

## Research paper

# Immersive VR safety training: Enhancing hazard recognition and compliance through 5M and 5S integration

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## ABSTRACT

Advancing a new frontier in workplace safety and forging a new boundary in accident prevention, this study redefines safety training by harnessing immersive Virtual Reality (VR) to integrate the 5M framework (Material, Machine, Man, Method, Measurement), a sharp tool for pinpointing workplace accident root causes, with the 5S approach (Sort, Set in Order, Shine, Standardize, Sustain), a dynamic strategy for masterful risk mitigation, addressing the persistent challenges of inconsistent application and fading engagement in traditional practices. Through meticulous industrial site observations and reviewing accident records, it expose prevalent hazards. It dissects faltering safety systems, while qualitative insights from 20 safety experts illuminate current methods, unveiling VR's potential to revolutionize adherence to gold standard protocols. Employing the Analytic Hierarchy Process (AHP) with 10 expert inputs, training options are ranked across five critical criteria: hazard recognition, safety compliance, realism, integration, and knowledge retention. Results reveal VR as the top countermeasure at 45%, outpacing computer-based training at 29% and traditional methods at 26%, transforming 5S and 5M principles into vivid simulations that sharpen risk detection, enhance workplace organization, and solidify procedural mastery. Experts praise VR's ability to spark engagement, heighten situational awareness, and embed safety protocols, particularly in high-risk industrial arenas, offering a bold blueprint for VR programs that boost efficiency and safeguard lives in a thrilling leap forward for accident prevention.

## 1. Introduction

Workplace Safety is a fundamental concern in all industries, necessitating comprehensive and effective training programs to mitigate risks and promote a proactive safety culture [25,65]. However, conventional safety training methods often fail to engage workers effectively, leading to inconsistent application of safety principles and reduced training retention [56,57]. Facility management plays a crucial role in ensuring safe and efficient operational environments [4,44] by integrating structured methodologies such as 5S (Sort, Set in Order, Shine, Standardize, Sustain) [18,22] and 5M (Man, Machine, Material, Method, Measurement). These methodologies have been widely adopted in lean management and industrial safety practices to improve workplace organization, standardization, and risk mitigation [62,55]. Despite their effectiveness, their application within immersive training environments, such as Virtual Reality (VR), remains under-explored [20].

The 5S methodology, originating from Toyota Production System (TPS) [42] to eliminate wastes and improve workflow according to lean

manufacturing principles [31,45], is designed to enhance workplace organization and efficiency, directly impacting safety outcomes by reducing environmental hazards [50]. Similarly, the 5M framework provides a structured approach to analyzing safety risks by identifying the key elements contributing to workplace incidents [26,37]. These methodologies, when applied in safety training, offer a systematic approach to identifying and mitigating hazards. However, traditional training methods struggle to translate these principles into practical and interactive learning experiences.

VR training presents a promising alternative by offering high features for skill training [61], including immersive simulations that replicate hazardous scenarios, enhance hazard recognition, and improve procedural compliance [58,52,14]. VR encompasses both immersive and non-immersive environments. Immersive VR fully engages users in a simulated environment through head-mounted displays (HMD) and interactive controls such as Oculus Quest 3, creating a sense of presence. Immersive VR also offers animation capabilities that enhance usability and adaptability [47], while non-immersive VR, such as desktop-based

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simulations [48], offers limited engagement [35]. This study focuses exclusively on immersive VR environments, leveraging their ability to replicate complex workplace scenarios for enhanced safety training.

Immersive VR enhances safety training by integrating proactive warning systems and improving hazard recognition, addressing limitations of traditional methods. According to Zhang, VR provides real-time alerts for dynamic risks, significantly outperforming static safety signs in a construction environment [64]. Furthermore, VR supports hazard recognition and risk perception (HRRP), which is critical to reducing risky behaviors in high-risk industries such as construction, where systematic studies highlight its role in simulating realistic scenarios to promote safer decision-making [58]. For instance, VR's tailored applications in construction safety training enhance hazard identification [3]. On the other hand, VR's realism in simulating fire scenarios, as demonstrated in maritime firefighting training, enhances training effectiveness [19]. For example, Jing's study explores VR's ability to simulate crowd evacuation in fire scenarios, improving safety planning in educational facilities [28]. Furthermore, combining VR with CAD and AI makes training simulations much more immersive and realistic. [24]. With these features, immersive VR is considered a practical training tool that seamlessly incorporates 5S and 5M principles into safety programs to enhance risk mitigation skills in the simulated environment.

Immersive VR effectiveness in safety training extends to skill development and behavioral change, particularly in high-risk settings. Studies like Evangelista demonstrate that VR provides hands-on practice training for reducing the risk of cascading accidents and therefore improves safety behaviors in actual workplace environments [17]. In addition to that, Radhakrishnan's review emphasized high VR training effectiveness for industrial skills, illustrating the immersive nature of VR and the ability to replicate complex tasks [46]. Ultimately, VR's technical and experiential features, such as haptics and biosensors, enhance skill learning outcomes, consequently integrating structured methodologies like 5S and 5M into safety protocols [61]. This study leverages these strengths to design immersive VR training applications that foster procedural compliance and workplace safety.

The 5M framework identifies risk causes systematically, while the 5S methodology enhances workplace organization and reduces hazards through structured practices, enabling targeted interventions; thus, 5S and 5M integration principles into VR training modules are critical for workplace safety advancement. By embedding these principles into immersive VR simulations, training can deliver interactive, standardized, and practical learning experiences that improve hazard recognition and safety compliance, addressing a significant gap in current safety training approaches [50,26].

VR environments enable workers to engage with safety protocols in real time, reinforcing risk perception and adherence to safety measures, with studies showing improved safety performance through proactive applications [64]. Recent studies have highlighted VR's effectiveness in enhancing knowledge retention, skills, and abilities for procedural compliance in workplace training [47,2], it also has a high impact in enhancing motivation and engagement [9,11,27,17]. However, existing research lacks a structured framework for integrating facility management and lean safety principles, such as 5S and 5M, into VR-based training modules. Additionally, opportunities and challenges must be addressed to ensure widespread implementation.

