

A data-analytics framework for optimizing user-centered virtual reality training

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ARTICLE INFO

Keywords:

Virtual reality analytics
Safety training data
Decision modeling
User data integration
Technical feature analytics
Immersive training evaluation

ABSTRACT

Safety training in high-risk industries often lacks user-centric design, leading to ineffective learning outcomes. This study presents a novel framework to optimize Virtual Reality (VR) safety training by integrating two decision-making methods to align user needs with technical design. The research addresses the problem of inadequate training efficacy by prioritizing user requirements and mapping them to technical solutions. A four-phase methodology identifies user requirements through expert consensus, prioritizes them using the Analytic Hierarchy Process (AHP), determines technical measures, and aligns them with user needs via Quality Function Deployment (QFD). SMART-FAST-CLEAR framework and consistency check used to validate expert agreement, though empirical user testing is recommended for future work. Results highlight VR's superiority over augmented reality and computer-based training, emphasizing enhanced learning effectiveness and immersion without relying on complex numerical metrics. This framework offers a replicable model for designing effective, user-focused VR safety training systems, contributing to improved safety practices in high-risk environments.

1. Introduction

Current safety training methods in high-risk industries, such as construction and manufacturing, often fail to engage trainees or simulate actual hazards effectively, leading to poor knowledge retention and increased risk of injuries or fatalities [1,2]. Virtual Reality (VR) emerges as a transformative solution, offering immersive, interactive environments to enhance skill acquisition and safety awareness [3,4]. However, its effectiveness depends on systematically addressing user needs and technical constraints. This study proposes an integrated Analytic Hierarchy Process (AHP) [5] and Quality Function Deployment (QFD) framework [6] to develop and evaluate VR solutions for safety training, comparing them with Augmented Reality (AR) [7] and Computer-based/Tablets (CBT) [8] alternatives. AR provides a hybrid approach that overlays digital information onto the real world, enhancing situational awareness, especially for workplace risk evaluation training, while CBT offers a cost-effective and accessible alternative [9] for training delivery in safety [4,10].

This research aligns with the decision analytics focus on prescriptive analytics, which seeks to provide actionable solutions for organizational decision-making. For instance, studies such as [11] address the application of analytics in complex systems, a theme resonant with

the research focus on safety-critical training environments. Furthermore, [12] delves into the use of Digital Twins in Industry 4.0 to enhance operational intelligence, providing a broader investigation into VR as a key technology for improving safety training. These connections affirm this research's alignment with the decision analytics mission to advance prescriptive analytics and decision-making in diverse organizational settings.

This study addresses the problem of ineffective safety training by developing a user-centric VR framework that enhances training efficacy and engagement. The objective is to integrate AHP and QFD to prioritize user requirements and align them with technical measures, creating an evidence-based model for VR safety training. The contribution lies in providing a replicable methodology that bridges user needs and technical design, improving safety outcomes in high-risk industries. By using AHP to select the optimal training module and QFD to prioritize technical measures, this framework guides designers and developers to focus on design features that enhance user experience (UX) and usability through appropriate hardware, software, and content, leading to improved knowledge retention, enhanced skill acquisition, and reduced training time. This study integrates AHP and QFD to optimize user-centric VR safety training in high-risk industries, addressing a gap in

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Table 1
List of abbreviations used in the manuscript.

Abbreviation	Full form
AHP	Analytic Hierarchy Process
AR	Augmented Reality
CBT	Computer-Based Training
CI	Consistency Index
CLEAR	Critical thinking, Logical grouping, Evidence-based, Analytical theming, Reflective review
CR	Consistency Ratio
DEMATEL	Decision Making Trial and Evaluation Laboratory
FAST	Flexible, Actionable, Simple, Transparent
HoQ	House of Quality
MCDM	Multi-Criteria Decision Making
QFD	Quality Function Deployment
SMART	Specific, Measurable, Achievable, Relevant, Time-bound
UCD	User-Centered Design
UX	User Experience
VR	Virtual Reality

tailored frameworks for immersive training and advancing prescriptive analytics with a data-driven methodology (see Table 1).

This study is driven by interconnected research questions that guide the development and assessment of VR solutions for safety training using an integrated AHP–QFD framework. These questions explore user requirements, technical feasibility, and comparative effectiveness to optimize training outcomes:

1. RQ1: What are the key user requirements for VR safety training? (Phase 1) This identifies essential criteria and sub-criteria through expert input, forming the foundation for design.
2. RQ2: How should user requirements be prioritized for VR development? (Phase 2) This uses AHP to rank criteria and sub-criteria, guiding resource allocation.
3. RQ3: What technical measures support VR safety training implementation? (Phase 3) This determines critical hardware, software, and content specifications via expert consensus.
4. RQ4: How can user requirements and technical measures be aligned to optimize VR training? (Phase 4) This applies QFD to match requirements with technical solutions, enhancing effectiveness.
5. RQ5: Which training method (VR, AR, or CBT) best enhances safety training outcomes? (Phase 2, 4) This assesses the effectiveness of VR against AR and CBT.

These questions collectively underpin a comprehensive framework, leveraging AHP for prioritization and QFD for integration, to advance VR-based safety training efficacy.

2. Literature review

This research explores the application of an integrated AHP and QFD methodology to enhance VR safety training systems. The methodology focuses on aligning user-centered requirements [13] with technical implementation [14], drawing from established frameworks. AHP, an MCDM tool, prioritizes user needs by structuring criteria hierarchically and assigning weights based on expert judgment [5], while QFD translates these priorities into technical specifications through a House of Quality (HoQ) matrix [6]. Recent studies in construction [15], mining [16], and chemical manufacturing [17] show VR improves safety training, but few integrate AHP and QFD for user-focused design. Drawing on contemporary research, the study investigates criteria, along with their sub-criteria, alternatives (VR, AR, and CBT), and technical measures, which are informed by the latest advancements in VR safety training, ensuring relevance with VR training design principles.

This research examines the integration of VR into safety training through a user-centered design (UCD) perspective, focusing on customer needs as criteria and their underpinning theories, alongside

technical measures for VR implementation. UCD emphasizes designing systems based on user requirements, a principle widely applied in training system development [18].

2.1. Criteria and sub-criteria

This study identifies key criteria that reflect the dimensions of VR safety training effectiveness. These criteria are grounded in established theories and supported by contemporary research, ensuring their relevance to user-centered design in safety training contexts.

Visual quality and aesthetics, encompassing visual appeal and attractiveness, are vital for boosting user engagement and immersion to enhance accident prevention [15]. High-quality visuals, grounded in improved color accuracy and clarity [19], enhance hazard recognition and user satisfaction, as demonstrated in industrial training environments [10]. Additionally, aesthetic elements aid information retention, a finding supported by research on user perception [20] and Explainable Visual Aesthetics principles [21], underscoring their role in sustaining engagement during safety training.

Cognitive experience includes immersive experience and safety and trustworthiness, leveraging presence theory to deepen learning outcomes [22]. Immersive VR environments enable realistic scenario engagement, reducing cognitive load [23] and enhancing decision-making skills [24]. [16] illustrates how such simulations foster trust and safety awareness among workers, while [1] emphasizes VR's ability to heighten the feeling of presence, thereby improving hazard recognition and emergency response capabilities.

Psychological aspects comprise emotional engagement and enjoyment, and psychological state and confidence, aligning with self-determination theory [25]. VR's capacity to evoke emotional engagement is pivotal, as it boosts user confidence and reduces anxiety across diverse occupational settings, a benefit underscored by [3]. Emotional engagement and enjoyment primarily enhance short-term user motivation during training sessions, while psychological state and confidence, developed through repeated VR exposure, support long-term retention of skills and knowledge. Furthermore, [17] notes that emotionally engaging VR experiences improve users' perceptions of safety training, making it more impactful.

Physiological aspects cover physical comfort and relaxation, drawing on ergonomic principles [26] to ensure user well-being during the training sessions [27]. Where VR serves as a tool for therapy [28]. Comfortable VR systems mitigate stress [29] and anxiety [30], enhancing user confidence in handling real-life hazards. Physical comfort ensures short-term engagement by reducing immediate discomfort, while consistent relaxation over multiple sessions supports long-term learning retention by encouraging sustained participation. Additionally, [31] highlights how VR-induced relaxation contributes. Furthermore, [32] highlights how VR contributes to an enjoyable training experience, further supporting its physiological benefits.

Content interaction includes user interface characteristics and content functional performance, grounded in interaction theory [33]. Intuitive interfaces and interactive elements enhance hazard identification performance [34] and UX [35]. [36] demonstrates that well-designed interfaces improve interaction efficiency in safety training modules, while [37] emphasizes the role of interactive content such as simulations and real-time feedback in delivering seamless and effective training experiences.

Training efficiency and effectiveness encompass learning effectiveness, learning efficiency, provision, narratives, and performance metrics, supported by adult learning theory [38], especially in safety training [39]. VR outperforms traditional methods in knowledge retention and skill acquisition [40]. Recent studies, including [10,41], confirm VR's ability to enhance learning outcomes in safety training applications. Moreover, VR's gamification features [42] and immersive narratives [43] significantly improve motivation and engagement, a finding corroborated by [44].

2.2. Technical measures

The technical measures for VR safety training are categorized into hardware, software, content, and support, each with targeted sub-measures to ensure system efficacy. Hardware such as head-mounted display units includes comfortability to enhance user endurance, high visual quality for realistic simulations, and durability for long-term reliability [29]. [27] stress well-being design, while [4] advocate high-resolution displays to mimic actual hazards. The software encompasses functionality for seamless operation, usability for intuitive navigation, reliability and stability for consistent performance, and performance for responsiveness. [10] highlights the need for reliable software to support effective trainee engagement. Content measures include usefulness for practical application, content features, scalability, and user interface for adaptability; scenario plans and task types for complexity; and adaptability, compatibility, and credibility for contextual fit. [36] emphasize adaptable interfaces, and [40] note the value of scalable content for diverse learners while [45] stresses ongoing customization to meet evolving safety standards. Support measures include continuous improvement, maintenance and testing, customization, flexibility, cost-effectiveness, and accessibility for individuals with disabilities, ensuring sustainability and inclusivity. These measures, rooted in current research, form a robust foundation for VR system design.

