2020; Tafakur et al., 2023).

These fundamental concepts and technologies are essential for comprehending the broader discussion on the applications, challenges, and mitigation strategies of virtual training in industrial settings. Each of these technologies offers unique benefits and can be integrated to create effective and engaging training programs that meet the diverse needs of various industries.

## PREVIOUS SYSTEMATIC LITERATURE REVIEWS

Several systematic literature reviews have explored virtual and augmented reality use in industrial training, providing comprehensive insights into current research trends, challenges, and effectiveness. Here are three selected previous reviews.

The first related review paper under consideration is the latest review, published in 2024. The study analyzed 60 relevant articles from Scopus and Web of Science, highlighting the growing trend in AR research and identifying key challenges such as technological adoption in complex industrial environments. The review revealed a significant increase in AR-related publications, with China leading in contributions, followed by the United States, Spain, and Italy (Morales Méndez & Del Cerro Velázquez, 2024).

The second review performs a comprehensive review of immersive mediums by assessing the effects of augmented reality (AR), virtual reality (VR), and mixed reality (MR) on performance in manual assembly task training. The findings indicated that AR-based training significantly improves performance, while VR-based training is comparable to traditional methods. Mixed reality training showed similar effectiveness to conventional approaches. The review also identified research gaps, including the need for realistic use cases and diverse sample populations (Daling & Schlittmeier, 2024).

The third review, focusing on immersive VR technologies for industrial skills training, emphasized the application of VR in sectors such as healthcare, manufacturing, and defense, highlighting the importance of parameters like immersion, presence, and memory in effective VR training. The study noted the underrepresentation of immersion in existing research and called for further investigation into these critical factors (Radhakrishnan, Koumaditis, et al., 2021).

These reviews collectively provide valuable insights into virtual and augmented reality research in industrial training, emphasizing these technologies' potential benefits and challenges. They also emphasize the need for continued research to address existing gaps and optimize the effectiveness of VR and AR training systems in industrial settings.

## REVIEW PROCESS

The review process for this paper involved a comprehensive and systematic approach to identify, select, and analyze relevant literature on the use of virtual and augmented reality in industrial training. The papers were screened based on specific inclusion and exclusion criteria, detailed in the subsections below.

### Literature Search

A comprehensive literature search was conducted using academic databases, including Scopus, IEEE Xplore, and ACM Digital Library. The search utilized the following keywords: “virtual training,” “e-learning,” “online training,” “digital training,” “industrial skills,” “industrial training,” “manufacturing skills,” “industrial workforce,” and “manual assembly.” The search focused on articles published in peer-reviewed journals, conference proceedings, and review papers from the past two decades to capture the evolution and current trends in the field.

### Inclusion and Exclusion Criteria

Specific inclusion and exclusion criteria were established to ensure the relevance and quality of the reviewed studies. The inclusion criteria encompassed studies focused on applying VR, AR, MR, and e-learning in industrial training environments. These included papers published in peer-reviewed journals, reputable conference proceedings, and studies providing empirical data, systematic reviews, or meta-analyses. Conversely, the exclusion criteria ruled out studies that did not specifically address industrial training. Importantly, this includes the exclusion of studies related to industrial assistant systems, as most AR papers fall under that category. Additionally, articles focusing solely on technical specifications without application context, papers published in non-peer-reviewed sources, and studies unrelated to VR, AR, MR, or e-learning technologies were also excluded.

### Selection of Studies

Given the substantial size of the combined database, which comprised 404 publications, filtering methods reduced the dataset to a manageable number. Initially, ten records were removed due to the inability to access the full text, and 13 were marked as duplicates. Subsequently, 95 records were excluded because some BIB entries contained only the conference proceeding names for unknown reasons when the selected papers were exported as a BIB file. After reviewing their titles and abstracts, many papers were eliminated, as they belonged to irrelevant domains of virtual training systems. This review paper focuses solely on industrial use cases. In the end, 65 papers were selected for full-text review.

### Data Extraction and Synthesis

After selecting studies, the authors carefully extracted essential information from selected papers, including the authors' names, publication year, objectives, methodologies, and findings. The data were then systematically organized to facilitate thematic analysis and synthesis. The thematic areas included the effectiveness of training technologies, technological challenges, and strategies for mitigating these challenges.

### Analysis and Interpretation

The extracted data were analyzed thematically to identify common trends, challenges, and opportunities in using VR, AR, MR, and e-learning for industrial training. The findings were interpreted in the context of existing literature, and gaps were identified to guide future research.

### Presentation of Findings

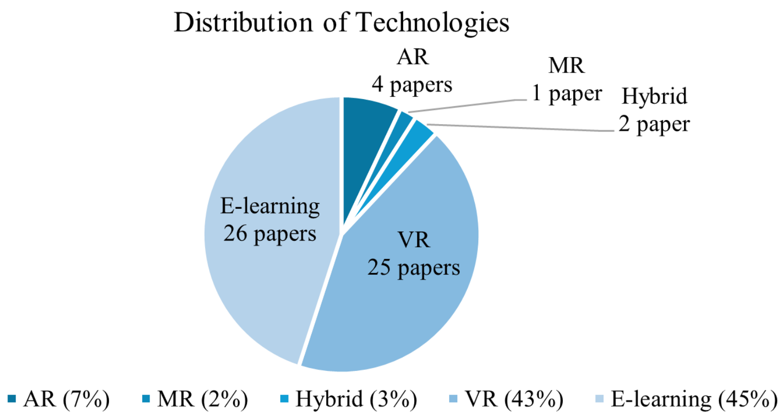
The review results were systematically presented, highlighting key insights, trends, and implications for practice and research. The synthesis of findings aimed to provide a comprehensive understanding of technological advancements in industrial training and offered recommendations for future research and implementation.

This systematic review process ensured a thorough and rigorous examination of the literature, providing a robust foundation for understanding the role and impact of technologies in industrial training.

## TECHNOLOGIES UTILIZED IN INDUSTRIAL VIRTUAL TRAINING SYSTEMS

Industrial virtual training systems utilize advanced technologies to create effective, immersive, and interactive learning environments. These systems are designed to address the unique challenges of industrial training, such as safety, cost, and the need for hands-on experience. By integrating technologies like virtual reality (VR), augmented reality (AR), and mixed reality (MR), along with digital twins, simulation technologies, and adaptive learning systems, these training programs offer scalable and flexible solutions. This section explores the technologies utilized in industrial virtual training systems and their contributions to enhancing the training process. Figure 1: Visualize the distribution of technology usage as a pie chart showing the number of papers focusing on various technologies.

**Figure 1. Distribution of technologies in industrial training studies**




## Virtual Reality (VR)

Integrating Virtual Reality (VR) into industrial training has significantly transformed traditional methods. This review highlights the enhancement of industrial training through immersive VR, the implementation of VR systems and tools, comparative evaluations of VR training versus conventional methods, and specific applications of VR training across different industries. The findings demonstrate VR technology's impact on improving training outcomes, user engagement, and knowledge retention, making it a valuable tool for modern industrial education.

Several studies emphasize the impact of immersive VR on industrial training. Training for detecting faults in electric motors has halved training time and improved knowledge retention compared to traditional methods (Caiza, Riofrio-Morales, Robalino-Lopez, et al., 2021) . Various motivations exist for adopting VR over conventional methods, including the technological characteristics of VR training, which have been reported to result in positive outcomes such as increased trainee motivation (Radhakrishnan, Chinello, et al., 2021). Positive computing principles in VR training scenarios using 360° panoramas of natural environments enhanced user experience by leveraging the psychological benefits of natural environments and customization (Gattullo et al., 2021, 2022). VR-based automotive assembly training leads to positive skill transfer and retention comparable to conventional methods by being realistic, engaging, and offering repeated practice (Boonmee et al., 2020). Additionally, VR training systems can reduce the need for physical training setups, lowering costs and logistical challenges. A study on the effectiveness of a low-cost VR system for procedural tasks emphasized the importance of tactile interaction and immersion (Grajewski et al., 2018).

Training in VR is beneficial for specialized educational skills and novice workers. The VR-Mine application simulates an underground VR environment for improving mining engineering education by integrating blended learning, gamification, and flipped classroom concepts. This project emphasizes health, safety, and complex 3D processes, enhancing student motivation and learning outcomes (Suppes et al., 2019). Controlled user studies showed that immersive VR environments with image cues significantly improved user performance compared to non-immersive setups with text cues by enhancing accuracy, speeding up task completion, and providing an effective training tool for complex manual assembly tasks (Dwivedi et al., 2018). VR training in a power plant environment led to better compliance with safety protocols and higher user engagement than traditional methods (Avveduto et al., 2017). VR training for industrial hydraulic maintenance showed no significant differences in performance compared to conventional methods, although VR training boosted confidence, especially for novice users (Hoang et al., 2022).

Various studies have implemented VR systems and tools to enhance industrial training. Observational learning in VR, combined with hands-on practice, has led to better skill transfer to real-world contexts (Fitton et al., 2024). A VR system with a Delta robot for tactile interaction enhanced training for manual assembly tasks by emphasizing the importance of tactile sensations and immersion (Grajewski & Hamrol, 2023). VR training in the electric vehicle industry highlighted cost-effectiveness and efficiency, enhancing training outcomes and providing an intuitive system for large-scale worker training (Boonmee et al., 2020). VR systems also addressed the high training costs and lengthy production times of conventional training by simulating a realistic virtual environment with interactive feedback and error demonstration (Liu et al., 2020). A field study in an automotive factory evaluated an immersive virtual reality training environment (VTE) for assembly training (Schwarz et al., 2020). The research findings indicate that the VTE led to a positive transfer of procedures to physical assembly with performance improvements over time, and it highlights benefits such as flexibility, time savings, and material protection. The "Interactive Virtual Elements" concept enhances the clarity and comprehensiveness of maintenance training by allowing for realistic simulations of maintenance tasks (Li et al., 2018). A system was developed to support procedural learning and skill development through haptic devices, providing comprehensive user interaction (Bhatti et al., 2008). VR training environments significantly improve object assembly skills, with users achieving high task performance scores by providing realistic simulations, enabling repetitive practice, offering immediate feedback, supporting cognitive learning, and facilitating physical interaction (Jia et al., 2009). An architecture for VR-based training systems using Petri nets formalism demonstrated feasibility and effectiveness through a CNC milling operations training prototype (Lin et al., 2002). VR technology contributes significantly to training efficacy by providing interactive and repeatable training sessions. This interactivity supports cognitive learning and procedural skill development, allowing trainees to practice until they achieve proficiency.