This research investigates how VR safety training can effectively translate and reinforce 5S and 5M principles, fostering a deeper understanding of workplace hazards, risk mitigation strategies, and procedural adherence. Unlike previous studies, which primarily focus on VR's general benefits in safety training, this study systematically embeds 5S and 5M into VR-based learning environments, evaluating their role in user engagement, hazard identification, and training effectiveness. Through workplace observations, semi-structured interviews with safety experts, and a comparative analysis of different training methods using the Analytic Hierarchy Process (AHP) [12], this study assesses the effectiveness, limitations, and feasibility of VR-based safety training.

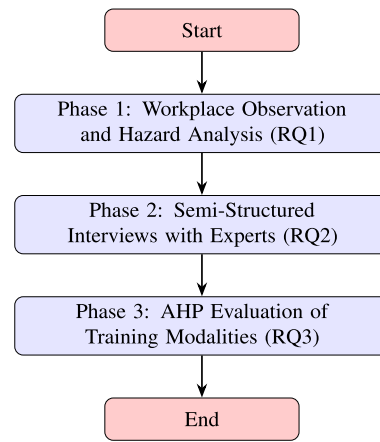


Fig. 1. Research Framework Illustrating the Stages of the Study.

AHP is employed due to its ability to facilitate multi-criteria decision-making [36], allowing for an objective comparison of training methods based on hazard identification accuracy [16], procedural compliance, and training retention.

### 1.1. Research questions

This study is guided by the following research questions:

1. RQ 1: What are the most prevalent workplace risks identified through the 5M framework, and how do they impact safety training needs? (Workplace observation)
2. RQ 2: How can integrating 5S and 5M principles into VR-based safety training improve hazard recognition, procedural compliance, and user engagement? (Interviews)
3. RQ 3: How does VR training compare to other methods in hazard recognition, safety compliance, realism, integration, and knowledge retention? (AHP)

These questions form a structured and interconnected inquiry, beginning with workplace risk assessment research question 1 (RQ1), followed by an exploration of how structured methodologies like 5S and 5M enhance safety training (RQ2), and concluding with a comparative evaluation of VR's effectiveness relative to other training approaches that facilitate multi-criteria decision-making (RQ3).

In summary, this study addresses a critical gap in workplace safety training by systematically integrating facility management principles, specifically 5S and 5M, into immersive VR environments. By leveraging a mixed-methods research approach, including workplace observations, expert interviews, and AHP ranking as shown in Fig. 1, this study provides actionable insights for designing and implementing VR-based safety training programs. Furthermore, this research highlights the potential industrial applications of VR-based safety training in sectors such as logistics, aviation, manufacturing, and construction. Ultimately, the findings contribute to the development of standardized, interactive, and effective safety training solutions, fostering safer and more organized workplaces.

## 2. Literature review

This literature review examines existing research on virtual reality applications in safety training and the role of 5S and 5M methodologies within facility management for enhancing workplace safety. Critically evaluates the strengths and limitations of current approaches, identifies gaps in the literature, and explores how VR can better integrate these methodologies to improve safety outcomes.

### 2.1. Facility management and safety management

Effective facility management is critical for maintaining safe working environments, particularly in high-risk settings such as manufacturing plants, construction sites, and warehouses [49,60]. Facility management encompasses the planning, design, and maintenance of workspaces to ensure operational efficiency and safety. A core function of facility management is to reduce safety hazards through organized and clean workspaces, which directly contribute to a safer and more productive work environment [51,32].

Recent studies have emphasized the importance of integrating facility management principles into safety training programs. For example, Denis [53] discusses the capabilities of facility managers in fire safety management, identifying their qualifications, organizational activities, and challenges faced. Additionally, [44] demonstrated that structured facility management practices significantly reduce workplace incidents. However, traditional training methods often fail to provide hands-on experience in implementing these practices, limiting their effectiveness. VR offers a promising solution by simulating real-world environments in which trainees can practice facility management procedures in a safe setting [35]. VR provides learning by doing approach [59] that enhances hazard recognition and procedural compliance, as highlighted by [5].

Despite these advancements, the specific mechanisms by which facility management principles are integrated into VR training remain under-explored. Further research is needed to understand how VR can best convey and reinforce these concepts, particularly in dynamic and high-risk environments.

### 2.2. 5M model application in workplace safety

Risks are caused by a combination of one or more unsafe acts or unsafe conditions [21]. Many studies investigated different types of models to analyze risks' root causes; for example, the 5M model (Man, Machine, Material, Method, and Measurement) provides a structured framework for analyzing and improving workplace operations, with a strong emphasis on safety. Organizations can identify potential hazards and develop targeted interventions by the 5 elements interaction [26,37]. The 5M model is used in conjunction with root cause analysis (RCA) techniques to investigate incidents and near misses, making it a valuable tool for safety management [43].

Many recent studies highlight the 5M model's effectiveness in high-risk industries. For example, Burduc utilizes only 4M (machine, material, method, man) to detect the risk factors [7]. While Lin uses slightly different 5M (Management-Machine-Man-Media-Mission) to find the accident root causes in Railway [38], Lyu also develops a 24Model for Smart Safety Management (SSM) to analyze accident cases [39]. Therefore, additional study is required to demonstrate the 5M to analyze incidents that led to a reduction in workplace accidents in a manufacturing setting.

However, traditional training methods often fail to provide a holistic understanding of how the 5M elements interact in actual scenarios. VR training can address this limitation by simulating complex environments where trainees can explore the relationships between man, machine, material, method, and measurement. For instance, trainees can practice identifying hazards related to improper material handling or machine operation, thereby enhancing their ability to apply the 5M model in practice.

The integration of the 5M model into VR training has received limited attention in the literature. Most studies focus on traditional applications of 5M, leaving a gap in understanding how immersive technologies can enhance their effectiveness. This gap underscores the need for further research into the design and implementation of VR-based 5M training programs.

### 2.3. 5S methodology and its role in workplace safety

The 5S methodology (Sort, Set in Order, Shine, Standardize, Sustain) [22] is a cornerstone of lean management and has been widely adopted for improving workplace organization, safety, and efficiency. According to Ohno, 5S focuses on five key principles: Sort (eliminate unnecessary items), Set in Order (organize remaining items), Shine (clean and maintain the workspace), Standardize (establish consistent procedures), and Sustain (maintain the improvements). Originating from the Toyota Production System (TPS) [42], furthermore, Gapp emphasizes that 5S eliminates waste, reduces clutter, and maintains standardized procedures [18]. 5S directly supports risk reduction and operational efficiency through the adoption of a continuous improvement culture.