2.3. Research gaps

Despite advancements in VR for safety training, several gaps persist, which this study addresses through an integrated AHP–QFD framework. These gaps show where current research falls short and why our approach is needed. These gaps are outlined below:

1. **Limited User-Centered Frameworks:** Existing studies lack a comprehensive user-centered requirement framework, often focusing solely on immersion [8]. Few cover all user needs like visuals, comfort, and learning, while this study addresses six criteria and 13 sub-criteria.
2. **Underused AHP for Prioritization:** AHP is rarely applied to prioritize VR training requirements [10]. This leaves the user's needs unranked. This study employs AHP to rank criteria quantitatively.
3. **Limited QFD Application:** QFD is seldom used to align technical measures with user needs [46]. Most studies miss-linking user wants to VR design. This study maps 22 sub-measures using QFD.
4. **Narrow VR Focus:** Research emphasizes VR's immersive benefits but overlooks diverse techniques [47]. Few explore VR across industries like mining or construction. This study broadens the scope with domain-specific applications.
5. **Lack of Expert Validation:** Expert consensus with performance data is missing [10]. This weakens VR system design. This study uses AHP for expert-driven validation.
6. **Limited Comparisons:** Comparisons with AR and CBT are rare [8]. This hides VR's true value. This study uses AHP to compare VR, AR, and CBT.
7. **Unprioritized Benefits and Challenges:** VR benefits and challenges lack prioritization [46]. This slows VR adoption. This study ranks them using AHP for integrated effectiveness.

These gaps highlight the need for a new approach. Our AHP–QFD framework fills these gaps by focusing on user needs, prioritizing them, and linking them to VR design across industries. This research novelty focuses on VR's role in safety training, where it is well-established, with studies like [45,47] documenting its effectiveness in simulating hazardous conditions. However, the combined use of AHP and QFD to systematically link user requirements with technical design remains underexplored. This integrated approach, supported by recent evidence,

offers a novel methodology to enhance VR training efficacy across industries.

The proposed AHP–QFD framework is designed to remain robust amid rapidly evolving VR hardware and software ecosystems. Its adaptability stems from a modular structure, allowing updates to technical measures such as hardware (e.g., head-mounted displays with haptic feedback) and software (e.g., scalable interfaces) as VR technology advances. For instance, Phase 3 in technical measure prioritization and Phase 4 in QFD mapping via the House of Quality facilitate integration of innovations by revising criteria weights and technical mappings. Iterative Delphi rounds ensure continuous expert feedback, aligning the framework with emerging standards and user needs. This dynamic process accommodates new VR features, such as enhanced ergonomics or adaptive content, while maintaining a user-centered focus. By leveraging AHP's prioritization and QFD's translational flexibility, the framework ensures scalability and longevity, making it a forward-looking tool for optimizing VR safety training across diverse contexts.

3. Methodology

This study employs a four-phase methodology to develop and assess VR solutions for safety training, integrating user requirements and technical measures via an AHP and QFD framework. Phase 1 identifies criteria and sub-criteria through the Delphi method and affinity diagramming and validates this structure guided by the SMART-FAST-CLEAR framework. Phase 2 prioritizes them using AHP, Phase 3 determines technical measures, and Phase 4 aligns these with user requirements through QFD. The research framework, illustrated in Fig. 1, guides the progression from requirement identification to technical implementation.

3.1. Phase 1: Delphi method with affinity diagramming for criteria and sub-criteria identification

This phase identifies and structures technical measures for user requirements, answering research question 1.

3.1.1. Phase 1.1 Delphi method

A panel of 10 experts — 4 academics, 3 industry practitioners, and 3 consultants with expertise in safety training and VR — was selected for expertise in safety training and VR. These experts were safety professionals from manufacturing, pharmaceutical, and construction fields, and they volunteered their time. Experts were selected through purposive sampling to ensure diverse expertise across academia, industry, and consultancy. Academic experts, specializing in VR research or safety training pedagogy, with practical experience. Industry practitioners, managing safety in manufacturing, pharmaceutical, or construction sectors, possessed industry-recognized certifications and ≥ 5 years' experience. Consultancy experts, with ≥ 5 years' experience in VR system design, demonstrated proficiency in immersive training technologies. Experts were recruited via professional networks, safety training workshops, and technology forums, ensuring proven expertise in safety training and immersive learning environments. Three rounds were conducted:

- **Round 1:** A panel of 10 experts listed attributes for VR, AR, and CBT safety training effectiveness, yielding 94 terms (e.g., “visualization” and “safe”).
- **Round 2:** Terms were rated (5-point Likert scale: 1 = Not Important, 5 = Extremely Important) via survey; those below 3.0 were excluded. Four additional terms (e.g., “transferability”) were added based on majority suggestion ($\geq 50\%$ endorsement), resulting in 63 terms.

Table 2
Final user requirements hierarchy.

Criteria	Sub-criteria	Terms
Visual Quality and Aesthetics	Visual Quality	Visualization, Intuitiveness, Rational, Graphics Quality, Clear Vision
	Aesthetics	Beautiful, Gorgeous
Cognitive Experience	Immersive Experience	Presence, Interactive, Real, Natural, Advanced Sense
	Safety and Trustworthiness	Substitution, Ingenious, Safe, Trustworthy
Psychological Aspects	Emotional Engagement and Enjoyment	Entertainment Value, Cheerful, Charismatic, Enjoyable, Pleasure
	Psychological State and Confidence	Casual, Lively, Dreamy, Confidence
Physiological Aspects	Physical Comfort Relaxation	Comfort, Endurable Relaxed
Content Interaction	User Interface Characteristics Content Functional Performance	Dynamic, Neat, Easy to Use, Simple, High User Interface Smooth, Sequential, Novel, Fluency, Performance, Compatibility
Training Efficiency and Effectiveness	Training Effectiveness	Reduced Learning Curve, Reduced Training Period
	Training Efficiency and Provision	Provide Knowledge, Provide Skills, Provide Abilities
	Narratives and Performance Metrics	Realistic Simulations, Engagement, Feedback Mechanisms, Adaptability, Scenario Complexity, Transferability of Skill/Knowledge, Gamification, Reduced Workload, Motivation, Affective Reaction, Return on Investment

Note: 55 terms grouped into 6 criteria and 13 sub-criteria

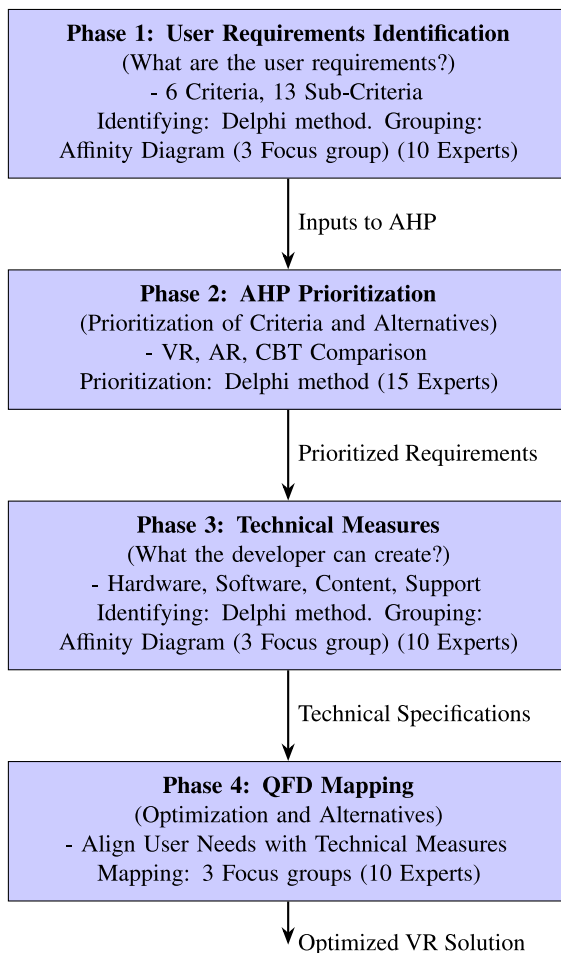


Fig. 1. Research Framework for VR-Based Safety Training Optimization.

- **Round 3:** The 63 terms were re-rated on the 5-point Likert scale, with consensus defined as $\geq 70\%$ of experts (7/10) rating terms ≥ 3.75 . Terms failing this threshold (e.g., 65% at 3.2) were excluded, finalizing 55 terms as shown in Table 2. Disagreements were resolved through moderated discussions, where experts provided written justifications, and facilitators synthesized feedback to achieve consensus via iterative revisions.

3.1.2. Phase 1.2 affinity diagramming

Three focus groups, one hour each, with 10 experts, were conducted. The 55 terms were grouped into 6 criteria (e.g., “Cognitive Experience”) and 13 sub-criteria (e.g., “Immersive Experience”), refined via thematic analysis as shown in columns 1 and 2 in Table 2. The same 10-expert panel, selected per Phase 1.1 criteria, participated to ensure continuity. Experts independently sorted terms into categories, then collaboratively refined groupings in focus groups. Consensus required $\geq 80\%$ of experts (8/10) to agree on category assignments, with terms rated ≥ 3.75 on a 5-point Likert scale for importance. Disagreements were resolved through majority voting.

The criteria include visual quality and aesthetics, focusing on the overall appearance and graphical quality of the virtual environment in VR training, enhancing user engagement, realism, and effectiveness by providing a visually immersive experience. Cognitive experience addresses the mental processes and experiences, including perception, attention, memory, and decision-making during VR safety training, ensuring effective learning, knowledge retention, and application of safety information. Psychological aspects pertain to the psychological well-being of users during VR training, contributing to user satisfaction, reducing anxiety, and creating a conducive learning environment. Physiological comfort emphasizes the physical well-being of users, preventing discomfort and fatigue to support prolonged engagement and effective learning. Content interaction highlights the level of engagement and interactivity users have with VR content, promoting active participation, deepening understanding, and providing an immersive experience for effective safety training. Lastly, training efficiency and effectiveness measure the efficiency and effectiveness of VR training in achieving safety objectives, ensuring users acquire necessary safety skills and knowledge efficiently, leading to enhanced safety practices and risk reduction.