Various methods and techniques have been employed to design and implement VR-based training systems, enhancing their practicality. An immersive authoring tool for VR-based training enables trainers to create detailed training modules and procedures, particularly for engineering components like wind turbines, without needing a VR expert's intervention (Cassola et al., 2021, 2022). Another innovative method, "Authoring-by-Doing," allows experts to record their actions in a VR environment, creating semi-transparent 'ghost' animations that trainees can mimic interactively (Wolfartsberger & Niedermayr, 2020). Combining adaptive learning with VR has emphasized the impact of strategic educational policies on industry performance by offering a multifaceted approach to training that benefits both organizations and employees (Martinetti et al., 2020). Agile methodologies applied to VR training systems for calibrating and assembling transmitters in the oil and gas industry improve functionality and usability, as these methods enable iterative development and user evaluation (Lozada-Martinez et al., 2019). A low-complexity method was designed to simplify the authoring of an interactive virtual maintenance training system, facilitating more accessible and more effective maintenance training for the heavy industry sector (Li et al., 2018). A modular approach integrates multiple processing modules running in parallel, leveraging multi-core processors to enhance system performance by enabling parallel processing, ensuring scalability, and supporting event-driven operations. This modular approach contributes to a more efficient and responsive user experience, ensuring robust and flexible training environments. In addition, using haptics in VR environments provides realistic force feedback, enhancing user engagement and training effectiveness (Jia et al., 2009). Transforming CAD models into interactive VR models for industrial equipment maintenance training highlights the significance of logical objects, user interaction points, and animations (Oliveira et al., 2007). Moreover, VR systems like the Virtual Mentor, which offers real-time assistance and error detection, further improve training outcomes by providing immediate, personalized feedback, reducing learning time, and enhancing learner engagement and confidence (Schwarz et al., 2020).

Integrating Virtual Reality (VR) into industrial training has significantly enhanced traditional methods by improving training outcomes, user engagement, and knowledge retention. Studies demonstrate that VR can halve training time, improve knowledge retention, and increase trainee motivation through realistic, interactive environments. Applications like VR-Mine for mining education and VR-based automotive assembly training show positive skill transfer and retention results. By providing effective, scalable solutions, VR also addresses high training costs and logistical challenges. Various techniques, such as immersive authoring tools, "Authoring-by-Doing," adaptive learning, and agile methodologies, have enhanced VR training systems. These systems offer realistic simulations, immediate feedback, and support for cognitive learning and physical interaction, making VR a valuable tool for modern industrial education.

## Augmented Reality (AR)

Recent publications demonstrate that augmented reality (AR) technologies have significantly transformed industrial virtual training systems. By integrating virtual and physical training environments, AR reduces cognitive load and helps clarify the complex underlying structures of tasks.

HoloCollab is a multi-user AR training system that uses spatially aware head-mounted displays (HMDs) for physical assembly training. It integrates scalable virtual industrial scenarios with on-site trainers, enhancing training efficiency and accessibility. This system's research underscores the benefits of AR-based training environments, proposing a collaborative learning space design. HoloCollab has the potential to revolutionize traditional hands-on training by combining virtual and physical training elements (Funk et al., 2017).

Another study evaluated the use of virtual humans in AR for industrial assistance, comparing 3D registered presentations with 2D screen-aligned presentations. The findings indicate that 3D-registered virtual humans with assistive behavior can significantly reduce cognitive load and errors, making them valuable for complex tasks requiring high cognitive attention. This study highlights the benefits of integrating virtual humans in AR, suggesting that this approach can enhance learning experiences, improve task performance, and increase engagement in industrial settings (Lampen et al., 2020).

Projection-based AR technology, which displays information directly onto the physical environment without requiring users to wear or hold display devices, is particularly effective in training scenarios where hands-on experience is critical, such as equipment maintenance, assembly procedures, and safety protocols. AR-based training can improve learning outcomes and operational efficiency by enhancing trainee engagement and providing clear, attainable goals. Integrating Self-Determination Theory (SDT) principles, such as clear goals and meaningful rationale, into AR training modules has been shown to positively influence perceived competence, intrinsic motivation, and task execution quality, thereby enhancing overall training effectiveness (Dhiman et al., 2024).

A conceptual framework for an adaptive AR-based digital guidance system tailored to high-mix, low-volume manual assembly environments has been proposed. This system employs a multi-mode assembly assist approach, adapting guidance based on task complexity and user experience levels. Integrating AR technology addresses traditional paper instructions' cognitive limitations and enhances assembly tasks' efficiency and accuracy. The framework includes an assembly information manager to track product variations and user performance, ensuring tailored and adaptive guidance. This approach reduces cognitive workload and enhances task comprehension (Gan et al., 2022).

These studies underscore the transformative potential of AR technologies in industrial training. AR systems such as HoloCollab and adaptive guidance frameworks improve learning outcomes and task performance while providing a more engaging and interactive training experience by offering scalable, flexible, and efficient solutions.

## Mixed Reality (MR)

Mixed Reality (MR) technology, which blends real and virtual worlds, is increasingly being utilized in industrial virtual training systems to enhance the learning experience and improve practical skills. One notable example is the Mixed Reality Guidance System (MRGS) for motherboard assembly (Reyes et al., 2020). The MRGS integrates MR with Tangible Augmented Reality to simulate hands-on manual assembly tasks without real-world parts. It uses tangible substitutes like illustration board cutouts of motherboard components covered with image markers to augment their 3D virtual counterparts. These substitutes allow users to interact with virtual objects as if they were real. Key elements of the system include natural interaction with virtual objects, a head-mounted display for an immersive experience, affordable technology choices, and a Guidance Module for real-time instructional feedback. The study participants revealed high usability scores for the system. They were satisfied with the effective guidance for assembly tasks, finding the interaction with the system natural and intuitive. Additionally, the system's immediate feedback further aids the learning process. The system enhances training programs, improves learning outcomes, and makes technical education more accessible by providing hands-on experience without physical components.

## Hybrid Technology Combining VR and AR

VR and AR technologies significantly enhance industrial training and operations by creating immersive learning environments and providing real-time visual assistance, which improves task efficiency and reduces errors. VR's immersive capabilities facilitate safe and effective training through interaction with digital twins, while AR overlays virtual content onto the physical world to aid in maintenance, quality control, and assembly. Both technologies act as cognitive aids, supporting complex decision-making and problem-solving by offering relevant information in real-time. They also enable remote collaboration, simulating collaborative environments for planning and executing tasks, thus improving teamwork and communication. Additionally, VR and AR are valuable for safety and ergonomic assessments of workstations, identifying hazards and ergonomic issues without exposing workers to risks. Finally, these technologies enhance knowledge sharing and training effectiveness, making it more accessible for both trainers and operators. Given their distinct benefits, implementing VR and AR for industrial training can be highly advantageous for trainees.

A comprehensive approach has been developed. It integrates Instructional Design, Work-Based Learning, and Gamification with VR and AR to enhance operator engagement and competence (Santos et al., 2022). This methodology employs game-based learning strategies to create a dynamic and interactive training environment, utilizing VR for initial safety training and AR for advanced application stages (Richard et al., 2021). The system is designed to be generic and configurable, allowing for adaptation to various scenarios and updates. This approach offers significant potential by providing personalized and adaptable training experiences. The study highlights the innovative combination of instructional design and immersive technologies to improve industrial training outcomes, addressing normal operations and complex problem-solving scenarios. Additionally, a comprehensive framework, INTERVALES, is necessary for developing hybrid technology industrial training. INTERVALES facilitates scenario authoring and usage in AR and VR industrial training applications, enabling seamless authoring of content in both AR and VR without unnecessary repetition.

In summary, integrating VR and AR technologies in industrial training provides numerous benefits, including enhanced training effectiveness, improved safety, and better decision-making support. Frameworks like INTERVALES and approaches that combine instructional design with immersive technologies show the potential to revolutionize industrial training, making it more engaging, adaptive, and efficient.

## E-Learning

Integrating e-learning technologies into vocational and industrial training has revolutionized educational methodologies and outcomes. These technologies provide innovative solutions for delivering education and skill development, particularly in scenarios where traditional hands-on training is not feasible. E-learning enables the incorporation advanced digital platforms, making learning more accessible and flexible. This review explores various applications, benefits, and advancements in e-learning within the industrial sector, highlighting the continuous evolution and adoption needed to meet the diverse needs of learners and industries alike.

E-learning has proven beneficial for vocational, high school, and graduate education in industrial skills. Research on integrating simulators in vocational education and training in Sweden highlights the emergence of new teaching practices and the need for teachers to develop digital competencies (Nyström & Ahn, 2024). The focus on automation and robotics vocational education supports European reindustrialization by utilizing e-learning to meet the needs of SMEs and enhance technological competencies (Smater & Zieliński, 2015). Lifelong education in the electro-mechanical industry is emphasized through e-learning solutions and remote working stations to keep up with rapid technological advancements (Rojko & Kozlowski, 2012). Vocational training as a tool for Total Quality Management in the electronics industry integrates exploration tasks in vocational and further training to optimize learning and improve quality and reliability in production (Urbancik & Pietrikova, 2009). The LIMA e-learning platform focuses on microelectronic applications, providing high-quality training material for graduate students and industry designers (Ostermann et al., 2003).