Several studies emphasized that 5S principles improve safety outcomes in high-risk environments, [50]. For instance, Gapp found that the likelihood of accidents is reduced through well organized storage areas and marked tools [18]. VR overcomes the limitations of traditional training by offering immersive, interactive simulations to practice 5S principles. For example, trainees can virtually sort tools, organize workspaces, and identify potential hazards, thereby [34]. Or using gamification VR as an educational game to implement 5S methodology in the workplace [33].

While 5S benefits are well-documented, its integration into VR training remains under-researched. The present studies primarily demonstrate 5S uses without addressing immersive technology combinations in order to enhance the training efficacy in detail. This gap highlights further exploration needs of how VR utilization can teach and reinforce 5S principles in diverse workplace environments.

### 2.4. Combining 5S and 5M models in VR safety training

5S methodology and 5M model integration in VR safety training provides a robust approach to improving safety outcomes. VR simulations present a hands-on experience following the learning-by-doing theory to develop participants' skills [5,13], improve hazard identification [20], and gain confidence in safety standards implementation. By combining the benefits of 5S in organizing with the analytical strength of the 5M model, VR training creates a comprehensive and immersive learning experience.

VR safety training allow workers to practice safety steps in a virtual setting, reduces incident rates and improves safety outcomes [6,52]. Trainees explore virtual spaces, applying 5S principles—sorting, organizing, cleaning, standardizing, sustaining, while spotting 5M risks like machine issues or material handling.

In practice, a VR session has workers sort tools (5S) and check for hazards tied to machines or materials (5M). This builds decision-making and risk-handling skills. Trainees actively engage with 5S concepts hands-on, strengthening safe work habits. VR also mimics 5M scenarios to tackle accident causes, like faulty equipment or worker errors. More research is needed to refine this approach for better safety.

By engaging with risk factors retrieved from the 5M analysis in VR real-time, trainees develop a deeper understanding of risks that contribute to workplace incidents. The integration of 5S and 5M in VR training ensures that both organizational efficiency and systematic risk analysis are applied simultaneously within training scenarios, leading to more effective hazard recognition and procedural compliance.

### 2.5. Research gaps

Despite existing research on VR in safety training and the application of 5S and 5M, several gaps remain, which this research aims to address:

- **Integrated Application of 5S and 5M in VR:** Limited research explores the integrated application of 5S and 5M within VR training programs. Most studies focus on either 5S or 5M in isolation, neglecting the synergistic potential of combining these frameworks within immersive training environments.

- **Facility Management Integration within VR:** The specific mechanisms by which facility management principles are effectively integrated into VR training environments require further investigation. Research is needed to understand how VR can reinforce these concepts.
- **Operational Feasibility and Adoption of VR Training:** There is a need for a more rigorous expert assessment of the operational feasibility and Adoption of VR training solutions in diverse workplace settings, focusing on opportunities, practicality, limitations, and implementation challenges.
- **Optimal Design Principles for Immersive VR Safety Training:** Research exploring the optimal design principles for immersive VR safety training programs, including the integration of 5S, 5M, and facility management concepts, is still developing. Further investigation is required to boost engagement, retention, and learning transfer.

This literature review highlights VR's role in revolutionizing safety training by integrating 5S, 5M, and facility management principles. By addressing these research gaps, the study aims to reveal the development procedures of standardized, interactive, and effective safety training solutions. The findings provide actionable insights for VR safety training program designers and developers, ultimately fostering safer and more organized workplaces.

### 3. Research methodology

This research uses a mixed-methods approach, combining qualitative and quantitative data through collection and analysis techniques to comprehensively evaluate VR safety training according to the combination of 5S and 5M principles.

The methodology comprises three interconnected phases:

#### 3.1. Phase 1: Workplace observation and hazard analysis

This phase examines workplace safety practices and hazards in logistics operations. It involves observing three distinct workplaces across different industries and reviewing past high-probability risks to document current practices and hazard occurrences. Combining live observations with historical data provides a clear, comprehensive view of safety and risks in the sector.

**Why?** The primary goal focuses on the follows:

- Identify critical workplace hazards and assess current safety management systems in logistics.
- Study three industries with unique operations, like heavy machinery or material handling, to uncover sector-wide and specific risks.
- Align with OSHA standards to pinpoint gaps and benchmark against best practices.
- Analyze three years of safety audit records to detect recurring hazards and trends.
- Compare current practices with historical data to highlight improvements or issues.
- Develop tailored safety standards and VR training to address diverse logistics challenges.

**What?** The data collection process emphasized identifying hazards related to the 5M framework; materials, machinery, methods, human factors (Man), and measurement systems, providing a proven methodology for analyzing workplace risks systematically and comprehensively. Specifically, the observations sought to understand how these elements interact and contribute to both safe and unsafe work practices. The use of structured safety audit checklists, based on international standards, ensured a consistent, comprehensive, and quantifiable data collection process. This structured approach, combined with insights gained from reviewing previous audit records, allowed for the collection of data on

the frequency, severity, and types of observed hazards, including near misses and unsafe behaviors. These data form a crucial baseline for later comparison with the impact of the VR training program.

**How?** Data was collected through safety audits and reviewing previous audits performed during actual operations. Each safety audit involves a walk-through of the work areas, employee interviews, and a review of safety documentation, including previous safety audit records for the past three years, especially the accident and incident records. These audits focused on real-time safety practices and hazard identification, capturing the dynamic nature of the workplace and the actual risks faced by employees. The employee interviews provided valuable qualitative insights into workers' perceptions of safety risks, their experiences with current safety practices, and their suggestions for improvement. The review of safety documentation, including training records, incident reports, and safety procedures, provided a further understanding of the existing safety management systems. To mitigate bias, a standardized 5M based observation protocol ensured consistent data collection, reducing observer bias by categorizing risk causes (e.g., man, method). Field observations were cross-referenced with incident and accident reports to enhance reliability [15].

#### 3.2. Phase 2: Semi-structured interviews to exploring the integration of 5S and 5M principles for enhancing safety training through VR

**Why?** This phase aims to explore how VR safety training integrates and translates 5S and 5M principles into immersive simulations. This phase also aims to identify the perceived benefits, limitations, and areas for improvement in VR-based safety training.