3.1.3. Phase 1.3 validation using SMART-FAST-CLEAR framework

The criteria and sub-criteria were validated using SMART (Specific, Measurable, Achievable, Relevant, Time-bound), FAST (Flexible, Actionable, Simple, Transparent), and CLEAR (Critical thinking, Logical, Evidence-based, Analytical, Reflective) principles. For example, the term “Visualization” was validated as follows: SMART ensured it was specific (defined as visual clarity), measurable (assessed via resolution), achievable (using existing VR technology), relevant (enhancing training visibility), and time-bound (evaluated within a short period). FAST confirmed its flexibility (applicable to VR and AR platforms), actionability (guiding display design), simplicity (clear concept), and transparency (documented in workshops). CLEAR involved critical thinking (debated for relevance, retained for visibility), logical grouping (under Visual Quality), evidence-based support (from VR studies), analytical theming (from expert feedback), and reflective review (for clarity). SMART ensured clear definitions (e.g., “Visual Quality” as clarity), measurable metrics (e.g., immersion scores), achievable goals (e.g., validated protocols), relevance to safety (e.g., “Training Effectiveness”), and time-bound evaluation. FAST provided flexibility across platforms (e.g., “User Interface Characteristics”), actionable design steps (e.g., feedback loops), simplicity with 6 criteria, and transparency in documentation. CLEAR involved critical term evaluation (e.g., retaining “Dreamy”), logical groupings (e.g., “Cognitive Experience”), evidence from 80% expert consensus, analytical thematic analysis, and reflective goal alignment. Validation achieved 80% expert agreement.

3.2. Phase 2: AHP prioritization

This section outlines the AHP methodology using the Delphi method from 15 experts used to prioritize user requirement criteria and sub-criteria and to evaluate safety training alternatives: A1: Virtual Reality (VR), A2: Augmented Reality (AR), and A3: Computer-based/Tablets (CBT) for optimizing training effectiveness, answering research question 2. The expert completes the AHP questionnaire as described in Appendix A.

AHP Procedure: The 6 criteria, 13 sub-criteria, and 3 alternatives were prioritized using AHP as follows:

- **Step 1: Hierarchy Construction:** The AHP hierarchy has four levels: the goal is to improve the effectiveness of safety training; six main criteria, thirteen sub-criteria, and three alternatives (VR, AR, and CBT) are combined for a full evaluation. The diagram in Fig. 2 illustrates this hierarchy.
- **Step 2: Pairwise Comparisons:** Using the Delphi method, 15 experts compared elements on Saaty’s 1–9 scale, generating weights with Consistency Ratio (CR) ≤ 0.10 .
 - **Step 2.1: Main Criteria Level:** Experts compared the 6 criteria relative to the goal (e.g., “Visual Quality and Aesthetics” vs. “Cognitive Experience”).
 - **Step 2.2: Sub-Criteria Level:** For each criterion, sub-criteria were compared (e.g., “Visual Quality” vs. “Aesthetics” under Visual Quality and Aesthetics).
- **Step 3: Weight Calculation:** Normalized priority weights were derived using the eigenvector method. For each comparison matrix, the principal eigenvector and eigenvalue (λ_{\max}) were computed. Consistency was assessed using the Consistency Ratio (CR), ensuring CR ≤ 0.10 . The Consistency Index (CI) was calculated as $CI = (\lambda_{\max} - n)/(n - 1)$, where n is the matrix size, and CR was obtained by dividing CI by the Random Index (RI). A CR ≤ 0.10 indicates acceptable consistency.
- **Step 4: Alternative Ranking:** VR, AR, and CBT were scored against each sub-criterion via expert pairwise comparisons. Global weights were calculated by aggregating local weights across the hierarchy, ranking alternatives by overall priority scores.

Table 3
Technical Measures Hierarchy.

Category	Sub-Measures
Hardware	Comfortability, High Visual Quality, Durability
Software	Functionality, Usability, Reliability and Stability, Performance
Content	How useful is it: Usefulness How nice is it: Content Features, Scalability, User Interface How complex is it: Scenario Plans, Task Types How fit is it: Adaptability, Compatibility, Credibility
Support	Continuous Improvement, Maintenance and Testing, Customization, Flexibility, Cost-Effectiveness, Accessibility (Individuals with Disabilities)

Note: 22 sub-measures grouped into four categories.

3.3. Phase 3: Delphi method with affinity diagramming for technical measures identification

3.3.1. Phase 3.1 Delphi method

The 10-expert panel identified technical measures for VR safety training over three rounds; their expertise spans hardware/software development, safety training design, and UX, answering research question 3.

- **Round 1:** Experts listed technical attributes (e.g., “high visual quality”, “usability”), producing 36 terms.
- **Round 2:** Terms were rated; those below 3.0 were excluded, and 4 were added (e.g., “cost-effective”), resulting in 28 terms.
- **Round 3:** Consensus ($\geq 75\%$ rating ≥ 4) finalized 22 terms under 4 categories. Table 3.

3.3.2. Phase 3.2 affinity diagramming

Three focus groups with one hour each, with 10 experts, grouped the 22 terms into four main technical measures: hardware, software, content, and support, and 22 sub-measures validated by 8/10 experts (95% agreement).

Technical measures for VR safety training encompass four key categories: hardware, software, content, and support. Hardware includes attributes like comfortability, high visual quality, and durability, ensuring the physical components enhance UX and longevity. The software covers functionality, usability, reliability, stability, and performance, focusing on seamless operation and user-friendly interfaces. Content is subdivided into usefulness (e.g., practical value), aesthetics and complexity (e.g., content features, scenario plans), and fit (e.g., adaptability, compatibility), ensuring engaging, scalable, and credible training materials. Support involves continuous improvement, maintenance and testing, customization, flexibility, cost-effectiveness, and accessibility for individuals with disabilities, providing robust ongoing assistance and inclusivity.

3.4. Phase 4: QFD for matching user requirements with technical measures

This phase employs QFD to align user requirements from Phase 2 with technical measures from Phase 3, constructing a House of Quality (HoQ) to guide the virtual development design process. QFD translates subjective user needs into quantifiable technical specifications, ensuring critical performance criteria are met. Ten experts in VR design, human–computer interaction, and systems engineering provided data via 3 focus groups to fill out the QFD questionnaire as shown in Appendix B. For example, the user requirement “Intuitiveness” under Visual Quality was mapped to the technical measure “User Interface” in the Content category, implemented as a streamlined, icon-based navigation menu to enhance visual clarity and ease of interaction in the VR system. Similarly, the requirement “Realistic Simulations” under Training Efficiency was mapped to “Scenario Plans” in the Content category, resulting in a VR training module with dynamic workplace

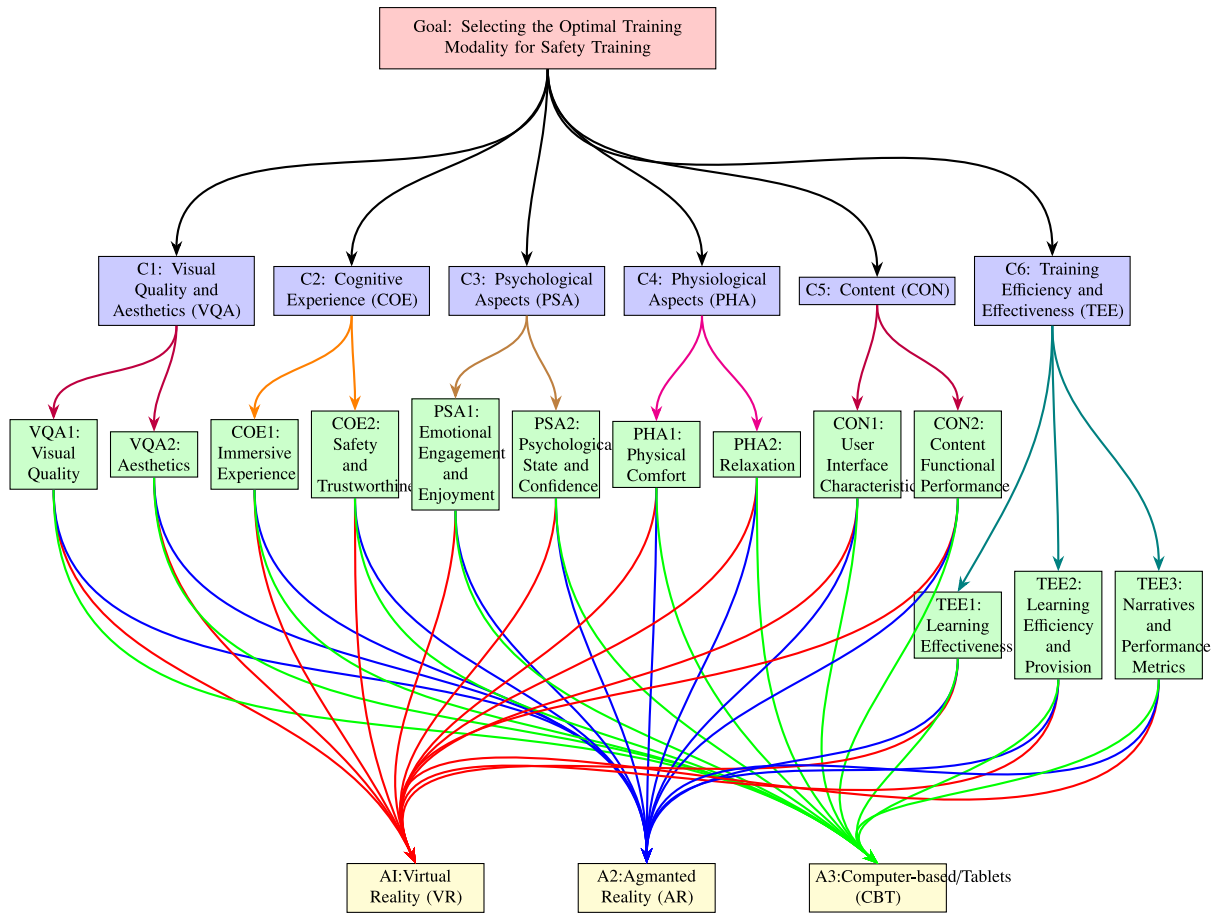


Fig. 2. AHP Hierarchy for Selecting the Optimal Training Modality.

hazard scenarios to simulate real-world safety challenges. These mappings were derived through HoQ analysis, guided by expert focus group consensus. This answers research question 4.