Integrating e-learning with traditional face-to-face instruction has been shown to enhance the overall educational experience by combining the strengths of both approaches. A hybrid learning model combining traditional face-to-face and online learning has been implemented to strengthen engineering education (Gergic, 2014). This approach includes a flipped classroom where students engage with course content outside class and use class time for active learning activities. Vocational training and certification in ICT and other industrial sectors are highlighted through the combination of e-learning with practical laboratory experiments for a comprehensive learning experience (Levicky et al., 2008).

As e-learning implementations become more widely accepted, comprehensive systems are being introduced. An LMS for automotive industry employees was analyzed and developed, emphasizing structured menus, downloadable materials, and various learning media to enhance training efficiency and user satisfaction (Tafakur et al., 2023). An LMS architecture for employee education in the manufacturing industry integrates web-based and collaborative problem-solving methods to improve knowledge management and training outcomes (Ma, 2009). Recognizing that each learner is unique, e-learning systems can provide personalized training content tailored to individual needs. A recommendation system for industrial training uses unsupervised sequence mining algorithms to personalize training recommendations based on employees' training and work history (Srivastava et al., 2017). An advanced virtual training system for automotive manufacturing, utilizing semantic modeling and RESTful web services to create an interoperable training environment, was introduced in the VISTRA project (Gorecky et al., 2017).

Making e-learning content more engaging is beneficial for both learners and stakeholders. The impact of gamification intensity in web-based virtual training environments for a procedural industrial task was investigated (Bohne et al., 2023). The ManuSkills project employs serious games and simulation-based training to attract young talent to the manufacturing sector (Costa et al., 2014). The Shell entity in Collaborative Virtual Environment for Training (CVET), which abstracts actors from their embodiment in the virtual world, allowing users and virtual agents to collaborate effectively, was introduced (Lopez et al., 2013). The concept facilitates knowledge sharing and interaction inputs accessible to users and virtual agents, enhancing collaboration and learning and improving team decision processes and collaboration through exchanging embodiments and knowledge. Game-based virtual training system design also enables virtual assembly training in the automotive industry (Stork et al., 2012). Remote experiments in microcontroller training, combining theoretical knowledge with practical virtual experimentation, enhance learning outcomes in the electro-mechanical industry sector (Dziabenko et al., 2012).

E-learning can also cater to specialized training needs. A Training Station e-learning concept was developed to teach novice workers how to assemble alpine skis without constant human supervision (Thomay et al., 2018). A haptic-based bar bending simulator for construction training was also developed (Menon et al., 2017). The impact of an intelligent tutor on risk and sound perception in CNC machining was examined, enhancing decision-making and reducing mental workload (Duffy, 1999). The creation of e-learning material often requires significant time and resources. A Digital Twin methodology was introduced to support discrete event control teaching, offering a cost-effective solution for teaching industrial skills (Altamirano-Avila et al., 2022). The importance of formalized enterprise data and open data formats has been emphasized (Stork et al., 2012). The study proposes a system architecture for managing virtual training content and applications, which could be applied in aerospace and train manufacturing industries. Aprend-e, designed to train electric power operators, ensures effective training and certification through a SCORM-compliant system (Argotte-Ramos et al., 2009).

E-learning has proven particularly beneficial during pandemic events. The challenges of delivering industrial training during the COVID-19 pandemic were addressed by implementing a digital platform for remote management and assessment (Hussain & Spady, 2020). E-learning can also increase environmental awareness and address specific industry needs. The importance of digital assembly instructions for quality assurance and efficiency in the modular building industry was emphasized (Kurdve, 2018). A web-based e-learning course on lead-free soldering was developed to address the electronics industry's environmental concerns and technical challenges (Illyefalvi-Vitez et al., 2006). E-learning system proposals should be systematically evaluated. The effectiveness of virtual training systems in mixed-model manual assembly was explored, proposing an evaluation framework to compare different systems and assess their industrial usability (Hoedt et al., 2016, 2017).

E-learning technologies have significantly enhanced vocational and industrial training by offering flexible, efficient, and personalized educational solutions. Studies have shown the effectiveness of integrating simulators, gamification, and hybrid learning models to improve skill acquisition and engagement. Developing comprehensive Learning Management Systems (LMS) and personalized training content has optimized training outcomes. During the COVID-19 pandemic, e-learning proved essential in maintaining training continuity. Additionally, e-learning has addressed environmental concerns and specific industry needs, demonstrating its broad applicability and potential. However, systematic evaluation and continuous improvement of e-learning systems are crucial to ensure their effectiveness and adaptability in various industrial contexts.

### Summary

Integrating advanced technologies such as VR, AR, MR, hybrid systems, and E-learning in industrial virtual training has revolutionized training methodologies by creating immersive, interactive, and effective learning environments. These technologies address safety, cost, and the need for hands-on experience, offering scalable and flexible solutions. VR enhances training outcomes and user engagement through realistic simulations, while AR reduces cognitive load and aids in task clarity. MR blends real and virtual worlds for improved practical skills, and hybrid systems combine the strengths of VR and AR to enhance decision-making and collaboration. E-learning technologies offer flexible, efficient, and personalized solutions, improving skill acquisition and engagement through simulators, gamification, and hybrid learning models while addressing environmental concerns and maintaining training continuity during the pandemic. These technologies significantly improve training effectiveness, safety, and knowledge retention, making them invaluable tools for modern industrial education. Each of the references is alphabetically listed under Table 1. The table categorizes and lists the number of papers focusing on Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), Hybrid (VR + AR), and E-learning technologies. The total number of papers for each category highlights the most researched areas in industrial training.

## TRENDS IN TECHNOLOGY AND METHOD USE FOR INDUSTRIAL VIRTUAL TRAINING SYSTEMS

Industrial virtual training systems increasingly leverage advanced technologies to create immersive, interactive, and adaptive learning environments. This shift is driven by the need for

**Table 1. Summary of literature on different technologies in industrial training**

| Technology | Literature | Total |
|---|---|---|
| **VR** | Avveduto et al., 2017; Bhatti et al., 2008; Boonmee et al., 2020; Caiza et al., 2021; Cassola et al., 2021; Cassola et al., 2022; Dwivedi et al., 2018; Fitton et al., 2024; Gattullo et al., 2022; Gattullo et al., 2021; Grajewski et al., 2018; Grajewski & Hamrol, 2023; Hoang et al., 2022; Jia et al., 2009; Li et al., 2018; Lin et al., 2002; Liu et al., 2020; Lozada-Martinez et al., 2019; Martinetti et al., 2020; Oliveira et al., 2007; Radhakrishnan et al., 2021; Schwarz et al., 2020; Schwartz et al., 2007; Suppes et al., 2019; Wolfartsberger & Niedermayr, 2020 | 25 |
| **AR** | Dhiman et al., 2024; Funk, Kritzler, & Michahelles, 2017; Gan et al., 2022; Lampen et al., 2020 | 4 |
| **MR** | Reyes et al., 2020 | 1 |
| **Hybrid (VR + AR)** | Richard et al. 2021; Santos et al., 2022; | 2 |
| **E-Learning** | Altamirano-Avila et al., 2022; Argotte-Ramos et al., 2009; Bohne et al., 2023; Costa et al., 2014; Duffy, 1999; Dziabenko et al., 2012; Gergic, 2014; Gorecky et al., 2017; Hoedt et al., 2016; Hoedt et al., 2017; Hussain & Spady, 2020; Illyefalvi-Vitez et al., 2006; Kurdve, 2018; Levický et al., 2008; Lopez et al., 2013; Ma, 2009; Menon et al., 2017; Nyström & Ahn, 2024; Ostermann et al., 2003; Rojko & Kozlowski, 2012; Smater & Zieliński, 2015; Srivastava et al., 2018; Stork et al., 2012; Tafakur et al., 2023; Thomay et al., 2018; Urbancik & Pietrikova, 2009 | 26 |
| | Total | 58 |

safe, effective, cost-efficient training solutions that closely mimic real-world scenarios. This section explores the key trends in technology use for industrial virtual training systems and their contributions to enhancing training effectiveness. The analysis of publication trends in industrial virtual training technologies from 1999 to 2024 reveals significant insights into the evolving landscape of this field. Figure 2 depicts the cumulative number of publications in industrial virtual training technologies. The data covers a variety of technologies, including Virtual Reality (VR), E-learning, Augmented Reality (AR), Hybrid technologies, and Mixed Reality (MR).