**What?** A qualitative approach using semi-structured interviews gathers 20 safety expert insights. Experience in warehouse operations, safety training, and/or VR training development. Participants have prior experience with VR safety training or are familiar with the 5S and 5M methodologies.

**How?**

**Participant:** Experts have been recruited through professional networks, and industrial organizations implementing safety training.

**Data Collection:** Semi-structured interviews gather qualitative data on the integration of 5S and 5M principles in VR safety training. Interviews were conducted online and in person, depending on participant availability and preference. Each interview lasts approximately 30–45 minutes. The timeline for this phase includes one week for preparation, finalizing interview questions, and recruiting participants, four weeks for data collection through interviews, three weeks for data analysis through thematic analysis, and one week for summarizing findings and preparing the report. Bias was minimized using a semi-structured format with open-ended questions (e.g., IQ.1–IQ.8) to categorize responses, reducing leading question bias. Interview summaries were shared with participants to verify accuracy [15].

The interview questions are classified into three main themes: 5S and 5M Integration, Benefits and Effectiveness, and Challenges and Limitations. This structure ensures a focused yet comprehensive exploration of the research question, as shown in Table 1

**Data Analysis:** This research uses thematic analysis to analyze the interview data using Microsoft Excel as software. The framework focuses on identifying recurring patterns and themes. Interview responses were quantified by the frequency of key themes (e.g., hazard recognition, procedural compliance) for each question (IQ.1–IQ.8), providing descriptive statistics to complement thematic analysis.

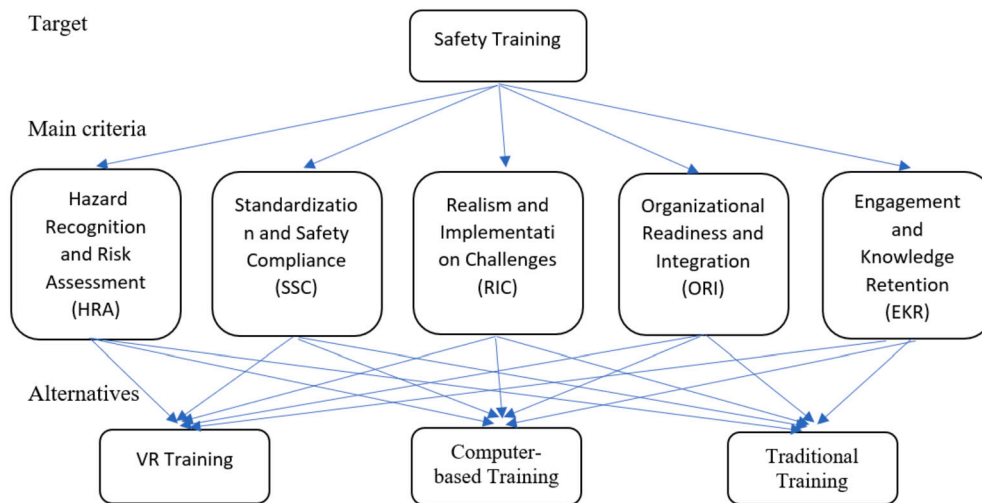
This phase provides valuable insights for refining VR safety training, ensuring a more effective and structured approach to warehouse safety.

#### 3.3. Phase 3: Analytic hierarchy process (AHP) for evaluating VR training modality adoption

This phase uses the Analytic Hierarchy Process (AHP) rank training modalities in this phase, including VR, for industrial safety programs

**Table 1**  
Interview Questions for Semi-Structured Interviews.

Theme	Interview Questions
5S and 5M Integration with VR	IQ.1 How does VR help organize and categorize materials and machines in the warehouse? (Sort) IQ.2 How does VR teach the optimal arrangement of materials and machines to improve workflow and safety? (Set in Order) IQ.3 How does VR emphasize cleaning and maintaining materials and machines, and how does it promote worker responsibility for cleanliness? (Shine) IQ.4 How does VR simulate standardized procedures for material handling and machine operation? (Standardize) IQ.5 How does VR instill accountability for maintaining a safe and clean workspace over time? (Sustain) IQ.6 How does VR simulate the 5M (Material, Machine, Man, Method, Measurement) framework in a warehouse environment?
Benefits and Effectiveness	IQ.7 What are the key strengths of VR in translating 5S and 5M principles into practical safety training, and how does it compare to traditional methods?
Challenges and Limitations	IQ.8 What limitations or challenges have you observed in using VR to teach 5S and 5M principles, and how can VR training be improved to better reflect real-world safety risks?



**Fig. 2.** AHP Levels.

based on five criteria. Ten experts provided judgments through delphi method to ensure accuracy. AHP ensures a transparent, rigorous evaluation of effectiveness and feasibility, combining quantitative and qualitative inputs. The complex decision of selecting a training modality is simplified by prioritizing alternatives based on safety training outcomes. The detailed questionnaire can be found in Appendix A.

**Why:** The core purpose of employing the AHP that it delivers a data-driven ranking of training modalities to boost workplace safety. Traditional Training may lack engagement for complex hazards, VR Training offers immersive learning but faces implementation hurdles, and Computer-based Training provides scalable digital options. AHP weighs these factors to prioritize VR Training, Computer-based Training, and Traditional Training, guiding organizations to invest in the most effective safety training.

**What:** The AHP process involves constructing a hierarchical model as shown in Fig. 2. That breaks down the decision problem into three levels. At the top level is the overall goal: selecting the optimal training modality for safety training implementation. The intermediate level consists of five criteria: Hazard Recognition and Risk Assessment (HRA), Standardization and Safety Compliance (SSC), Realism and Implementation Challenges (RIC), Organizational Readiness and Integration (ORI), and Engagement and Knowledge Retention (EKR), informed by expert input and organizational needs. The bottom level of the hierarchy consists of the training alternatives being considered:

- **VR Training (A1):** Immersive training scenarios simulated in virtual reality.

- **Computer-based Training (A2):** Using computers and software as training methods.
- **Traditional Training (A3):** Conventional methods such as classroom-based instruction and manual safety drills.