Step 1: Structuring Requirements and Measures: The process begins by organizing user requirements into 13 sub-criteria under six main criteria with global weights derived from prior expert and stakeholder assessments. Concurrently, 22 technical measures are defined and grouped into four domains: hardware, software, content, and support, as shown in Table 4.

Step 2: Mapping Sub-Level Relationships: Experts populate the HoQ matrix by assigning relationship scores (1 = weak, 3 = moderate, 9 = strong) between sub-criteria and technical measures, quantifying their influence on meeting user needs (e.g., “Immersive Experience” → “High Visual Quality”: 9). The impact scores (H = 9, M = 3, L = 1) were validated across three focus groups involving 10 experts, with ratings aggregated using the geometric mean to ensure consistency, as recommended by QFD methodologies [6,48]. Inter-rater agreement was assessed using Fleiss’ kappa ($\kappa = 0.78$), indicating substantial agreement among experts [49]. Disagreements were resolved through moderated discussions within the focus groups, with final scores determined by majority voting (at least 70% agreement) to align with user-centric design principles [36].

Step 3: Computing Technical Priorities: Final Technical Weights are calculated to prioritize measures using:

$$\text{Final Weight}_j = \sum_i (\text{Global Weight}_i \times \text{Relationship Score}_{i,j}), \quad (1)$$

where i denotes sub-criteria and j represents technical measures, aggregating weighted contributions for ranking.

Step 4: Assessing Main-Level Relationships: Relationships between the six main criteria and four technical domains are evaluated by

averaging expert ratings, classified as low (average ≤ 2), moderate ($2 < \text{average} < 6$), or high (average ≥ 6) impact, revealing high-level dependencies.

Step 5: Analyzing Outcomes: The HoQ identifies critical technical measures (e.g., “High Visual Quality”, “Usability”) essential for VR effectiveness, integrating sub-level and main-level insights to optimize design.

Step 6: Analyzing Interdependencies Among Technical Measures: To address the complexity of technical measure interdependencies, the Decision Making Trial and Evaluation Laboratory (DEMATEL) method was applied to the top 10 technical measures with the highest final technical weights [48]. The same 10 experts from the focus groups assessed pairwise influences among these measures using a scale of 0 (no influence), 1 (low influence), and 2 (high influence), based on QFD design. A direct-relation matrix was constructed, normalized, and used to compute the total relation matrix, yielding prominence (D + R) and relation (D - R) scores to identify cause-and-effect factors.

This four-phase approach delivers a rigorous, reproducible framework, integrating user-centered criteria with technical measures for optimizing VR safety training as illustrated in Fig. 3. This structured approach, spanning four phases, systematically maps user needs to technical solutions, ensuring a tailored, efficient design that enhances training efficacy and user experience.

4. Result and discussion

This section presents the comprehensive results of the integrated VR system for safety training, combining data from Phase 1, user requirements, and Phase 3, technical measures, as foundational inputs.

Table 4
House of quality matrix for matching VR user requirements with technical measures.

VR Criteria / Sub-Criteria	Technical measurement																						
	Hardware			Software				Content						Support									
	Comfortability	High Visual Quality	Durability	Functionality	Usability	Reliability and Stability	Performance	Usefulness	Content Features	Scalability	User Interface	Scenario Plans	Task Types	Adaptability	Compatibility	Credibility	Continuous Improvement	Maintenance, Testing, Debugging	Customization	Flexibility	Cost Effective	Individuals with Disabilities	
Visual Quality and Aesthetics																							
Visual Quality																							
Aesthetics																							
Cognitive Experience																							
Immersive Experience																							
Safety and Trustworthiness																							
Psychological Aspects																							
Emotional Engagement and Enjoyment																							
Psychological State and Confidence																							
Physiological Aspects																							
Physical Comfort																							
Relaxation																							
Content Interaction																							
User Interface Characteristics																							
Content Functional Performance																							
Training Efficiency and Effectiveness																							
Learning Effectiveness																							
Learning Efficiency and Provision																							
Narratives and Performance Metrics																							

Note: H = High impact (9), M = Medium impact (3), L = Low impact (1).

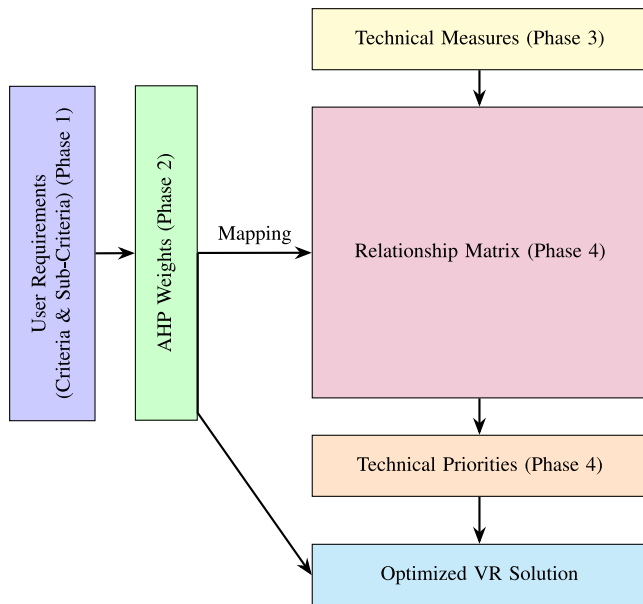


Fig. 3. AHP and QFD Schematic.

The result analysis continues with Phase 2, employing the AHP to prioritize criteria and rank alternatives, followed by Phase 4, utilizing QFD to align these priorities with technical measures, as detailed in the subsequent subsections.

4.1. AHP criteria prioritization

This section presents the outcomes of the AHP applied to prioritize user requirements and evaluate three safety training alternatives (A1,

Table 5
Priority weights of main criteria.

Criterion	Weight
C1: Visual Quality and Aesthetics	0.159
C2: Cognitive Experience	0.198
C3: Psychological Aspects	0.117
C4: Physiological Aspects	0.067
C5: Content	0.114
C6: Training Efficiency and Effectiveness	0.346

A2, A3) across six main criteria and 13 sub-criteria. Based on pairwise comparisons from 15 experts, the AHP methodology comprises hierarchy construction, pairwise comparisons, weight calculation, and alternative ranking to quantify preferences for optimizing training effectiveness, answering research question 5. Additionally, consistency was monitored across all pairwise comparison matrices. AHP analysis details were described in Appendix C.

4.1.1. Main criteria

The AHP analysis prioritized six main criteria, as shown in Table 5 and Fig. 4. Training Efficiency and Effectiveness (C6) emerged as the top criterion with a weight of 0.346, highlighting its pivotal role in safety training. Cognitive Experience (C2) followed at 0.198, emphasizing immersive engagement, while Visual Quality and Aesthetics (C1) scored 0.159. Psychological Aspects (C3) and Content (C5) received weights of 0.117 and 0.114, respectively, with Physiological Aspects (C4) ranking lowest at 0.067. Consistency was validated with $\lambda_{max} = 6.109$, a Consistency Index (CI) of 0.022, and a resulting Consistency Ratio (CR) of 0.018, which is below the 0.10 threshold, ensuring reliable expert judgments.

4.1.2. Sub-criteria

Sub-criteria weights, detailed in Table 6 and Fig. 5, further refine priorities. Learning Effectiveness (C6.1) topped the list with a global weight of 0.150, followed by Learning Efficiency (C6.2) at 0.124,

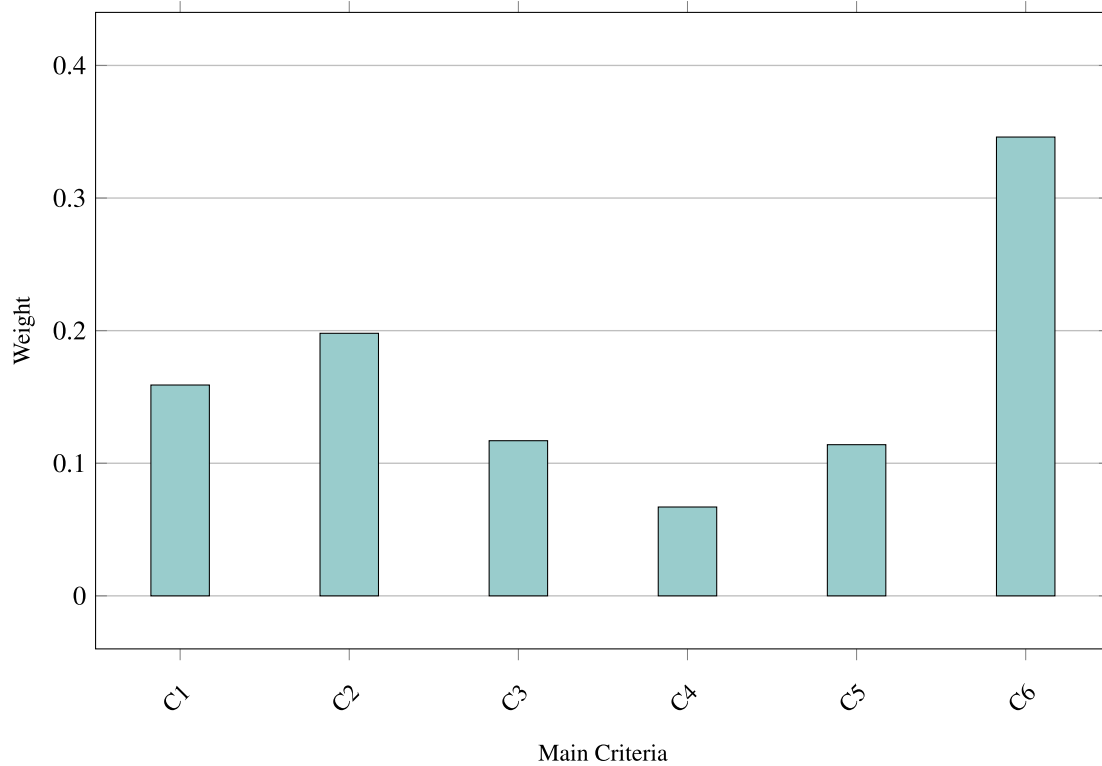


Fig. 4. Priority Weights of Main Criteria.