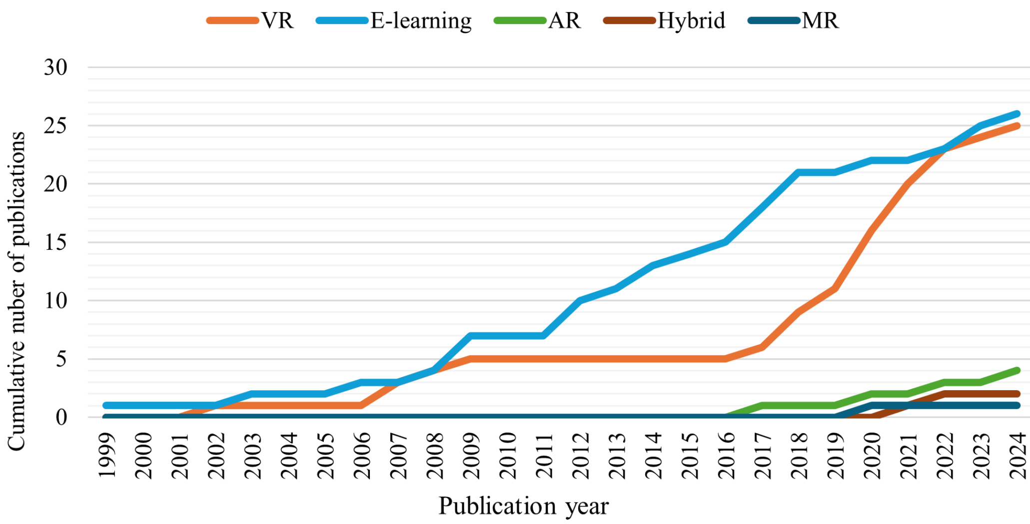
## Virtual Reality (VR)

Virtual Reality (VR) has significantly transformed traditional industrial training methods. Studies highlight enhancing training outcomes, user engagement, and knowledge retention through immersive VR environments. The early phase (1999-2006) saw minimal publications, with notable spikes in 2002 and a more considerable increase in 2007. During the growth period (2007-2016), there was steady but slow growth in VR-related publications, reflecting increasing interest and research in this area as it offers cost reductions and logistical advantages by eliminating the need for physical setups (Grajewski et al., 2018). The significant surge period (2017-2020) shows a substantial increase in publications, peaking in 2020 as the technology has been proven to halve training time and improve knowledge retention compared to traditional methods (Caiza, Riofrio-Morales, Robalino-Lopez, et al., 2021). Additionally, various motivations exist for adopting VR over conventional methods, including increased trainee motivation and improved skill transfer (Radhakrishnan, Chinello, et al., 2021). Recent trends (2021-2024) show continued interest with fluctuations, maintaining a high frequency of VR publications.

## E-Learning

E-learning technologies have revolutionized vocational and industrial training by providing flexible, efficient, and personalized educational solutions. These technologies enable the incorporating of advanced digital platforms, making learning more accessible. During the early adoption phase (1999-2009), there was initial steady growth with some fluctuations, indicating early interest

**Figure 2. Cumulative number of publications in industrial virtual training technologies (1999-2024)**




in e-learning technologies. The expansion phase (2010-2016) saw continued growth with many publications, showing widespread acceptance and integration. The mature phase (2017-2024) is characterized by a high frequency of publications demonstrating the established importance and application of e-learning, as evidenced by the increasing trends of comprehensive research on the development of learning systems. Developing Learning Management Systems (LMS) and personalized training content further optimizes training outcomes, proving essential during the COVID-19 pandemic for maintaining training continuity (Hussain & Spady, 2020). In addition, a comprehensive system highlights the benefits of combining e-learning with traditional instruction, improving skill acquisition and engagement through simulators, gamification, and hybrid learning models (Nyström & Ahn, 2024).

## Augmented Reality (AR)

Augmented Reality (AR) technologies have also made significant strides in industrial training, offering the ability to overlay digital information onto the physical world. This integration reduces cognitive load and helps clarify complex tasks. The emergence phase (1999-2016) featured minimal presence in the early years, with sporadic publications indicating initial exploration. During this period, the system utilizes the environment projection-based AR or specialized design hardware to display AR contents. The growth phase (2017-2024) showed increased publications from 2017 onwards, indicating growing interest and research in AR technologies. This increase is primarily due to the technology becoming more common and accessible to the public. Systems like HoloCollab, which uses spatially-aware head-mounted displays for physical assembly training, have demonstrated improved training efficiency and accessibility (Funk et al., 2017).

## Hybrid Technologies

Combining VR and AR technologies provides comprehensive training solutions that address complex skill development needs. This approach leverages the strengths of both VR's immersive capabilities and AR's real-time visual assistance. Initial publications on this combined approach appeared in 2017, showing gradual growth and emerging interest in integrating VR and AR technologies. The most recent work, a comprehensive framework called INTERVALES, facilitates the development of hybrid training technologies, enhancing decision-making and collaboration (Richard et al., 2021).

### Mixed Reality (MR)

Mixed Reality (MR), blending real and virtual worlds, is increasingly utilized to enhance practical skills in industrial training. MR is in the emergence phase (2020-2024) and saw its first publications in 2020. An example is the Mixed Reality Guidance System (MRGS) for motherboard assembly, which simulates hands-on tasks without real-world parts, providing effective guidance and immediate feedback (Reyes et al., 2020). MR technologies enhance training programs by offering natural interactions and immersive experiences.

In summary, the trends reveal an apparent increase in the adoption and research of immersive and interactive technologies in industrial training. VR and E-learning have shown the most significant growth, reflecting their established role in modern training methodologies. AR and hybrid technologies are gaining traction, while MR is still in its early stages and showing potential for future growth. These trends highlight the evolving landscape of industrial training, driven by technological advancements and the need for more effective training solutions.

## REPORTED LIMITATIONS AND CHALLENGES OF INDUSTRIAL VIRTUAL TRAINING TECHNOLOGIES

Despite the significant potential of industrial virtual training technologies, including Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), and e-learning platforms, numerous factors affect their effectiveness and scalability. These factors encompass both limitations, which are inherent constraints of the technologies, and challenges, which are difficulties encountered during their implementation or usage. Understanding these aspects is essential for developing more effective and scalable training solutions.

### Virtual Reality (VR)

Technological constraints encompass computing capacity and immersion issues, hardware and software limitations, and resolution and display issues. Low-cost solutions, such as cardboard VR setups, are often excluded due to insufficient computing power for rendering detailed environments (Suppes et al., 2019). Additionally, integration challenges with third-party libraries for immersive devices and applications limit user interactions, reducing the effectiveness of the training (Bhatti et al., 2008) (Bhatti et al., 2008). Hardware setups, including haptic devices, may also fall short of providing adequate immersion and interaction. Authoring tools often lack integration with existing data like CAD files and require desktop-oriented, non-immersive authoring processes (Cassola et al., 2021). Moreover, low-resolution VR displays can hinder the perception of details, leading to errors in physical tasks (Santos et al., 2022).

Simulation and visualization of VR content are essential for realistic training, but they face technical challenges due to the nature of the developer tools. Game engines are not designed for rendering high polygon count models, necessitating simplifications or trade-offs to maintain frame rates, which can result in potential FPS drops when displaying complex visualizations, thus affecting the realism and effectiveness of training (Wang et al., 2015).

Evaluation challenges are another significant barrier. There is no universal method for assessing the effectiveness of VR training in industrial settings (Boonmee et al., 2020). Furthermore, statistical proof is often lacking when comparing virtual training systems to traditional methods (Hoang et al., 2022). This suggests that VR training systems are generally comparable to existing methods. Many studies do not cover the full spectrum of evaluation models, such as Kirkpatrick's, focusing primarily on the initial levels (Avveduto et al., 2017). Measuring the long-term impact of VR training compared to traditional methods remains underexplored, leaving a gap in understanding its sustained effectiveness.

Practical implementation issues further complicate the use of VR for industrial training. VR systems sometimes impose physical geometric constraints that limit natural interaction with virtual environments (Bhatti et al., 2008). Training systems may lack natural interaction with virtual tools, necessitating additional physical task repetition for effective learning (Fitton et al., 2024). Developing VR training experiences is often expensive and time-consuming, requiring specialized software development skills (Cassola et al., 2021). Integrating VR into existing teaching and training frameworks can be challenging due to costs and the need for repeated training (Lin et al., 2002). Safety and realism concerns also arise, as the disparity between virtual training and real-world experiences can cause discomfort, particularly when training involves heavy objects (Grajewski et al., 2018). Ensuring safety through VR requires additional physical tools and equipment, which are not always present in VR environments (Grajewski & Hamrol, 2023). Moreover, there is a lack of personalized training experiences tailored to individual needs, which can limit the effectiveness of the training (Radhakrishnan, Chinello, et al., 2021).

Despite extensive exploration of Virtual Reality (VR) in industrial training, several limitations hinder its effectiveness, categorized into technological constraints, evaluation challenges, and practical implementation issues. Technological constraints include inadequate computing capacity, hardware and software limitations, and low-resolution displays, which affect immersion and interaction. Evaluation challenges arise from the lack of universal methods to assess VR training effectiveness and the absence of long-term impact studies. Practical implementation issues involve high costs, time-consuming development, integration difficulties, and safety and realism concerns. These limitations highlight the need for advancements in evaluation methods, technological capabilities, and practical application to enhance VR training's effectiveness and applicability in industrial settings.

## Augmented Reality (AR)

Augmented Reality (AR) technologies, despite their promising potential in industrial training systems, face several notable limitations that affect their effectiveness and practicality. These limitations can be grouped into four main categories: user interaction challenges, variability in training tasks, cost and implementation issues, and the need for empirical validation.

One significant limitation of AR-based training systems is users' difficulty interacting with virtual tools and controls. An evaluation of HoloCollab found that trainees experienced challenges with gesture controls, such as the Air Tap gesture on Microsoft HoloLens, which could slow down the training process and affect user engagement. Additionally, the interaction with virtual tools was reported as unnatural, suggesting that trainees might still need to practice with physical tools to gain complete proficiency. This limitation indicates that while AR systems can support learning task sequences and tool identification, they may not effectively simulate the tactile feedback of using real tools (Funk et al., 2017).

The effectiveness of AR systems in managing diverse and complex training tasks is another area of concern. The variability in product complexity introduces managing challenges for virtual training in AR, hence requiring a robust and flexible framework to handle different assembly tasks effectively. The challenge is particularly relevant in High-Mix Low-Volume manufacturing environments where product variations are common. The system must adapt to the complexity of each task and the operator's experience level, which can be a significant challenge (Gan et al., 2022).

The high initial costs for implementing and maintaining AR-based training systems are a significant barrier, especially for small and medium-sized enterprises (SMEs). The setup, development, and ongoing maintenance of AR systems could be prohibitive, limiting widespread adoption. Additionally, the reliance on current AR technology, which has limitations such as hardware quality dependency and the need for continuous updates, further complicates the system's practicality and scalability (Gan et al., 2022).