The AHP then involves pairwise comparisons between the criteria to determine their relative importance and pairwise comparisons between the training alternatives concerning each criterion to assess their relative performance.

**How:** The AHP methodology follows clear steps with precise calculations. First, a hierarchy is set, defining the goal—selecting the best training modality—and listing alternatives. This structure guides the evaluation.

Safety and technology experts complete the AHP questionnaire with pairwise comparisons of criteria and alternatives as shown in Appendix A. Their judgments averaging by the geometric mean for consensus, then weighted and ranked in Excel for accuracy. The pairwise comparison matrix is normalized by dividing each element by its column sum, with row averages yielding priority weights for criteria or scores for alternatives, determining the final ranking. A consistency index (CI) checks computed by:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{1}$$

Where:

$\lambda_{max}$  is the principal eigenvalue of the pairwise comparison.  
 $n$  is the number of criteria or alternatives in each comparison.

The consistency ratio (CR) is then computed by dividing the CI by the random index (RI) for the corresponding  $n$ .

$$CR = \frac{CI}{RI} \quad (2)$$

The Random Index (RI), a constant based on matrix size, reflects the average Consistency Index (CI) for random comparisons. A Consistency Ratio (CR) below 0.1 indicates reliable expert judgments. If CR exceeds 0.1, experts revise their judgments for better consistency. Once consistent, the final ranking is calculated by multiplying criteria weights by alternative scores and summing these for each alternative's overall score.

## 4. Result and discussion

### 4.1. Phase 1 Results: Observation result

Workplace observations and hazard analyses done in the logistics areas of three separate sectors are presented in this section. The findings are organized according to the 5M framework to provide a structured overview of the identified hazards and their interrelationships. The discussion integrates the information gained from field notes through observations and reviews of previous incidents and accidents to provide a comprehensive and direct understanding of the safety challenges present in observed workplaces. This method addresses the following research question:

**RQ 1: What are the most prevalent workplace risks identified through the 5M framework, and how do they impact safety training needs?**

**Man (Human Factors):** Rushing, shortcut-taking, inadequate training, inconsistent PPE use, and a general lack of safety awareness were recurring issues. Workers were observed not wearing safety harnesses at heights and operating machinery without authorization. PPE, such as gloves and safety glasses, was frequently neglected, even during potentially hazardous tasks.

**Machine (Equipment and Machinery):** Machinery hazards included missing or inadequate guarding, malfunctioning equipment (faulty brakes, damaged wires), and insufficient maintenance. Equipment was often used improperly, exceeding capacity, or by untrained personnel. Several pieces of equipment were observed to be broken or malfunctioning but still in use.

**Material (Materials and Substances):** Improper storage of hazardous materials, cluttered aisles and walkways, and damaged or leaking containers were common. Materials were frequently handled incorrectly, with overloaded pallets and improper lifting techniques observed. Materials and equipment were often disorganized and scattered, creating tripping hazards and hindering efficient retrieval.

**Method (Work Processes and Procedures):** A lack of standardized procedures, inadequate communication between workers, and poor adherence to safety protocols were observed. Lockout/tagout procedures were inconsistently applied. A lack of visual guides and workflow indicators further contributed to confusion and errors.

**Measurement (Monitoring and Feedback):** Inconsistent safety monitoring and feedback mechanisms were evident. Some workplaces lacked regular safety inspections, and near-miss/incident reporting systems were inadequate. Feedback loops were ineffective, with identified hazards often left unaddressed. Performance monitoring was limited, hindering the assessment of safety compliance. A continuous improvement culture regarding safety was largely absent.

### Discussion

The observations reveal a clear and concerning pattern answering the RQ1: safety practices are not consistently implemented, and a reactive rather than proactive approach to safety management prevails. Workers are taking shortcuts (Man) likely due to time pressure or production demands, directly compromising their safety. This is exacerbated by inadequate training (Man), which leaves workers ill-prepared

to handle hazardous situations. The inconsistent use of PPE (Man) demonstrates a disregard for basic safety precautions as noted in [23]. These human factors are intertwined with machine-related issues (Machine) as investigated by [30,41]. Broken and malfunctioning equipment [60] (Machines), often used due to a lack of maintenance, creates direct hazards. Improper material handling (Material), including cluttered workspaces and improper storage, creates further risks. The lack of standardized procedures (Methods) leads to inconsistent practices and increases the likelihood of errors. Inefficient communication (Method) compounds these issues, leading to misunderstandings and safety lapses. Finally, the lack of effective monitoring and feedback systems (Measurement) prevents the identification and correction of hazards before they lead to incidents, supported by [8]. The absence of a continuous improvement and safety culture [10] (Measurement) means that safety issues are not being systematically addressed. The disorganization of materials and equipment (Material), coupled with inefficient inventory management, further contributes to workflow inefficiencies and human factor hazards. The lack of visual guides and workflow indicators standards [40] (Method) makes it difficult for workers to follow proper procedures and increases the risk of accidents. The frequent machine downtime (Machine), due to maintenance gaps, adds to the pressure to take shortcuts and increases the risk of using malfunctioning equipment, consistent with the 5M framework [26,37].

In short, the observed workplaces suffer from a combination of human error, equipment deficiencies, flawed processes, and a weak safety culture. These interconnected issues create a hazardous environment and underscore the urgent need for comprehensive safety improvements. This data provides a clear and direct justification for the development and implementation of a targeted VR training program that addresses these specific and pressing safety gaps.

### 4.2. Phase 2 Results: Simi-structure interview: exploring the integration of 5S and 5M principles for enhancing safety training through VR

The semi-structured interviews provided detailed qualitative insights into the VR safety training program and its integration of 5S and 5M principles. The 5S principles and their application to the 5M components organize the results. Each section includes a discussion of how VR contributes to better safety and operational practices.

Research question number two (RQ.2) was comprehensively addressed through the structured analysis of the 5S and 5M principles within the VR safety training framework as shown in Fig. 3. The findings illustrate how VR facilitates organization, arrangement, maintenance, and standardization in warehouse environments, directly answering interview questions IQ.1 to IQ.5. The 5M framework was explicitly integrated into the discussion, showing how VR simulates real-world scenarios for material handling, machine operation, and workforce management, ensuring adherence to safety protocols. The effectiveness of VR training in enhancing hazard recognition, risk assessment, and decision-making was demonstrated through performance tracking and real-time feedback mechanisms, addressing IQ.6 on the benefits of VR over traditional methods. Additionally, while challenges and limitations were touched upon—such as potential gaps in realism and user adaptation—there is room to further explore IQ.7, particularly regarding how VR training could be improved to better reflect real-world safety risks. Overall, the results provide a clear link between the VR-based implementation of 5S and 5M and its role in improving warehouse safety, aligning directly with the research objectives.