Table 6
Priority weights of sub-criteria.

Sub-Criterion	Local	Global
C1.1: Visual Quality	0.721	0.115
C1.2: Aesthetics	0.279	0.044
C2.1: Immersive Exp.	0.590	0.117
C2.2: Safety & Trust	0.410	0.081
C3.1: Emotional Eng.	0.556	0.065
C3.2: Psych. State	0.444	0.052
C4.1: Physical Comfort	0.769	0.052
C4.2: Relaxation	0.231	0.015
C5.1: User Interface	0.415	0.047
C5.2: Content Perf.	0.585	0.067
C6.1: Learning Effect.	0.435	0.150
C6.2: Learning Effic.	0.359	0.124
C6.3: Narratives	0.206	0.071

Table 7
Final weights and scores of alternatives.

Sub-Criterion	Wt.	A1	A2	A3
C1.1: Visual Quality	0.115	0.562	0.295	0.143
C1.2: Aesthetics	0.044	0.632	0.249	0.119
C2.1: Immersive Exp.	0.117	0.644	0.236	0.119
C2.2: Safety & Trust	0.081	0.442	0.341	0.217
C3.1: Emotional Eng.	0.065	0.461	0.285	0.254
C3.2: Psych. State	0.052	0.378	0.328	0.294
C4.1: Physical Comfort	0.052	0.312	0.325	0.364
C4.2: Relaxation	0.015	0.311	0.297	0.393
C5.1: User Interface	0.047	0.545	0.303	0.152
C5.2: Content Perf.	0.067	0.593	0.296	0.111
C6.1: Learning Effect.	0.150	0.513	0.272	0.215
C6.2: Learning Effic.	0.124	0.589	0.236	0.175
C6.3: Narratives	0.071	0.537	0.301	0.162
Total	1.000	0.508	0.282	0.210

both under C6, reinforcing training outcomes as paramount. Immersive Experience (C2.1) and Visual Quality (C1.1) scored 0.117 and 0.115, respectively, while Safety and Trustworthiness (C2.2) and Narratives (C6.3) weighed 0.081 and 0.071. Content Performance (C5.2) and Emotional Engagement (C3.1) recorded 0.067 and 0.065, with lower weights for Physical Comfort (C4.1), Psychological State (C3.2), User Interface (C5.1), Aesthetics (C1.2), and Relaxation (C4.2) at 0.052, 0.052, 0.047, 0.044, and 0.015, respectively. CR values below 0.10 confirm consistency.

Main and sub-criteria result discussion. The prominence of C6 (0.346) aligns with prior research emphasizing measurable training outcomes like skill acquisition [46] Ranks high for efficacy; prioritize skill-focused modules. C2's weight (0.198) reflects the value of immersive, trustworthy environments, consistent with findings on technology-enhanced learning [41]. C1's third-place ranking (0.159) suggests visual appeal enhances engagement but is secondary to efficacy. Lower weights for C3 (0.117) and C5 (0.114) indicate balanced but lesser priority, while C4's minimal weight (0.067) may undervalue comfort in extended training [29]. C4's low ranking likely stems from experts

prioritizing learning outcomes (C6) and immersion (C2) over physical comfort and relaxation, as safety training sessions are typically short [27]. However, this suggests a practical need for ergonomic hardware, like lightweight headsets, to support longer sessions without fatigue, enhancing user well-being [29]. These priorities guide the selection of training solutions, favoring educational impact and cognitive engagement.

4.1.3. Alternative

Table 7 and Fig. 6 summarize the local and global weights of alternatives A1, A2, and A3 across all sub-criteria, yielding overall scores of 0.508, 0.282, and 0.210, respectively. A1 outperforms others, excelling in high-weighted sub-criteria like Learning Effectiveness (C6.1, 0.513) and Immersive Experience (C2.1, 0.644), contributing 0.077 and 0.075 to its score.

Discussion of alternatives result. A1's strength in C6.1 (0.513) and C6.2 (0.589) under C6 (0.346) underscores its educational superiority, vital

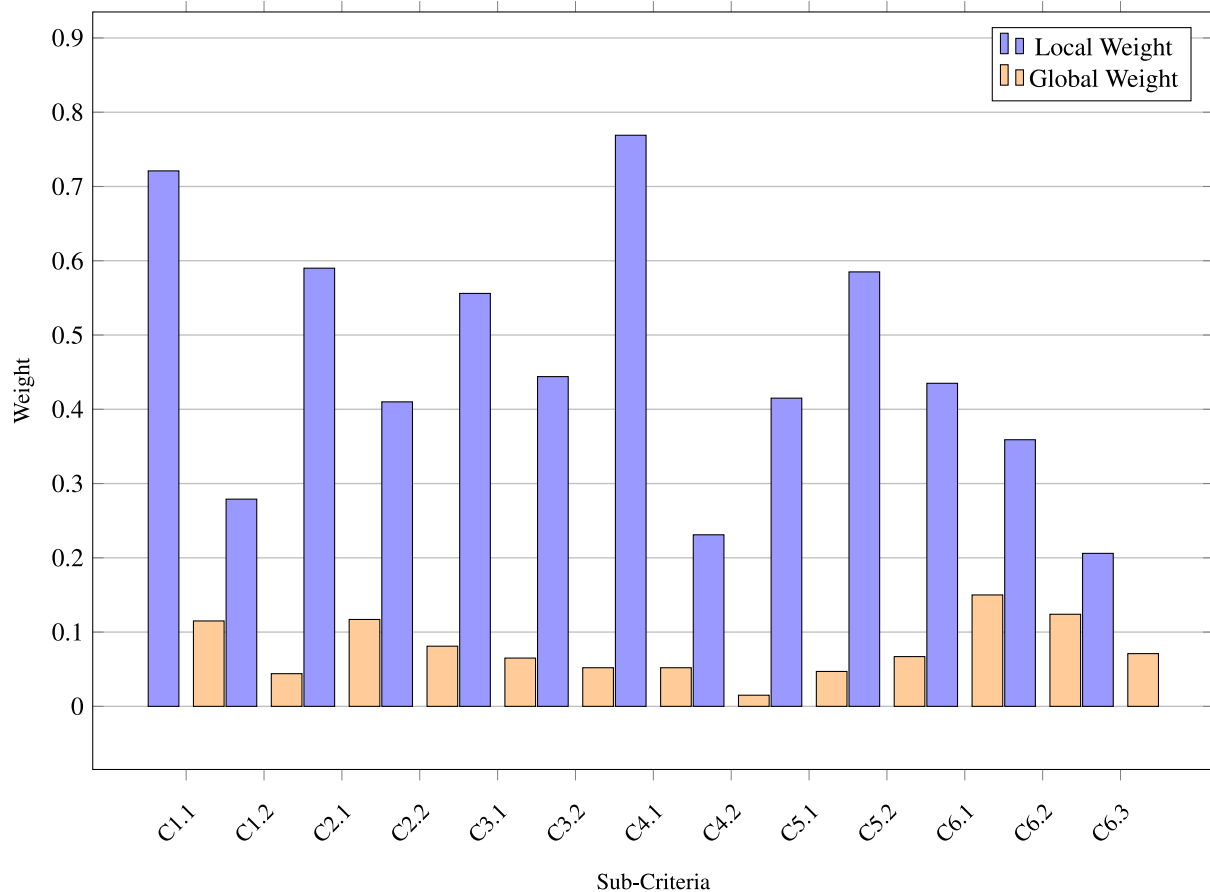


Fig. 5. Priority Weights of Sub-Criteria.

Table 8
AHP Results by Main Criteria.

Criterion	Wt.	A1	A2	A3
C1: Visual Appeal	0.159	0.579	0.285	0.136
C2: User Experience	0.198	0.563	0.277	0.161
C3: Emotional Impact	0.117	0.428	0.303	0.269
C4: Physical Impact	0.067	0.312	0.318	0.371
C5: Content Quality	0.114	0.572	0.298	0.130
C6: Learning Outcomes	0.345	0.547	0.268	0.185

for safety training efficacy. Its high scores in C2.1 (0.644) and C1.1 (0.562) enhance cognitive and visual engagement, aligning with user needs for immersion and clarity. A2’s moderate performance, peaking in C2.2 (0.341), ensures reliability but lacks A1’s breadth. A3 excels in C4.1 (0.364) and C4.2 (0.393), yet its low-weighted criteria limit its impact. A1’s alignment with top priorities (C6, C2) makes it the optimal choice.

4.2. AHP result summary

Table 8 and Fig. 7 aggregate sub-criteria into main criteria scores. A1 leads in C6 (0.547), C1 (0.579), C2 (0.563), and C5 (0.572), with A2 and A3 trailing at 0.282 and 0.210 overall.

User requirements. A1’s dominance reflects user demands for effective learning (C6, 0.547), immersion (C2, 0.563), and visual clarity (C1, 0.579), with lesser emphasis on comfort (C4, 0.312). This prioritizes training solutions enhancing safety skills over secondary factors.

A1’s top ranking (0.508) validates its alignment with core user requirements, offering a balanced, effective safety training solution, as supported by the robust AHP framework.