There is a notable lack of comprehensive empirical evidence validating the effectiveness of AR training systems in real-world settings. While these systems show the potential to enhance learning and reduce errors, the findings are often based on specific industrial use cases, which limits their generalizability. Furthermore, the participant sample size and diversity are not always thoroughly discussed, potentially affecting the broader applicability of the results. This limitation underscores the need for extensive testing and validation to confirm the benefits and identify any unforeseen drawbacks of AR training systems (Lampen et al., 2020).

Despite their potential, AR technologies in industrial training systems face significant limitations that impact their effectiveness. These challenges include user interaction difficulties with virtual tools, managing the complexity and variability of training tasks, high implementation and maintenance costs, and a lack of empirical validation. Interaction issues, such as the unnatural feel of gesture controls, limit user engagement and proficiency. Additionally, AR systems must adapt to varying product complexities and user experience levels, posing challenges in high-mix, low-volume environments. The high costs associated with AR technology further hinder its adoption, particularly for SMEs. Lastly, the lack of comprehensive empirical evidence raises concerns about AR training systems' generalizability and real-world applicability, emphasizing the need for more extensive testing and validation.

## Mixed Reality (MR)

Mixed Reality (MR) technology offers significant advantages for industrial virtual training, such as enhanced spatial clarity and large interaction spaces. However, it also presents some limitations. The related paper suggests that the system's effectiveness depends on the hardware used, directly affecting the quality of video input and tracking capabilities. Additional hardware improvements are needed to overcome challenges like premature recognition and occlusion, indicating that the current system may face limitations in more complex assembly scenarios (Reyes et al., 2020).

This review paper expands the discussion of limitations by including additional MR studies in enterprise training, remote assistance, and smart factories. One major challenge is the high cost and time investment required to create an MR training experience. Hence, the need for software development experts to develop highly customized and complex industrial training tools results in longer cycle times, which can be a drawback.

## E-Learning Platforms

Implementing e-learning technologies in industrial training systems has encountered several limitations that can impact their effectiveness and scalability. These limitations span various aspects, including technological, pedagogical, and practical challenges. One significant limitation is integrating digital twins and high-fidelity simulation models with actual machinery. While digital twins are effective for conceptual applications, synchronization between physical and digital spaces remains problematic as there is insufficient real-time synchronization, a lack of high-fidelity simulation models, and uncertainty in real-world human behavior. These limitations hinder the realization of comprehensive digital twin environments (Altamirano-Avila et al., 2022). Similarly, the need for minimal data authoring effort and automated integration of existing data structures to create efficient virtual training scenarios is often tricky due to the lack of standardized interfaces and semantic modeling (Gorecky et al., 2017).

The transferability of technology-enhanced learning (TEL) solutions across different regions presents another limitation. Barriers related to infrastructure, accessibility, legislation, and education policies can vary significantly across countries, limiting the scalability of solutions developed in one region to others (Costa et al., 2014). This issue is compounded by the difficulty in quantifying the long-term impacts of e-learning initiatives due to the dynamic nature of the manufacturing sector. The practical implementation of e-learning systems often faces significant hurdles. Challenges in providing practical experience through remote training arise as virtual roles may not fully cover the psychomotor and affective learning domains critical for industrial training (Hussain & Spady, 2020). Similarly, the high costs of transitioning to new equipment and processes can be prohibitive for many organizations (Illyefalvi-Vitez et al., 2006).

The effectiveness of e-learning methodologies in industrial training is also limited by the diversity of evaluation methods and the difficulty in ensuring uniform learning outcomes. The lack of uniform methodologies for comparing different virtual training systems and the challenges in achieving statistically significant proof of learning transfer due to varied evaluation techniques and training strategies present significant obstacles (Hoedt et al., 2016, 2017). Additionally, the transition effect from virtual to real-world scenarios may affect performance, posing challenges in seamless skill transfer. User acceptance and the quality of interaction between trainees and virtual environments are critical for the success of e-learning systems. The extensive authoring effort required to set up virtual environments and the difficulty in achieving user integration and acceptance due to the complexities of mapping diverse input data and ensuring user-friendly interfaces are substantial barriers (Stork et al., 2012). Similarly, restricted collaborative interactions in the current Collaborative Virtual Environment for Training (CVET) systems limit training effectiveness by not fully utilizing the potential of team knowledge models (Lopez et al., 2013).

The availability of resources, including financial and technological investments, is another significant limitation. Funding cuts lead to insufficient simulators and subsequent delays in training implementation, and the need for teachers to develop digital competencies and the vulnerability of teaching practices to external disruptions, such as server crashes, further complicate the issue (Nyström & Ahn, 2024). The effectiveness of recommendation systems for industrial training is limited by the absence of feedback mechanisms and the inability to consider the temporal ordering of training sessions (Srivastava et al., 2018). Additionally, the high costs associated with training and the need for continuous updates to teaching techniques to meet modern educational demands are considerable challenges (Ma, 2009).

While e-learning technologies offer significant potential for industrial training, their implementation is fraught with various limitations that must be addressed to enhance their effectiveness and scalability. These limitations include technological integration challenges, transferability issues, practical implementation hurdles, pedagogical constraints, user acceptance, resource allocation, and assessment mechanisms. Addressing these limitations through continuous research and development is essential to fully realizing the benefits of e-learning in industrial training contexts.

### Summary

Industrial virtual training technologies face limitations and challenges that hinder their effectiveness and scalability. VR technologies encounter issues related to computing capacity, hardware and software limitations, and the integration of authoring tools with existing data systems. AR systems struggle with user interaction challenges, high costs, and the need for empirical validation of their effectiveness. MR technologies present challenges in hardware requirements, interaction techniques, and integrating didactic concepts. E-learning platforms face technological integration challenges, transferability issues, and difficulties in practical implementation and user acceptance. Addressing these limitations through continuous research and development is crucial for enhancing the effectiveness and applicability of these technologies in industrial training contexts.

## CURRENT MITIGATION STRATEGIES FOR REPORTED LIMITATIONS AND CHALLENGES

Current mitigation strategies for the reported limitations and challenges of integrating Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), and e-learning technologies into various industries are critical to enhancing training, education, and operational efficiency. This section delves into these strategies, addressing issues related to cost and maintenance, user engagement, creation of training materials, realism in VR environments, system scalability, and evaluation methods. Reviewing various approaches and solutions, we aim to highlight the ongoing efforts to make these technologies more accessible, effective, and sustainable.

## Addressing the Cost and Maintenance

The integration of Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) technologies into various industries promises significant advancements in training, education, and operational efficiency. However, one of the primary barriers to widespread adoption is the high cost associated with developing and implementing these immersive technologies. This paper explores several strategies and methodologies that have been proposed and tested to reduce these costs, making VR, AR, and MR technologies more accessible and sustainable for enterprises.

One of the major concerns reported by various publications is the cost associated with creating and adopting VR, AR, and MR technologies. For instance, a low-cost VR system designed for the interactive education of industrial operators, making advanced training more affordable and accessible, mitigating the adoption limitation of VR systems (Grajewski & Hamrol, 2023). This system utilizes the Oculus Rift CV1, introduced in 2016, with an introductory price of 600 USD. The underlying cost of developing training mediums for immersive reality is also a challenge for enterprises. By utilizing the ADDIE (Analysis, Design, Development, Implementation, Evaluation) model for instructional design, creating these mediums can be more cost-effective. This structured, systematic approach improves efficiency, reduces waste, ensures effective use of resources, and leads to higher-quality instructional materials (Boonmee et al., 2020). Presenting virtual human experts in AR allows trainees to mimic their behavior directly, reducing the overall cost of creating and maintaining AR applications for training purposes (Lampen et al., 2020). Leveraging existing technologies and platforms and incorporating domain-specific ontologies helps structure knowledge and information to reduce the complexity and cost of content creation and management. Consequently, the total ownership cost of an E-learning platform can be lowered (Ma, 2009). Although this is not directly related to the mitigation of the expenses for adopting a virtual training system, it is worth mentioning that in some cases, the immersive training system itself is beneficial as it can reduce training costs by minimizing the need for physical training setups, which require materials or a dedicated training area (Dwivedi et al., 2018; Grajewski et al., 2018; Liu et al., 2020; Menon et al., 2017; Wang et al., 2015).

In summary, while the initial investment in VR, AR, and MR technologies can be substantial, the long-term benefits and cost-saving potential are significant. By adopting structured approaches such as the ADDIE model, utilizing cost-effective hardware, and leveraging existing technological platforms and domain-specific ontologies, enterprises can reduce the overall expenses associated with immersive training systems. These strategies lower the barriers to entry and enhance the quality and efficiency of training programs, ultimately leading to a more skilled and adaptable workforce. As technology evolves, organizations must stay informed about these cost-reduction methodologies to maximize their return on investment in immersive technologies.

## Addressing the User Engagement

The effective engagement of users in virtual training technologies is critical for maximizing the benefits of these systems. Despite various studies reporting increased user engagement by adopting virtual training technologies, some limitations and challenges remain. This paper explores several strategies to enhance user engagement, drawing on techniques such as gamification, flipped classrooms, and the integration of VR and AR technologies. Additionally, it discusses the importance of designing systems that accommodate non-IT users and the psychological impact of collaborative training environments.

The importance of tangible representation of training material is also highlighted by the training of motherboard assembly (Reyes et al., 2020). The lack of tangible items is a significant limitation of immersive technologies. The paper introduces an economical replica of the material digitally projected by MR technology, enhancing its realism. Combining VR and AR allows users to engage with the material hands-on, making learning more engaging and effective (Richard et al., 2021). The challenge lies in finding effective strategies to overcome these engagement barriers and making the virtual training technologies more accessible and engaging for a broader audience. Gamification is one of the techniques widely adopted by researchers to tap into users' natural desires for competition and achievement (Santos et al., 2022).