#### 1. Material & machine → sort (IQ.1)

VR helps workers organize and categorize materials and machines by simulating real warehouse environments where clutter and disorganization pose significant risks. In the VR setting, trainees practice sorting materials based on necessity, type, and function. By identifying unnecessary or misplaced items, they learn to remove or relocate them to appropriate storage areas.

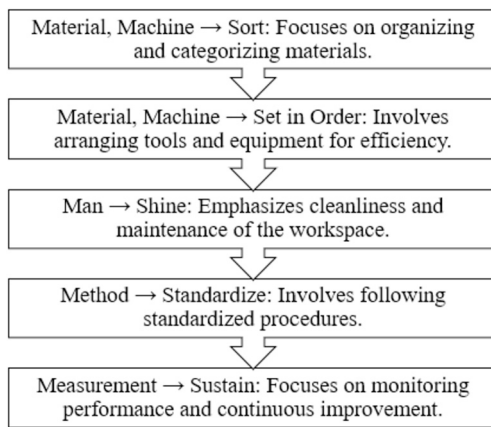


Fig. 3. 5M 5S Integration.

This supports the 5S “Sort” principle, which focuses on eliminating unnecessary items and organizing materials. VR provides a risk-free environment for trainees to practice identifying and addressing disorganization, which directly improves workflow efficiency and hazard reduction in real-world warehouse operations.

#### 2. Material & machine → set in order (IQ.2)

VR application allows workers to experience the materials and machine arrangement procedures by visualizing different layouts within a simulated warehouse. Trainees practice positioning tools, equipment, and materials in a way that maximizes space usage and minimizes search time.

This supports the 5S “Set in Order” principle, which emphasizes creating an efficient and logical arrangement of items. VR enables trainees to experiment with different layouts and understand how proper organization contributes to productivity and safety. By practicing these skills in a virtual environment, workers are better prepared to implement them in real-world settings.

#### 3. Man → shine (IQ.3)

VR emphasizes the importance of cleanliness and equipment maintenance through interactive scenarios. Workers encounter messy or malfunctioning equipment in the simulation and are tasked with cleaning and performing basic maintenance tasks. Also, VR training promotes individual responsibility by assigning each trainee their virtual workspace. The immersive environment encourages workers to manage their area, ensuring it remains clean and organized throughout the day. This aligns with IQ.3 by showing how VR fosters personal responsibility in maintaining workspace cleanliness.

This supports the 5S “Shine” principle, which emphasizes a clean, safe workspace. VR training shows cleanliness is a daily duty, not a one-time task. Practicing maintenance in simulations helps trainees build habits that prevent accidents and prolong machinery life.

#### 4. Method → standardize (IQ.4)

VR training simulates standardized warehouse procedures for material handling and machine operation, guiding workers step-by-step through safe lifting and safety standard adherence, with immediate feedback for deviations from established procedures.

This supports the 5S principle of “Standardize”, which focuses on establishing consistent and repeatable processes. VR ensures that workers internalize company standards by practicing them repeatedly in a controlled environment. The real-time feedback mechanism helps correct unsafe behaviors, ensuring that safety protocols are consistently followed.

#### 5. Measurement → sustain (IQ.5)

VR tracks performance metrics, for example, task completion times, accuracy, and compliance with safety protocols. After each simulation, workers receive data-driven feedback on their performance, including where they excelled or fell short.

This supports the 5S “Sustain” principle, which emphasizes continuous improvement. By providing measurable feedback, VR enables workers and supervisors to identify areas for improvement and refine training programs. This feedback loop ensures that safety and organizational improvements are consistently maintained over time. Whereas IQ.5 is addressed as VR facilitates ongoing safety improvements through systematic performance tracking.

#### 6. Overall integration of 5S and 5M in VR training (IQ.6)

5S and 5M methodologies integrated in VR by creating immersive environments where workers must apply the principles of sorting, organizing, cleaning, standardizing, and sustaining the key warehouse elements—materials, machines, manpower, methods, and measurements. For example, in one scenario, a worker organized and sorted excess tools and materials, reducing the risk of tripping and improving the speed of material movement through the warehouse.

The integration of 5S and 5M in VR training enhances both safety and efficiency by allowing trainees to practice in a realistic, risk-free environment that mirrors the complexities of actual warehouse operations. This holistic approach ensures that workers understand how each principle contributes to a safer and more organized workplace. IQ.6 demonstrates VR’s immersive nature makes it more effective than traditional methods for reinforcing 5S and 5M principles.

#### 7. Benefits and effectiveness (IQ.7)

The semi-structured interviews provided valuable insights into the strengths of VR training for integrating 5S and 5M principles, as captured by Interview Question 7. IQ.7 focused on the key strengths of VR in translating 5S and 5M principles into practical safety training compared to traditional methods. Interviewees emphasized that VR’s immersive simulations enable realistic practice of 5S principles, such as organizing materials (Sort) and standardizing procedures (Standardize), which enhance procedural compliance and workplace organization. For the 5M framework, VR effectively simulates interactions between man, Machine, and method, improving hazard recognition and fostering accountability for safety practices. Compared to traditional methods, such as lectures or manuals, VR provides dynamic, hands-on learning experiences that improve trainee engagement and retention of safety protocols. Therefore, VR’s considered a powerful tool for 5S and 5M implementation in warehouse safety training.

#### 8. Challenges and limitations (IQ.8)

Interviews revealed VR training challenges according to 5S and 5M principles, as covered by Interview Question 8. IQ.8 explored limitations and ways to improve VR’s reflection of real safety risks. Interviewees noted several issues affecting VR’s effectiveness, including:

- Motion sickness and VR fatigue, which may prolong training sessions
- The need for higher realism in physics-based interactions, such as weight simulation when handling heavy materials, to better replicate warehouse tasks.
- VR training scaling problems across diverse warehouse environments layouts that limit users’ adaptability.