4.3. QFD results

This section presents the QFD results for matching user requirements with technical measures. The outcomes optimize VR applications for safety training, leveraging the HoQ matrix to prioritize technical measures based on user needs, as detailed in Table 9.

4.3.1. Sub-criteria and sub-technical measure relationships

Expert-derived ratings (H = 9, M = 3, L = 1) reveal significant sub-level influences, ordered by technical measure domains: Regarding hardware, comfortability supports emotional engagement ($0.065 \times 9 = 0.585$) and physical comfort ($0.052 \times 9 = 0.468$), enhancing user well-being, while high visual quality enhances visual quality ($0.115 \times 9 = 1.035$) and immersive experience ($0.117 \times 9 = 1.053$), boosting visual fidelity and presence. In software, performance strongly impacts learning effectiveness ($0.150 \times 9 = 1.350$) and immersive experience ($0.117 \times 9 = 1.053$), reflecting its critical role in training and engagement, and usability drives user interface characteristics ($0.047 \times 9 = 0.423$) and learning efficiency and provision ($0.124 \times 9 = 1.116$), emphasizing intuitive functionality. For content, content features drive content functional performance ($0.067 \times 9 = 0.603$) and narratives and performance metrics ($0.071 \times 9 = 0.639$), highlighting content richness, while scalability influences learning effectiveness ($0.150 \times 9 = 1.350$) and content functional performance ($0.067 \times 9 = 0.603$), supporting adaptable training scenarios. Finally, in support, cost-effectiveness enhances training efficiency and effectiveness ($0.150 \times 9 = 1.350$ and $0.124 \times 9 = 1.116$), ensuring sustainable, high-impact training delivery over time. These granular mappings, unique to this VR safety training context, underscore the interplay between UX and technical design across all domains.

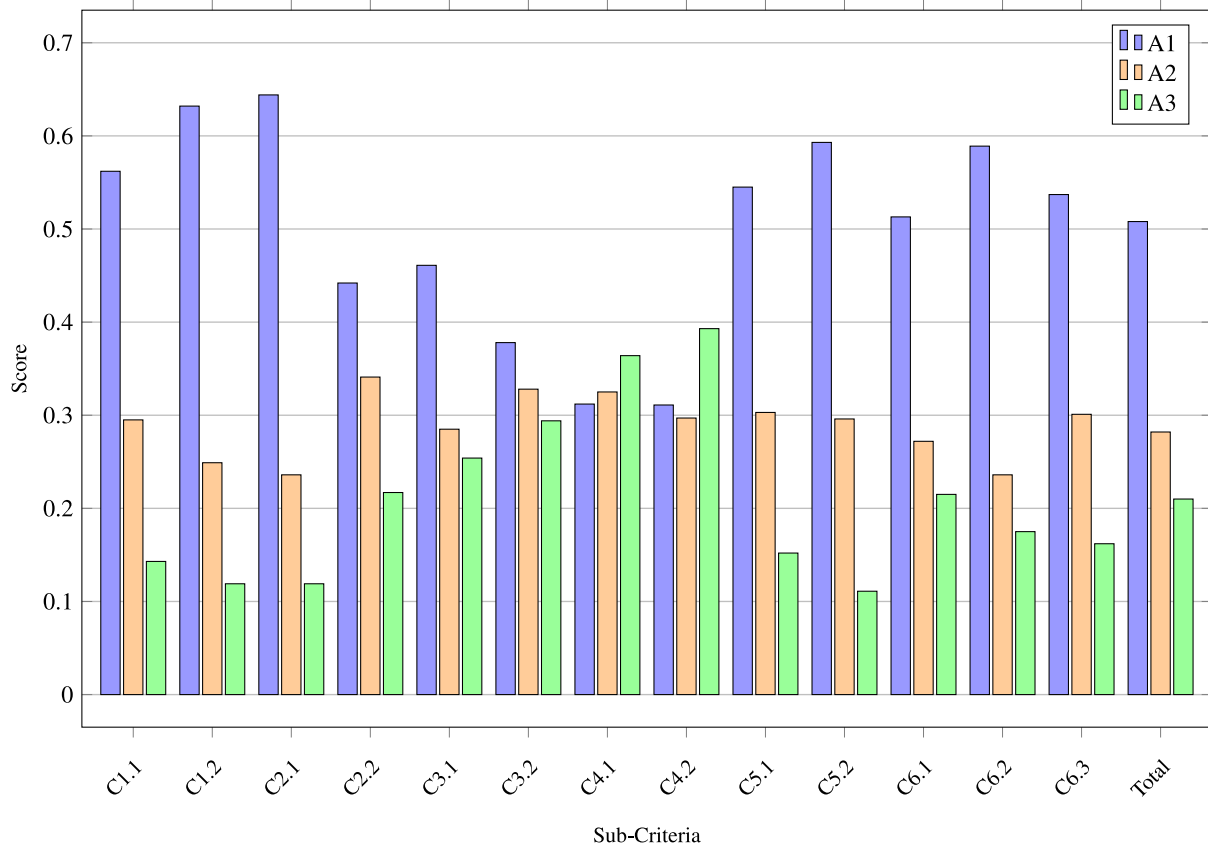


Fig. 6. Final Scores of Alternatives Across Sub-Criteria.

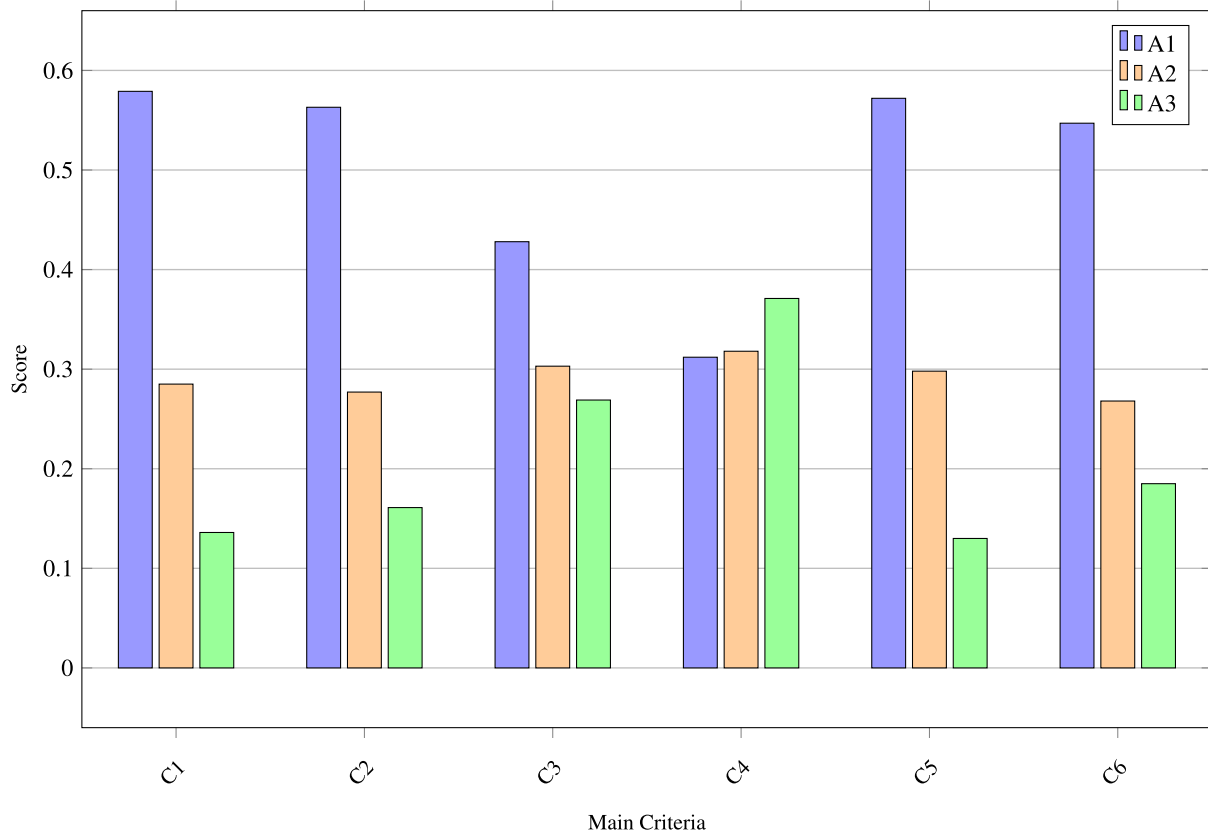


Fig. 7. Final Scores of Alternatives Across Main Criteria.

Table 9
House of quality matrix for matching VR user requirements with technical measures.