Similarly, in addition to the gamification concept, the traditional idea of the flipped classroom can be introduced to encourage students to take a central role, making the training more engaging (Suppes et al., 2019). Furthermore, the design of such systems should accommodate non-IT users and adopt the concept of collaborative training, which can psychologically motivate peers. Using the ADDIE model to create instructional training is also beneficial as it thoroughly addresses and verifies user pain points, leading to user acceptance and engagement with the system (Boonmee et al., 2020). A sense of presence is reported to increase user engagement, which can be achieved by minimizing distractions and boosting the realism of immersive training material (Avveduto et al., 2017). The implementation of immersive theater experiences also improves user engagement as it promotes collaboration between VR users on shared material (Wang et al., 2015). Additionally, the incorporation of human-computer interface devices can improve user engagement. By introducing haptically enabled devices to an existing VR system, physical force feedback can enhance user interaction and engagement by providing a more tactile and immersive experience that closely mirrors real-life scenarios (Bhatti et al., 2008).

In summary, addressing user engagement in virtual training technologies requires a multifaceted approach that combines various pedagogical and technological strategies. The strategies include gamification of content, flipped classrooms, and integration of VR and AR technologies, which can significantly enhance engagement. Additionally, designing user-friendly systems that cater to non-IT users and incorporating collaborative training environments are essential. By focusing on these areas, developers and educators can create more engaging and effective virtual training experiences that meet the diverse needs of learners.

### Addressing the Creation of Virtual Training System Material

Creating material for a virtual training system can be complex and time-consuming. This subsection explores several innovative approaches and tools designed to simplify the authoring of training materials, reducing the required time and expertise.

Immersive authoring tools streamline the creation of VR training environments by simplifying the setup of visual spaces, procedure demonstrations, and course structures. By leveraging pre-existing CAD data, these tools enhance the authenticity and engagement of VR-based training materials, making the creation process less challenging (Cassola et al., 2021; Oliveira et al., 2007). Modules that define 3D object characteristics, manage user interactions across devices, streamline scene state modifications, and simplify scenario creation and content import/export significantly reduce authoring efforts in VR and AR systems. Integrating external CAD and PLM tools further leverage existing assets and workflows, enhancing efficiency (Richard et al., 2021). The "Authoring-by-Doing" approach allows experts to perform tasks directly in VR to create training modules, eliminating the need for programming skills. This hands-on method is intuitive and accessible, promoting the creation of VR content with non-expert peers (Wolfartsberger & Niedermayr, 2020). This approach significantly reduces development efforts by modularizing and standardizing complex equipment into reusable interactive virtual elements (IVEs) and encapsulating component models. It also enhances scalability and flexibility in simulating maintenance processes for training scenarios (Li et al., 2018). Integrating existing enterprise data and developing a unified model for virtual training simplifies the authoring process. This integration enables the transfer of enterprise data into a format easily used for training purposes, making the system more efficient (Stork et al., 2012). Proposing an innovative hardware setup for enhanced user interaction streamlines training content creation (Argotte-Ramos et al., 2009). This setup promotes user engagement and acceptance, reducing the need for repeated training sessions. In addition, utilizing SCORM compliance enables efficient content packaging, extended classification capabilities, adaptability for dynamic courses, and a comprehensive repository of learning objects. This standardization streamlines the process of creating and updating training content.

In conclusion, various innovative approaches and tools have been developed to simplify the creation of virtual training systems. Immersive authoring tools, modularization, and standardization of interactive elements, the “Authoring-by-Doing” approach, integration of enterprise data, and innovative hardware setups collectively reduce the complexity and effort required. These strategies ensure that training systems are easier to create and more engaging and effective, enhancing the overall training experience.

### Addressing the Lack of Realism in VR Training Environments

Enhancing virtual reality (VR) education's realism and immersion in manual assembly procedures is crucial for creating effective training experiences. This subsection discusses strategies and methods introduced in several papers to address the lack of realism in VR training environments.

Several strategies exist to enhance realism and immersion in VR education for manual assembly procedures, including stereoscopic visualization for depth perception and physical models of digital objects for tactile feedback (Grajewski & Hamrol, 2023). Tactile feedback is achieved by simulating virtual objects and providing tactile stimuli. These methods ensure fluid and intuitive interactions, resulting in a highly immersive and realistic VR educational experience. Several methods in Danish industry cases include high visual fidelity to create accurate replicas of real environments, haptic feedback to simulate touch and physical interactions, and methods to mimic real-world object manipulation (Radhakrishnan, Chinello, et al., 2021). These methods collectively ensure a realistic training experience.

Similarly, haptic feedback is reported as a strategy to enhance realism in virtual training environments (Jia et al., 2009). Using haptic devices to provide realistic force feedback allows users to experience the tactile sensation of handling real objects, significantly improving the authenticity and effectiveness of training for tasks requiring fine motor skills, such as object assembly. Another approach to boosting realism involves high-quality 3D rendering, effective didactic concepts, behavioral data utilization, and feedback from trainers and users, particularly in VR automotive assembly training. These methods create an immersive and realistic training environment, enhancing skill transfer and retention (Schwarz et al., 2020).

Furthermore, semi-transparent “ghost” animations are a novel approach to enhance realism in VR learning environments by recording expert actions and displaying them, allowing trainees to mimic real-life tasks interactively. This method ensures a realistic and effective training experience (Wolfartsberger & Niedermayr, 2020). Using photorealistic visualization and integrating simulation results with photorealistic 3D models of equipment and facilities is another way to enhance realism in virtual environments (Wang et al., 2015). Later, combined with immersive theater setups and interactive software, these approaches significantly improve the user's ability to understand and engage with complex industrial processes.

In conclusion, various strategies and methods have been proposed to enhance the realism and immersion of VR training environments. These include stereoscopic visualization, physical models, haptic feedback, high-quality 3D rendering, didactic concepts, and semi-transparent animations. By implementing these techniques, VR training systems can provide more realistic, engaging, and compelling training experiences, significantly improving skill transfer and retention across industrial applications.

### Addressing the Challenges in System Scalability

Scalability is critical to virtual and e-learning training systems, ensuring they can grow and adapt to meet increasing demands and evolving technological advancements. This section discusses the strategies for scalability in VR training systems and e-learning platforms.

The VR training system is designed for scalability through its modular structure using High-Level Parallel Compositions (HLPC), which allows for the easy addition of new modules and future expansion to cover a broader range of training scenarios. Agile methodologies adapt and grow with user needs, ensuring the system remains responsive and effective (Caiza, Riofrio-Morales, Gallo, et al., 2021). Additionally, the e-learning system for employee education in the manufacturing industry achieves scalability through several key features (Ma, 2009). These key features include low development costs, enabling efficient resource allocation, and ensuring scalability without significant additional investment. The system's extensible architecture, interoperability with other software and platforms, and use of domain-specific ontologies allow it to quickly expand to meet growing demands while maintaining organized and accessible content. The use of Petri nets for flexible scenario modeling and a practical demonstration with a CNC milling operations prototype further illustrate the system's adaptability (Lin et al., 2002). This comprehensive approach ensures that the VR-based training system can grow and evolve in response to changing training needs and technological advancements.

In summary, the VR training system and e-learning platform achieve scalability through modular design, low development costs, extensible architecture, and advanced modeling techniques. These strategies ensure that both systems can efficiently expand to meet the increasing demands of training scenarios and employee education in the manufacturing industry, maintaining performance, usability, and adaptability.

## Addressing Evaluation Methods for Assessing Effectiveness

Effective evaluation methods are crucial for assessing the impact and efficiency of training systems, especially those incorporating advanced technologies like virtual reality (VR) and augmented reality (AR). Various research papers have proposed frameworks and methodologies to evaluate different aspects of training systems, ranging from industrial settings to remote learning platforms and safety training. This section reviews several studies that suggest comprehensive approaches for assessing the effectiveness of these training systems, highlighting the importance of standardized methods, user feedback, and continuous improvement.

The research paper on the INTERVALES framework suggests several inferred evaluation methods to assess its effectiveness in integrating virtual reality (VR) and augmented reality (AR) in industrial settings (Richard et al., 2021). These methods include evaluating the user-friendliness of the authoring process by comparing the time and technical expertise required to create VR/AR content with and without the INTERVALES framework and testing the framework's flexibility and adaptability through user studies and surveys from IT professionals and other job experts. Additionally, effectiveness can be measured by analyzing improvements in training efficiency, error rates, and operational efficiency in industrial use cases and examining the framework's facilitation of operations and interactions within virtual and augmented environments through user experience studies. Another study outlines evaluation methods for assessing the effectiveness of proposed digital platforms for remote industrial training during the COVID-19 pandemic (Hussain & Spady, 2020). Essential methods include the Outcome-Based Education (OBE) model, which aligns educational activities with specific student outcomes to ensure effectiveness, and using EvalTools 6 for comprehensive remote technical and transversal skills assessment. Automated digital systems are also suggested to streamline the collection and reporting of outcomes data, ensuring the proposed system maintains high educational standards and objectives. The paper proposes a detailed comparative approach to assess the effectiveness of VR safety training against traditional methods (Avveduto et al., 2017). It employs Kirkpatrick's model to evaluate training outcomes across reaction, learning, behavior, and results, supplemented by an experiment comparing traditional and VR training groups.