IQ.8’s result reveal that VR improvement enhances applicability to actual safety scenarios. Suggested solutions for future research include exploring additional innovations, such as haptic feedback, AI-driven adaptive training modules, and integration of actual warehouses to improve VR’s applicability and realism. In addition to that, participants suggest further hardware advancements are needed to mitigate motion

**Table 2**  
Quantitative Summary of Interview Themes.

Question	Key Theme	% of Experts
IQ.1	Effective material sorting	90% (18/20)
IQ.2	Improved workflow via arrangement	80% (16/20)
IQ.3	Enhanced cleanliness responsibility	70% (14/20)
IQ.4	Standardized procedure adherence	85% (17/20)
IQ.5	Sustained safety via continuous improvement	70% (14/20)
IQ.6	Realistic 5M simulation	70% (14/20)
IQ.7	Superior engagement vs. traditional methods	80% (16/20)
IQ.8	Motion sickness	70% (14/20)

sickness and improve scalability to ensure VR training fully supports the practical application of 5S and 5M principles in diverse industrial settings.

#### 9. Root cause analysis of 5S and 5M integration

The 5M components were analyzed to understand how VR training addresses each element:

- **Material & Machine** → **Sort**: VR simulates crowded warehouse environments, allowing trainees to practice organizing and categorizing materials.
- **Material & Machine** → **Set in Order**: VR models the arrangement of machinery and materials, teaching trainees to maximize productivity and reduce disorder.
- **Man** → **Shine**: VR creates scenarios where trainees encounter messy or broken equipment, emphasizing individual accountability for cleanliness.
- **Method** → **Standardize**: VR simulates standardized warehouse procedures, ensuring adherence to best practices.
- **Measurement** → **Sustain**: VR includes performance indicators and feedback mechanisms to monitor and improve 5S implementation.

#### Quantitative summary of interview themes

Responses to IQ.1–IQ.8 were coded to quantify key themes. Table 2 summarizes the percentage of experts (out of 20) mentioning each theme. These results reinforce qualitative findings, showing strong expert agreement on VR's benefits for 5S/5M integration and identified limitations. For example, 90% (18/20) of experts emphasized VR's effectiveness in sorting materials (IQ.1), while 85% (17/20) highlighted its role in enhancing adherence to standardized procedures (IQ.4), and 80% (16/20) highlight improvements in workflow through better arrangement (IQ.2). Additionally, 80% (16/20) valued the superior engagement offered by VR compared to traditional methods (IQ.7). On the other hand, 70% (14/20) identified motion sickness as a notable challenge while using VR (IQ.8). These patterns confirm strong expert consensus on VR's value in supporting 5S/5M implementation.

This analysis demonstrates how VR training addresses each 5M component through the lens of the 5S methodology. By providing a structured and immersive learning environment, VR ensures that workers understand the root causes of inefficiencies and safety risks and are equipped to address them effectively.

#### Discussion

The results of the semi-structured interviews answering the RQ2 highlight the effectiveness of VR training in integrating 5S and 5M principles into warehouse safety practices [50,43]. By addressing each component of the 5M model through the 5S methodology, VR provides a comprehensive and immersive training experience that enhances hazard recognition, risk assessment [63,20,52], and adherence to safety protocols [29,40]. The feedback and performance metrics generated by VR training support continuous improvement, ensuring that safety and organizational practices are sustained over time.

These findings underscore VR technology as a transformative tool for safety training [52,60], offering actionable insights for organiza-

tions looking to improve workplace safety and operational efficiency. Future research could explore the scalability of VR training across different industries and the long-term impact of VR-based safety programs on workplace culture and performance.

Based on the Phase 2 semi-structured interviews with safety experts, the following five key criteria can be investigated using the AHP:

1. C1: Hazard Recognition and Risk Assessment (HRA): Workplace hazards identification, assessing risks, and improving decision-making (IQ.1, IQ.6).
2. C2: Standardization and Safety Compliance (SSC): Reinforcing structured safety protocols and consistent training outcomes (IQ.4).
3. C3: Realism and Implementation Challenges (RIC): Addressing simulation accuracy, physics-based interactions, and adoption barriers (IQ.7, IQ.8).
4. C4: Organizational Readiness and Integration (ORI): Workforce adaptation, infrastructure requirements, and management support (IQ.5).
5. C5: Engagement and Knowledge Retention (EKR): Interactive and immersive level, its ability to enhance engagement and long-term knowledge retention (IQ.3, IQ.6)

These criteria directly align with expert opinions gathered during the interviews and will help assess the strategic feasibility of VR integration for workplace safety. Would you like any refinements or additional details?

#### 4.3. Phase 3 Results: AHP evaluation of training modalities

AHP ranks VR Training (A1), Computer-based Training (A2), and Traditional Training (A3) for industrial safety to evaluate adoption feasibility. Ten experts used pairwise comparisons, refined by the Delphi method, to score five criteria: Hazard Recognition (HRA), Safety Compliance (SSC), Realism and Challenges (RIC), Organizational Fit (ORI), and Engagement (EKR). The process yields a clear ranking, answering the Research Question.

#### RQ 3: How does VR training compare to other methods in hazard recognition, safety compliance, realism, integration, and knowledge retention?

The AHP analysis considered the effectiveness of each alternative across the five criteria. The structured weighting process ensured consistency in evaluating these alternatives. Specifically, the results demonstrate the relative effectiveness of each modality as perceived by the expert.

The criteria weights, as shown in Table 3, reflect the relative importance the experts assign to each of the five criteria in evaluating safety training modalities. ORI received the highest weight of 0.29, indicating its critical role in adoption decisions to support new technology integration, followed closely by SSC at 0.21 and HRA at 0.20. EKR at 0.16 and RIC at 0.14 were deemed less influential but still significant, providing a balanced framework for assessing the training alternatives' performance across diverse aspects of safety training effectiveness.