VR Criteria / Sub-Criteria	Global Weight	Technical Measurement																					
		Hardware					Software					Content					Support						
		Comfortability	High Visual Quality	Durability	Functionality	Usability	Reliability and Stability	Performance	Usefulness	Content Features	Scalability	User Interface	Scenario Plans	Task Types	Adaptability	Compatibility	Credibility	Continuous Improvement	Maintenance, Testing, Debugging	Customization	Flexibility	Cost Effective	Individuals with Disabilities
Visual Quality and Aesthetics																							
Visual Quality	0.115	M	H	L	M	M	M	H	M	H	H	H	L	M	M	M	L	L	L	L	L	M	L
Aesthetics	0.044	L	H	L	L	M	L	M	L	H	M	M	L	L	L	L	L	L	L	L	L	L	L
Cognitive Experience																							
Immersive Experience	0.117	M	H	L	H	H	H	H	M	H	H	M	M	H	H	M	M	M	M	M	M	M	M
Safety and Trustworthiness	0.081	L	M	M	H	M	H	H	H	M	L	L	L	M	M	M	H	M	M	L	M	M	M
Psychological Aspects																							
Emotional Engagement and Enjoyment	0.065	H	M	L	M	M	M	H	M	H	M	H	H	H	M	L	M	M	L	M	M	M	L
Psychological State and Confidence	0.052	M	L	L	M	M	M	M	H	M	M	M	M	M	M	M	M	M	M	M	M	M	L
Physiological Aspects																							
Physical Comfort	0.052	H	M	M	M	M	L	M	L	L	L	L	L	L	L	H	L	L	M	M	M	L	H
Relaxation	0.015	H	M	L	L	M	L	L	L	L	L	L	L	L	M	M	L	L	L	M	M	L	M
Content Interaction																							
User Interface Characteristics	0.047	L	M	L	H	H	M	H	H	H	M	H	M	M	M	L	M	M	M	M	M	M	M
Content Functional Performance	0.067	L	M	M	H	H	M	H	H	H	M	H	H	H	H	M	M	M	M	M	M	M	M
Training Efficiency and Effectiveness																							
Learning Effectiveness	0.150	M	H	M	H	H	H	H	H	H	H	M	H	H	H	H	H	H	H	H	H	H	H
Learning Efficiency and Provision	0.124	L	M	M	H	H	H	H	H	M	H	M	M	M	H	H	M	H	H	H	H	H	H
Narratives and Performance Metrics	0.071	L	M	L	M	M	M	M	H	H	H	M	H	H	H	M	H	H	M	M	M	H	M
Final Technical Weight		2.92	5.45	1.95	6.40	6.03	5.61	7.57	6.33	6.92	6.57	4.07	4.50	5.60	5.98	5.14	4.27	4.62	4.17	4.16	4.33	4.85	4.40

Note: H = High impact (9), M = Medium impact (3), L = Low impact (1).

4.3.2. Final technical priorities

Final technical weights, shown in the last line of Table 9, rank performance at 7.57 as the top priority, followed by content features at 6.92 and scalability at 6.57, highlighting training efficacy and adaptability. Functionality 6.40, usefulness 6.33, usability 6.03, and adaptability 5.98 reflect operational and adaptive strengths. Hardware measures like High Visual Quality 5.45 and support measures like Cost Effective 4.85 and Individuals with Disabilities 4.40 indicate visual and inclusive priorities, while Durability 1.95 ranks lowest, suggesting minimal influence. This prioritization, derived from safety-specific sub-criteria, offers a novel technical focus for VR applications.

4.3.3. Main criteria and main technical measure relationships

Averaged ratings in Table 10 show Software excelling (H) in Cognitive Experience, Content Interaction, and Training Efficiency and Effectiveness, driven by Performance and Usability. Content dominates (H) in Content Interaction and Training Efficiency and Effectiveness via Content Features and Scalability. Hardware supports most criteria moderately (M), except content interaction (L), with high visual quality and comfortability keys. Support heights (H) in training efficiency and effectiveness, bolstered by cost-effectiveness, with moderate impacts elsewhere (M), except in visual quality & aesthetics, where they did not interact. These domain-specific insights reveal a balanced yet targeted technical emphasis.

4.3.4. DEMATEL analysis of technical measure interdependencies

To enhance the QFD analysis, the DEMATEL method was applied to examine causal interdependencies among the top 10 technical measures: performance, content features, scalability, functionality, usefulness, usability, adaptability, high visual quality, task types, and compatibility [50]. Detailed calculations are provided in Appendix D. The analysis revealed performance as a primary cause factor (high D - R), significantly influencing usability, content features, and scalability

Table 10
Main criteria vs. Technical measures.

Criteria	HW	SW	CT	SP
Visual Quality & Aesthetics	M	M	M	L
Cognitive Experience	M	H	M	M
Psychological Aspects	M	M	M	M
Physiological Aspects	M	L	L	M
Content Interaction	L	H	H	M
Training Efficiency & Effectiveness	M	H	H	H

H = High (≥6), M = Medium (2–6), L = Low (≤2).
HW = Hardware, SW = Software, CT = Content, SP = Support.

due to its critical role in real-time safety simulations. High visual quality and adaptability also emerged as cause factors, driving immersion and flexible training scenarios, respectively. Conversely, task types and compatibility were effect factors (low D - R), influenced by other measures, indicating their dependence on system performance and content design. These findings, summarized in Table 11, highlight critical interdependencies, guiding the prioritization of technical enhancements for VR safety training.

In summary, the results identify performance, content features, and scalability as critical drivers, integrating high-impact sub-criteria like learning effectiveness and immersive experience with broader training goals. Hardware's moderate role, led by High Visual Quality, ensures visual fidelity, while Software's Usability and Content's Task Types enhance interaction and scenario relevance. Supports cost-effective and continuous improvement, sustaining long-term efficacy, a novel finding for VR safety training. This multi-level analysis, unique in its training focus, provides a detailed, actionable roadmap, distinguishing this study from generic VR design frameworks.

Table 11
DEMATEL Prominence and Relation Scores for Top 10 Technical Measures.

Technical measure	Prominence (D + R)	Relation (D - R)
Performance (PER)	11.77	0.99
Content Features (CFE)	10.46	0.26
Scalability (SCA)	9.89	0.03
Functionality (FUN)	10.30	0.08
Usefulness (USE)	9.71	-0.41
Usability (USA)	10.47	0.25
Adaptability (ADA)	10.55	0.33
High Visual Quality (HVQ)	9.82	0.08
Task Types (TAT)	9.79	-0.81
Compatibility (COM)	9.49	-0.79

Note: Positive D - R indicates a cause factor; negative D - R indicates an effect factor.

4.4. QFD result discussion

This section interprets the QFD outcomes for optimizing VR safety training, supported by Tables 9 and 10, highlighting their implications for technical prioritization.

4.4.1. Sub-technical measures: Enhancing safety training

Performance (7.57) drives real-time safety simulations [51] per ISO 9241-11 [52], crucial for effective training, while Content Features (6.92) support scenario-based learning and cognitive benefits [53], enhancing hazard recognition. Additionally, scalability (6.57) [54] and “adaptability” (5.98) [55] enable customizable safety modules, a distinct advantage over static VR systems. High visual quality (5.45) and “usability” (6.03) improve immersion and interaction [41,51], sharpening trainee focus, whereas comfortability (2.92) reduces stress [29] and anxiety [30], supporting extended sessions. These results emphasize safety-specific technical enhancements over generic VR design.

4.4.2. Main-level insights: Strategic optimization

Software’s strong influence (avg. 7.25–8.25) on cognitive experience, content interaction, and training efficiency and effectiveness, driven by performance and usability, ensures seamless safety simulations. Content’s significant role (avg. 6.22–7.22) via content features and scalability facilitates dynamic, adaptable scenarios, surpassing traditional VR approaches. Hardware’s moderate impact (avg. 4.00–4.67), led by high visual quality and comfortability, balances immersion and comfort. In contrast, Support’s peak (avg. 7.50) in Training Efficiency and Effectiveness, powered by Cost Effective, promotes sustainable training solutions. Strategic recommendations include low-latency software, scalable content, ergonomic hardware, and cost-efficient support systems.

4.4.3. DEMATE results discussion

The DEMATEL analysis, detailed in Appendix D, quantifies interdependencies among the top 10 technical measures, enhancing the QFD analysis by identifying causal relationships critical for VR design prioritization. The prominence and relation scores, derived from the total relation matrix T , are presented in Table 11. Prominence ($D_i + R_i$) indicates a measure’s overall importance, while relation ($D_i - R_i$) classifies measures as cause (positive) or effect (negative) factors. Performance (PER) exhibits the highest prominence (11.77) and relation (0.99), confirming its role as the primary driver influencing other measures, such as content features and usability. Adaptability (ADA, prominence = 10.55, relation = 0.33) and usability (USA, prominence = 10.47, relation = 0.25) also rank high, acting as cause factors that shape system performance. Conversely, Task Types (TAT, prominence = 9.79, relation = -0.81) and Compatibility (COM, prominence = 9.49, relation = -0.79) are effect factors, heavily influenced by others, suggesting they are outcomes of system design rather than drivers. These results align with the QFD technical weights (Table 9), reinforcing performance’s critical role (weight = 7.57) while highlighting interdependencies not captured by QFD alone. By prioritizing cause factors like performance and adaptability, the VR design can optimize resource allocation, ensuring robust, user-centric systems [36].

4.5. Decision-support dashboard for practitioners

To operationalize the four-phase AHP-QFD framework for VR safety training, a conceptual decision-support dashboard was developed for practitioners in organizations, such as safety training providers and educational institutions. The dashboard, shown in Fig. 8, integrates outputs from all four phases — Phase 1 (User Requirements Identification), Phase 2 (AHP Prioritization), Phase 3 (Technical Measures Identification), and Phase 4 (QFD Mapping) — to deliver an intuitive, actionable interface. This tool aligns with the decision analytics that emphasizes prescriptive analytics.

The dashboard comprises five interactive panels:

- Phase 1: User Requirements Panel:** Presents the 6 criteria and 13 sub-criteria from Table 2 as a collapsible tree, with tooltips detailing terms. This panel contextualizes user needs validated by SMART-FAST-CLEAR principles, enabling practitioners to explore training requirements.
- Phase 2: AHP Prioritization Panel:** Displays AHP weights via bar charts for main criteria (Table 5), sub-criteria (Table 6), and alternatives (Table 7). A dropdown allows filtering by criterion or alternative, recommending VR as the optimal modality.
- Phase 3: Technical Measures Panel:** Lists 22 technical sub-measures under Hardware, Software, Content, and Support (Table 3) in a categorized table. Filters by category and brief descriptions aid design planning.
- Phase 4: QFD and DEMATEL Panel:** Combines QFD technical weights (Table 9) in a gauge chart and DEMATEL interdependencies (Table 11) in a directed graph.
- Recommendation Panel:** Synthesizes all phases to prescribe actions, such as “Select VR (AHP score: 0.508) and prioritize Performance (QFD: 7.57, DEMATEL cause factor) and Content Features (QFD: 6.92) for safety training; allocate 60% resources to Software enhancements”.

The dashboard’s interactivity enables practitioners to filter by phase, adjust AHP weights or QFD scores to simulate design scenarios, and highlight DEMATEL cause factors for prioritization. This supports optimization modeling by facilitating optimal module and feature selection and prescriptive analytics by prescribing actionable design decisions by leveraging expert-derived analytics to enhance organizational outcomes. By integrating all four phases into a practical interface, the dashboard ensures the framework’s accessibility and utility for actual training applications, setting a novel benchmark for data-driven training design.