Additionally, the Witmer and Singer Presence Questionnaire was used to measure the sense of presence in VR sessions, ensuring a comprehensive evaluation of VR training's effectiveness. Another research paper introduces an evaluation framework for assessing virtual training systems in mixed-model manual assembly, which is pivotal for comparing studies and enhancing training efficiency and effectiveness (Hoedt et al., 2017). The framework standardizes evaluation methods, allowing for comparing different virtual training studies. It also classifies experiments based on evaluation methods, interaction interfaces, and product complexity to understand their impact on training effectiveness. It also proposes a benchmark for assessing industrial usability and outlines future research directions to optimize learning processes and improve training outcomes in low-volume, high-variety production environments. Finally, a comprehensive approach is proposed to evaluate the effectiveness of the ManuSkills project, focusing on increasing young talent's interest in manufacturing and enhancing their skills (Costa et al., 2014). Essential evaluation methods include tracking participation and engagement levels in ICT-based training tools, analyzing social media and gamification impact, and collecting feedback on pedagogical frameworks and personalization. The project's success will also be measured through pre- and post-training assessments and tracking participants' career progression in manufacturing.

In summary, these studies collectively highlight the importance of using diverse and robust evaluation methods to assess the effectiveness of training systems. Standardized frameworks, comprehensive assessment tools, and continuous feedback loops are essential for ensuring training programs meet educational standards and achieve desired outcomes, particularly in rapidly evolving fields such as VR and AR-based training.

### Addressing the Adaptability and Transferability

Enterprise faces significant challenges in keeping their workforce's skills up to date. Training modules under the virtual training system must be easily transferable across different industrial contexts. The goal of leveraging modern e-learning platforms, agile development methodologies, and active stakeholder collaboration is to create adaptable training systems that fit the industry's dynamic needs.

One paper leveraged an e-learning platform, agile development methodologies, and close stakeholder collaboration to design adaptable and relevant modules for industry needs, with customizable learning content and a user-friendly interface ensuring accessibility and applicability across different contexts, thereby enhancing transferability (Smater & Zieliński, 2015). Another paper detailed an approach to ensure the virtual assembly training system is adaptable and transferable across various environments, particularly within and beyond the automotive industry, by developing a unified model from enterprise data, integrating product and manufacturing design processes, and using game-based user interaction to create a flexible and relevant system for diverse assembly needs (Stork et al., 2012). Furthermore, the research on scalability in virtual reality-based training systems (VRTSs) emphasized their transferability across various industrial applications, with a modular architecture allowing easy expansion and modification of components and the use of Petri nets for adaptable and flexible scenario modeling (Lin et al., 2002). A CNC milling operations prototype demonstrated these principles, showcasing how the system can be tailored to meet diverse industrial needs, highlighting its scalable and transferable nature.

In conclusion, these studies highlight the importance of developing adaptable, scalable, and easily transferable virtual training systems across different industrial sectors. By employing modular architectures, integrating enterprise data, and utilizing user-friendly interfaces, these training systems can meet the evolving needs of enterprises in the manufacturing industries. The findings demonstrate that training modules can provide significant value with the design principles by being flexible enough to adapt to various contexts while maintaining their effectiveness and relevance.

### Summary

In summary, addressing the adaptability and transferability of virtual training systems is crucial for meeting the dynamic needs of various industries. The reviewed studies highlight the importance of leveraging e-learning platforms, agile development methodologies, and close stakeholder collaboration to design flexible and relevant training modules. These systems benefit from customizable learning content, user-friendly interfaces, and unified enterprise data models, ensuring their applicability across different contexts. Additionally, employing scalable architectures and advanced modeling techniques enhances the transferability of these systems. These strategies demonstrate that well-designed virtual training modules can provide significant value by adapting to diverse industrial needs while maintaining effectiveness and relevance.

## DISCUSSION

In this section, the paper addresses the identified gaps in virtual training technology and suggests potential research. The rapid advancement of Virtual Reality (VR), Augmented Reality (AR), and e-learning has transformed industrial training. However, several challenges still hinder these technologies' optimal deployment and effectiveness. Future research can enhance the efficiency, scalability, and overall impact of virtual training technologies in industrial contexts by addressing these gaps, from computing capacity and hardware limitations to user interaction and realism in AR.

### Gaps in Virtual Training Technology

The rapid advancement of virtual training technologies such as Virtual Reality (VR), Augmented Reality (AR), and e-learning has revolutionized industrial training. However, despite their potential, several gaps hinder these technologies' optimal deployment and effectiveness. This subsection explores the primary challenges within current VR, AR, and e-learning training systems, focusing on computing capacity and hardware limitations, integration with existing data and authoring tools, evaluation methods, practical implementation issues, real-time data integration, scalability and transferability, user interaction and realism in AR, managing complexity and variability in training tasks, and high initial costs and maintenance. Addressing these gaps is essential to enhance the efficiency, scalability, and overall impact of virtual training technologies in industrial contexts.

#### *Computing Capacity and Hardware Limitations*

Current solutions in VR training technologies often struggle with inadequate computing power and hardware limitations. These constraints hinder the ability to render detailed environments necessary for an immersive training experience, especially with low-cost setups. Low-cost VR solutions, such as cardboard VR setups, are often excluded due to insufficient computing capabilities to render high-quality, detailed environments (Suppes et al., 2019). Advances in affordable, high-performance VR hardware could support detailed and immersive environments without compromising quality. Innovations in GPU technology and more efficient processing units could drive this development. Implementing cloud-based rendering can offload the computational workload from local devices, allowing for more detailed and complex environments to be rendered remotely and streamed to the VR headset.

#### *Integration with Existing Data and Authoring Tools*

Many VR, AR, and e-learning authoring tools lack seamless integration with existing CAD files and other industrial data systems, leading to inefficiencies and increased time and effort in creating content (Cassola et al., 2021). Developing robust authoring tools that can easily integrate with existing CAD systems and other industrial data platforms would streamline training content creation. Creating and adopting standardized data formats that facilitate easy import and export of data between CAD systems and authoring tools could improve efficiency and reduce the complexity of content creation.

#### *Evaluation Methods*

To the best of the authors' knowledge, there is no standardized method for comprehensively evaluating the effectiveness of VR, AR, and e-learning training systems. Existing evaluation methods often focus only on initial levels, such as user satisfaction and immediate learning outcomes, without assessing long-term impacts (Boonmee et al., 2020). Developing and adopting comprehensive evaluation frameworks that evaluate multiple dimensions of training effectiveness, including long-term skill retention, transfer of training to the job, and overall impact on performance, is crucial. Conducting longitudinal studies to assess the long-term effectiveness and impact of these training methods compared to traditional ones would provide valuable data on their sustained benefits (Avveduto et al., 2017).

### *Practical Implementation Issues*

VR, AR, and e-learning training systems often face practical implementation issues, such as high costs, time-consuming development processes, and the need for specialized software development skills. Integrating these technologies into existing training frameworks can be challenging and costly (Fitton et al., 2024). Adopting structured development models like ADDIE (Analysis, Design, Development, Implementation, Evaluation) can help streamline the creation of training materials and reduce costs. Designing these systems to be modular and scalable can reduce initial development costs and allow for incremental updates and expansions as needed. Providing training and resources for developers to acquire the necessary skills to create and implement training systems can help alleviate the dependency on specialized software development expertise.

### *Real-Time Data Integration*

E-learning platforms often face challenges integrating digital twins and high-fidelity simulation models with actual machinery. This lack of real-time synchronization and high-fidelity simulation models hampers the effectiveness and realism of e-learning scenarios (Altamirano-Avila et al., 2022). Developing solutions that enable real-time data integration between physical machinery and digital twins can enhance synchronization and realism. Leveraging IoT (Internet of Things) technologies and advanced data analytics to ensure real-time updates and interactions and investing in high-fidelity simulation models that accurately replicate the behavior and interactions of physical systems can improve the realism and effectiveness of e-learning scenarios.

### *Scalability and Transferability*

Due to regional infrastructure and policy variations, E-learning solutions often face challenges in scaling and adapting to different industrial contexts, which limits their widespread adoption and effectiveness (Cassola et al., 2022). Designing e-learning platforms with flexible and modular architectures can facilitate their adaptation to different industrial contexts and regional requirements. This approach allows for easy customization and scalability without significant redevelopment efforts. Developing region-specific modules and content that cater to other regions' unique needs and regulatory requirements can enhance the transferability and applicability of e-learning solutions. Collaboration with local industry experts and stakeholders can help ensure the relevance and effectiveness of these customized solutions.

### *User Interaction and Realism in AR*

AR-based training systems often struggle with user interaction challenges, such as unnatural gesture controls and a lack of realistic tactile feedback (Funk et al., 2017). Developing more intuitive and user-friendly interaction interfaces, such as advanced gesture recognition and more natural user interface designs, can enhance user experience and engagement. Integrating haptic feedback devices that simulate the tactile sensation of using real tools can significantly improve the realism of AR training environments. These devices can provide physical force feedback, enhancing the training experience and effectiveness.

### *Managing Complexity and Variability in Training Tasks*

AR systems often struggle to manage the complexity and variability of industrial training tasks, particularly in high-mix, low-volume manufacturing environments (Gan et al., 2022). Developing adaptive AR training systems that can adjust to the complexity of each task and the operator's experience level can enhance training effectiveness. These systems should use machine learning algorithms to personalize training content and adjust to different scenarios dynamically. Implementing modular training frameworks that can be easily customized and scaled to different product complexities and industrial environments can improve flexibility and applicability.

### *High Initial Costs and Maintenance*

The high initial costs associated with developing and maintaining AR-based training systems are significant barriers to their adoption, especially for small and medium-sized enterprises (SMEs). Reliance on current AR technology, which requires continuous updates and high-quality hardware, further complicates practical implementation and scalability (Gan et al., 2022). Developing cost-effective AR solutions can facilitate broader adoption by reducing the financial burden on SMEs. This could involve using more affordable hardware, open-source software, and cloud-based AR platforms to lower development and maintenance costs. Establishing sustainable maintenance practices, including regular software updates and hardware maintenance plans, can ensure AR training systems' long-term viability and effectiveness.