Table 4 illustrates the local priorities of the three training alternatives under each criterion, combined with their respective weights,

**Table 3**  
Criteria Weights.

Criterion	Weight
Hazard Recognition and Risk Assessment (HRA)	0.20
Standardization and Safety Compliance (SSC)	0.21
Realism and Implementation Challenges (RIC)	0.14
Organizational Readiness and Integration (ORI)	0.29
Engagement and Knowledge Retention (EKR)	0.16

**Table 4**  
Local Priorities and Criteria Weights.

Criterion	Weight	(A1)	(A2)	(A3)
HRA	0.20	0.58	0.24	0.18
SSC	0.21	0.51	0.26	0.23
RIC	0.14	0.53	0.28	0.19
ORI	0.29	0.23	0.37	0.40
EKR	0.16	0.55	0.26	0.19

Note: A1 = VR Training, A2 = Computer-based Training, A3 = Traditional Training

**Table 5**  
Ranking of Training Alternatives.

Training Alternative	Priority Weight (%)
VR Training (A1)	45.2%
Computer-based Training (A2)	29.1%
Traditional Training (A3)	25.7%

providing insight into how each modality performs across the five dimensions. VR Training consistently scored highest in HRA (0.58), SSC (0.51), RIC (0.53), and EKR (0.55), showcasing its strengths in hazard recognition, compliance, realism, and engagement, though it lagged in ORI (0.23) due to integration challenges. Computer-based Training performed moderately across all criteria (0.24–0.37), with a notable strength in ORI (0.37), reflecting its scalability. Traditional Training excelled in ORI (0.40) due to its practicality and ease of integration but scored lower in HRA (0.18), RIC (0.19), and EKR (0.19), indicating limitations in engagement and realism.

Expert evaluations of the training alternatives further contextualize the rankings in Table 5. VR Training, with the highest priority weight of 45.2%, was praised for its immersive nature and capability to provide risk-free, highly engaging training experiences. Computer-based Training, at 29.1%, was valued for its scalability and digital format, though experts noted its lack of immersive realism compared to VR and highlighted technological and implementation challenges as limitations. Traditional Training, ranked lowest at 25.7%, was critiqued for lower engagement levels and limited capacity to simulate complex or hazardous scenarios, despite remaining an available effective option.

The consistency check was conducted to ensure the reliability of the expert judgments. The Consistency Ratio (CR) was below the 0.1 threshold, confirming the acceptability of expert judgments and validating the decision-making process. This analysis ensured that minor changes in expert preferences did not significantly alter the final rankings, strengthening the results' stability.

### Discussion

The AHP results reveal critical findings about safety training adoption answering the RQ3 as follows:

- **VR's Trade-offs:** While VR excelled in hazard recognition (HRA: 0.58) and engagement (EKR: 0.55), its low ORI score (0.23) reflects organizational barriers like technical integration [61]. This aligns with [64], who emphasized VR's need for proactive implementation strategies.

- **Computer-based Training:** Its moderate scores (0.24–0.37 across criteria) suggest a scalable compromise, though limited by immersion VR [35].
- **Traditional Training's Limitations:** Despite practicality (ORI: 0.40), its poor HRA (0.18) and EKR (0.19) scores highlight risks in high-risk scenarios [20,58].

AHP findings indicate that VR Training is the most effective modality for safety training, as validated by [56], followed by Computer-based Training, with Traditional Training as the least preferred, according to Table 4. While implementation challenges associated with VR training should be considered, its benefits in terms of improved safety outcomes, supported by [54,1] may justify the investment. The use of five criteria provided a comprehensive evaluation, consistent with [36,12], highlighting VR Training's strengths in engagement and realism, Computer-based Training's scalability, and Traditional Training's practicality. Therefore, VR Training stands out as the most preferred option due to its high engagement and realism in safety training simulations.

### 5. Conclusions

The study findings from three research phases highlight the critical role of VR-based safety training in improving workplace hazard identification and risk management. This study advances warehouse safety training through a pioneering multi-phase approach that addresses three critical research questions, delivering original contributions to engineering safety practices. For RQ1, Phase 1 observations identified prevalent workplace risks using the 5M framework, revealing critical safety gaps such as inadequate training, equipment malfunctions, and poor monitoring (e.g., inconsistent PPE use, missing machine guards). This structured risk identification, uniquely tailored to inform VR training design, underscores the need for targeted interventions to enhance hazard recognition and safety compliance. For RQ2, Phase 2 interviews demonstrated how our novel integration of 5S and 5M principles into VR training, a first in warehouse safety applications, fosters procedural compliance and user engagement. e.g., VR's immersive sorting and standardization simulations. This original contribution provides a scalable framework for embedding structured methodologies into immersive training environments, driving efficiency and safety through real-time feedback and performance tracking. The approach significantly improves hazard recognition and accountability, addressing RQ2 by offering a transformative tool for safety behavior enhancement. For RQ3, Phase 3's AHP analysis ranked VR training as the most effective modality with 45.2% priority weight, surpassing computer-based with 29.1% and traditional training with 25.7% in hazard recognition (HRA: 0.58), engagement (EKR: 0.55), and realism (e.g., immersive simulations). Using AHP to evaluate training modalities against five criteria (HRA, SSC, RIC, ORI, EKR) offers a rigorous, data-driven contribution to training assessment methodologies. This analysis, uniquely combining expert inputs and AHP, confirms VR's superiority in addressing RQ3, providing actionable insights for organizations to optimize safety training effectiveness.

This study's original multiple-phase methodology by integrating 5M risk assessment, 5S/5M-driven VR training, and AHP evaluation to establish VR as the leading solution for warehouse safety, validating its role in modern safety training through a robust, immersive, and data-driven approach. The results confirm VR's effectiveness in enhancing hazard recognition, risk assessment, and procedural compliance, while its structured framework supports continuous learning and performance tracking, addressing contemporary safety training needs.

### 6. Future work

Future studies should explore quantitative measures of VR training effectiveness, such as actual accident reduction or long-term knowledge

retention. Expanding this research to other industrial sectors could reveal broader applications of VR safety training using the 5S and 5M models. This methodology aims to provide a comprehensive qualitative understanding of how VR training can improve safety in warehouse environments through the integration of critical thinking and established

### Declaration of generative AI in scientific writing

During the preparation of this work, the author(s) used Chat-GPT 4. To improve readability and language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

### CRedit authorship contribution statement

**Abdallah Al-Hamad:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Attila Gilányi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration.

### Ethics declarations

Not applicable.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Appendix A. Supplementary material

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.rineng.2025.105135>.

### Data availability

Data will be made available on request.

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