4.6. Scalability and future-proofing of the framework

The AHP-QFD framework is designed for scalability and adaptability, ensuring its utility across diverse contexts and emerging VR technologies. This subsection addresses these aspects through structured points, extending the adaptability discussion in the literature review.

Scalability: The framework’s scalability is achieved through its flexible application across various contexts, supported by the decision-supporting interface as illustrated in Fig. 8:

- Multiple industries:** For example, in aviation, customizing criteria for pilot safety training; in mining, prioritizing hazard recognition via AHP weights; in construction, focusing on specific safety protocols; and in healthcare, adapting for patient safety and medical VR training.
- Diverse user groups:** This includes novice trainees: Simplifying interfaces for beginners; university students: integrating educational content; and experienced professionals: enhancing advanced skill training.

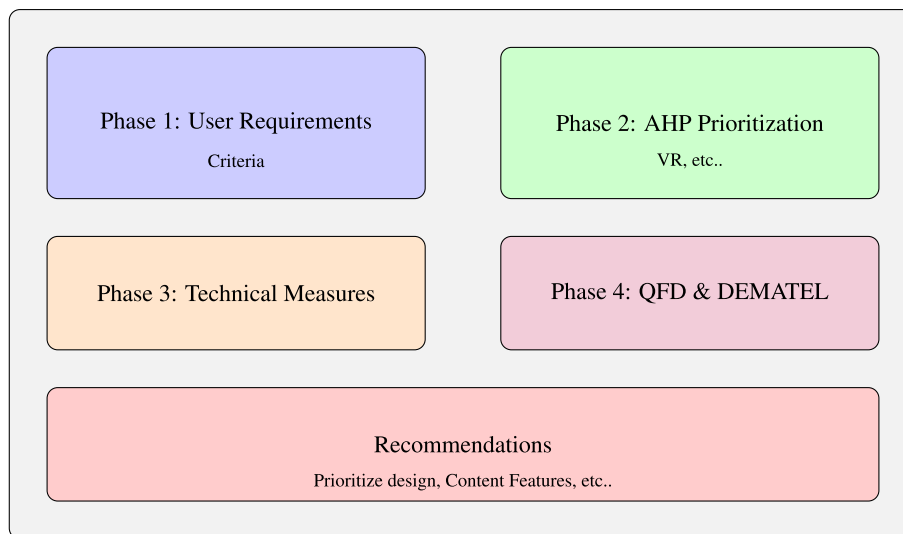


Fig. 8. Mock-up of the Decision-Support Dashboard for training model Practitioners.

3. **Different training program scales:** This ranges from small workshops to Tailoring for limited resources to enterprise-wide programs: Scaling for large organizations via the interface's adjustable AHP and QFD settings.

The framework's six criteria and 13 sub-criteria, prioritized in Phase 2, enable customization for these contexts, ensuring broad applicability.

Adaptability: The framework adapts to new VR applications and further technologies through its modular structure, as the following examples:

1. **Wireless head-mounted displays (HMDs):** Phase 3 updates technical measures for low-latency streaming, and Phase 4 maps user needs to enhanced hardware ergonomics via the HoQ.
2. **Haptic gloves for tactile feedback:** Phase 3 prioritizes sensory feedback measures, and Phase 4 integrates tactile interfaces for immersive training.
3. **Advanced software interfaces:** Phase 3 incorporates interoperability protocols, and Phase 4 ensures scalable content delivery through QFD mappings.

This builds on the literature review's discussion of VR ecosystem evolution, leveraging Phases 3 and 4 for seamless integration.

Future-Proofing Recommendations: To ensure long-term relevance, it proposes updating the expert panel frequently to incorporate insights on new VR technologies. Develop standardized protocols for technical measure evaluation to ensure consistency across iterations and promote VR training data and evaluation results sharing to foster collaborative advancements.

Providing continuous expert feedback, aligning with user needs and industry standards. The interactivity of the interface of Fig. 8 supports future proofing by allowing real-time scenario testing. By leveraging AHP's flexible prioritization and QFD's translational capabilities, the framework remains a scalable, adaptable, and future-ready tool for VR safety training, advancing prescriptive analytics through data-driven optimization.

To further enhance the rigor of the AHP-QFD framework, future research should supplement expert-based prioritization with empirical user studies, such as randomized controlled trials (RCTs). These studies could compare VR, AR, and CBT on measurable safety outcomes, including hazard recognition accuracy, reaction time, and long-term knowledge retention. This addresses the Limited Comparisons gap identified in the Literature Review, which notes the scarcity of direct comparisons between these modalities. RCTs would validate the AHP-derived prioritization by testing its effectiveness in actual settings,

ensuring robust, data-driven insights. The decision-supporting interface (Fig. 8) could facilitate such studies by enabling practitioners to collect and analyze user performance data, aligning with prescriptive analytics principles.

4.7. Implications and novelty

The combined AHP and QFD results offer a robust, safety-centric framework, aligning with IEEE VR/AR standards [56] and ISO 9241-11 [52]. The AHP prioritizes Training Efficiency and Effectiveness (0.346) and Cognitive Experience (0.198), with Alternative A1 (0.508) excelling in learning outcomes and immersion, providing a reproducible basis for VR solution selection. QFD extends this by emphasizing performance (7.57), content features (6.92), and scalability (6.57) for efficacy and adaptability, alongside cost-effectiveness (4.85) for economic viability and novel integrations absent in generic VR studies. This dual approach sets a new benchmark for domain-specific VR safety training, enhancing efficacy through evidence-based technical and user-focused prioritization.

4.8. Contributions

This study offers significant theoretical and practical contributions to the field of VR-based safety training through its integrated AHP-QFD framework.

4.8.1. Theoretical contributions

Theoretically, this research advances decision-making methodologies by combining the AHP and QFD into a novel, safety-centric framework. It extends AHP's multi-criteria prioritization by quantifying user requirements (e.g., training efficiency at 0.346, cognitive experience at 0.198) with high consistency, providing a robust model for evaluating immersive training alternatives. QFD's mapping of these priorities to technical measures (e.g., performance at 7.57, content features at 6.92) enriches VR design theory, introducing a structured approach to align user needs with technical capabilities. This dual methodology bridges gaps in existing literature, offering a replicable, evidence-based tool that enhances understanding of VR's role in safety training efficacy.

4.8.2. Practical contributions

Practically, the framework delivers actionable insights for practitioners in high-risk industries. The prioritization of VR alternatives (0.508) and key technical measures like scalability (6.57) and cost effective (4.85) provides a clear roadmap for developing effective, adaptable, and sustainable VR training systems. Supported by the SMART-FAST-CLEAR criteria and expert-driven phases, this study equips developers and trainers with a systematic guide to improve learning outcomes, immersion, and operational efficiency in safety-critical contexts.

5. Conclusions

This study effectively integrates the AHP and QFD to enhance VR-based safety training, aligning user requirements with technical measures. AHP results prioritize Training Efficiency and Effectiveness (0.346) and Cognitive Experience (0.198), with alternative VR (0.508) excelling in learning effectiveness and immersion. QFD further identifies performance (7.57), content features (6.92), and scalability (6.57) as critical technical drivers, ensuring efficacy, rich scenarios, and adaptability. Supported by the SMART-FAST-CLEAR framework and expert input across four phases, this approach confirms VR's superiority over AR and CBT alternatives, offering a replicable, evidence-based model for safety training in high-risk industries. This novel framework bridges user needs and technical design, setting a new standard for immersive training solutions.

6. Future work

Future research could validate these findings through actual VR training implementations, assessing trainee performance and retention against AHP-QFD predictions. To enhance the practical contributions of the AHP-QFD framework, a simulation study is proposed using the decision-support dashboard introduced in the results section. Practitioners will test the framework's outputs across various training fields by interacting with the dashboard's interface to explore user requirements, prioritize criteria via the analytical hierarchy process, select technical measures, and visualize interdependencies from quality function deployment with integrated decision-making analysis. The dashboard's interactive features allow practitioners to adjust outputs and simulate training designs. Feedback on usability, adaptability to diverse training contexts, and alignment with organizational needs will validate the framework's applicability. This study prescribes actionable training designs, optimizes resource allocation, and provides data-driven insights, aligning with practical advancements.

Future research is needed to extend the research's impact by validating it in real-world training settings using the dashboard, expanding to diverse training domains for generalizability, and exploring advanced VR technologies, such as haptic feedback or AI-driven scenarios, to enhance technical measures. Expanding the expert pool in contexts like healthcare and construction will refine criteria weights, while broadening stakeholder input from practitioners and trainees will address biases from a limited expert pool. The study's focus on safety training, constrained interdependency analysis, and lack of real-world validation may limit its applicability, which these efforts aim to overcome. Its applicability to training organizations needing data-driven solutions supports analytical decision-making and scalable training designs. The dashboard's role in facilitating testing, feedback, and domain adaptation ensures the framework's scalability and organizational alignment.

To maximize the impact of the AHP-QFD framework, future research should pursue additional high-impact directions, building on the technological adaptability and empirical validation already proposed. Cross-disciplinary applications, such as VR safety training in education or emergency response, could broaden the framework's relevance. Integrating adaptive, personalized VR training scenarios would

enhance user engagement and learning outcomes. Additionally, global scalability studies could assess the framework's applicability across diverse cultural and regulatory contexts, supporting international training standards. These directions, facilitated by the decision-support dashboard, would amplify the framework's impact by fostering innovative, data-driven solutions for VR safety training, aligning with prescriptive analytics principles.

CRedit authorship contribution statement

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

Ethics declarations

Not applicable.

Declaration of Generative AI and AI-assisted technologies in the writing process

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.

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.

Acknowledgments

Supported by the University of Debrecen Program for Scientific Publication.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.dajour.2025.100610>.

Data availability

Data will be made available on request.

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