In summary, while VR, AR, and e-learning technologies offer promising advancements for industrial training, several critical gaps must be addressed to realize their full potential. These include overcoming hardware limitations to support immersive environments, integrating seamlessly with existing data systems, developing comprehensive evaluation frameworks, addressing practical implementation challenges, enabling real-time data integration, enhancing scalability and transferability, improving user interaction and realism, managing complexity in training tasks, and reducing high initial costs and maintenance barriers. By tackling these challenges, the adoption and effectiveness of virtual training technologies in industrial settings can be significantly improved, leading to better training outcomes and more impactful learning experiences.

## Potential Future Research Directions

The rapid advancement of VR, AR, and e-learning technologies has opened up numerous possibilities for enhancing industrial training. However, future research must address several key areas to leverage these technologies' potential fully. This subsection discusses potential research directions that can help overcome current limitations and pave the way for more effective, scalable, and accessible virtual training solutions.

### *Integration of AI and Machine Learning*

Future research could explore the use of AI to develop more adaptive learning systems that can personalize training based on individual learners' progress and needs. This includes real-time adjustments to the difficulty level of tasks and personalized feedback. For instance, in the realm of fitness, systems like the virtual personal trainer that utilize Convolutional Neural Networks (CNN) and Bidirectional Long Short-Term Memory (BiLSTM) networks to recognize and analyze user actions can serve as a model. Such technology accurately identifies exercises and provides feedback, demonstrating the potential for similar AI-driven adaptive features in industrial training environments (Arora et al., 2021). Evaluating the effectiveness of generative AI for automatically creating training scenarios, simulations, and content based on predefined parameters could significantly reduce the time and effort required to develop comprehensive training materials. Machine learning can predict training outcomes and identify areas where trainees might need additional support or assistance in the material authoring process (Rusch et al., 2021; Ying Li & Chitra Dorai, 2004). Adopting these technologies can help design more effective training programs and streamline the creation process.

### *Enhanced Realism in VR and AR*

Research can focus on improving haptic feedback systems to provide more realistic tactile sensations during VR training. This could involve developing more sophisticated haptic devices or integrating existing ones with VR systems. Additionally, advancements in photorealistic rendering techniques can enhance the visual realism of VR environments, making them more immersive and compelling for training.

### *Scalability and Accessibility*

Evaluating cloud-based solutions to make high-quality VR and AR training accessible to organizations with limited resources may be worthwhile. This approach can help scale training programs without significant hardware investments. Additionally, research can focus on developing more affordable VR and AR hardware solutions without compromising the quality of the training experience. Recently, integrated VR glasses such as Meta Quest have been used to reduce costs in other industries. These devices offer a self-contained, wireless VR experience that can reduce the need for additional hardware and setup costs. Future research can evaluate their effectiveness in industrial training scenarios and develop best practices for their implementation. Investigating the use of projection-based AR to overlay digital information onto physical environments without needing AR/VR head-mounted displays (HMDs) should be reconsidered. This approach can reduce the cost and complexity of setting up AR systems, making them more accessible for training. Future research can explore its effectiveness in various industrial training applications and develop guidelines for its optimal use.

### *Cross-Platform Integration*

Establishing standards for interoperability between different VR/AR platforms and tools can facilitate seamless integration and data sharing, making it easier to develop and deploy training programs across various platforms.

### *Evaluation and Effectiveness*

Developing and validating comprehensive frameworks for evaluating the effectiveness of VR and AR training programs is recommended. In addition, the inclusion of long-term studies to assess knowledge retention, skill transfer, and overall impact on job performance should be addressed. Lastly, in-depth studies on user experience should also be conducted to identify factors that enhance or hinder engagement and learning in virtual training environments.

### *Emerging Technologies*

Using Mixed Reality (MR), which combines VR and AR elements, to create more versatile training environments can help mitigate various limitations posed by VR and AR. This could include research on the applications of MR in different industrial contexts. Additionally, integrating digital twins with VR and AR training systems can provide real-time simulations of physical systems and processes.

In summary, while VR, AR, and e-learning technologies have made significant strides in industrial training, several areas require further research to maximize their potential. By focusing on the integration of AI and machine learning, enhancing realism in VR and AR, improving scalability and accessibility, establishing cross-platform integration standards, developing comprehensive evaluation frameworks, and exploring emerging technologies like MR and digital twins, future research can address current limitations. These efforts will lead to more effective, scalable, and accessible virtual training solutions, ultimately transforming industrial training practices.

### *Applying Knowledge Management in Virtual Training Systems*

Integrating knowledge management (KM) strategies may boost the success of industrial virtual training systems. KM involves the systematic process of creating, sharing, using, and managing the knowledge and information of an organization. By incorporating KM principles, training systems can ensure that valuable knowledge is captured, stored, and easily accessible, leading to continuous improvement and innovation. For example, in STEM education, knowledge management has been identified as a critical skill for equipping lifelong knowledge workers, as it helps individuals identify, search, analyze, apply, and disseminate information and media products effectively (Fan & Shum, 2023). Applying these KM practices to industrial training systems can enhance the quality and efficiency of training programs, ultimately leading to better outcomes and a more skilled workforce.

### *Enhancing Training Quality in Virtual Training Systems*

One promising avenue for future research is the application of structured modeling techniques to better understand and improve the various factors influencing training quality. For example, one of the studies employs interpretive structural modeling (ISM) and MICMAC analysis to identify and analyze the complex interrelationships among key factors affecting teaching quality (Almerino Jr et al., 2024). Applying similar methodologies to industrial virtual training systems could provide valuable insights into the interconnected drivers of training effectiveness. By identifying critical factors and their interdependencies, researchers, and practitioners can develop more targeted and effective training interventions. Such structured approaches can guide decision-making and strategic planning, ultimately leading to enhanced training outcomes and more efficient resource allocation.

## CONCLUSION

The integration of advanced technologies such as Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), and e-learning into industrial training systems marks a significant transformation in how training is conducted. These technologies offer immersive, interactive, and scalable solutions that address traditional training challenges, such as safety concerns, high costs, and the need for hands-on experience. By leveraging these cutting-edge tools, industries can enhance the effectiveness and efficiency of their training programs, thereby fostering a more skilled and adaptable workforce.

The comprehensive review of enabling technologies highlights the diverse applications and benefits of VR, AR, MR, and e-learning in industrial settings. Through highly realistic and interactive simulations, VR has demonstrated significant potential in improving training outcomes, user engagement, and knowledge retention. These simulations allow trainees to practice complex tasks in a safe, controlled environment, reducing the risk of accidents and equipment damage. Similarly, AR enhances task performance by overlaying digital information onto the physical world, thus reducing cognitive load and aiding in the precise execution of complex procedures. This technology is particularly beneficial in providing real-time instructions and visual aids, which help trainees perform tasks more accurately and efficiently. MR combines the best of both VR and AR by blending real and virtual worlds to provide an interactive environment where real and virtual objects coexist. This technology is beneficial for collaborative industrial training and the simulation of complex tasks, facilitating enhanced interaction and cooperation among trainees. The ability to manipulate digital objects within their physical space enables users to gain practical skills directly transferable to real-world scenarios. Conversely, E-learning offers flexible, efficient, and personalized educational solutions that have revolutionized vocational and industrial training. It provides the convenience of remote learning, allowing employees to access training materials at their own pace and from any location.

Despite the promising potential of these advanced technologies, their adoption is not without challenges. High initial costs, technical complexities, user acceptance, and health concerns pose significant barriers to widespread implementation. The initial investment required for developing and implementing VR, AR, and MR systems can be substantial, deterring many organizations from adopting these technologies. Additionally, the technical complexity of these systems necessitates specialized knowledge and skills for their practical use, which can be a barrier to entry for some users. User acceptance is another critical factor, as the effectiveness of these training tools largely depends on the willingness and ability of trainees to engage with them. Health concerns, such as motion sickness and visual strain associated with prolonged use of VR headsets, must also be addressed.

Various strategies have been proposed to mitigate these limitations. Cost-effective solutions, such as utilizing low-cost VR setups and leveraging existing technologies, can significantly reduce the financial burden of adopting these systems. Improved usability through intuitive interfaces and user-friendly designs can enhance user acceptance and engagement. High-quality 3D rendering, haptic feedback, and immersive theater setups can enhance simulation realism, providing a more authentic and practical training experience. Robust assessment mechanisms, including standardized evaluation methods and comprehensive feedback systems, are essential for measuring these training tools' effectiveness and identifying improvement areas.

Future research and innovation are essential to optimize these advanced training tools further. Continuous technological advancements, combined with systematic evaluation and feedback, will ensure the effective implementation and sustainability of industrial virtual training systems. Researchers and practitioners must collaborate to develop new methodologies and technologies that address the existing limitations and enhance the overall effectiveness of these training systems.

The findings from this review underscore the transformative potential of VR, AR, MR, and e-learning in revolutionizing industrial training. As these technologies evolve, their integration into training programs will be crucial in meeting modern industrial operations' diverse and dynamic needs. By embracing these advanced technologies, industries can significantly improve workforce training, enhance productivity, and ensure safety, ultimately contributing to a more skilled and adaptable industrial workforce. These tools' ongoing innovation and adaptation are vital to maximizing their potential and achieving the desired outcomes in industrial training.

In conclusion, integrating VR, AR, MR, and e-learning into industrial training systems represents a significant advancement in training methodologies. These technologies offer scalable, flexible, and highly effective solutions that address the limitations of traditional training methods. By continuing to innovate and refine these tools, industries can enhance the quality of their training programs, leading to improved performance, safety, and adaptability in the industrial workforce. The future of industrial training lies in the successful integration and continuous improvement of these advanced technologies.

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The authors of this publication declare there are no competing interests.

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