Optimization of EMG-Derived Features for Upper Limb Prosthetic Control

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sustainability

Systematic Review

Rethinking Education on Critical Infrastructure Resilience and Risk Management: Insights from a Systematic Review

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Abstract

The growing complexity and interdependence of critical infrastructures (CIs), increasingly exposed to natural and technological hazards, call for educational approaches to enhance resilience and risk management. This study examines trends, patterns, and challenges in integrating digital and immersive technologies into education and training for stakeholders in critical infrastructure management. A systematic review of peer-reviewed literature was conducted using Scopus as the primary source, covering the last decade and analyzing the corpus across six dimensions: technological approach, pedagogical model, hazard typology, infrastructure domain, stakeholder category, and implementation phase. Following the PRISMA framework, 5635 records were identified and screened through a multistage process combining rule-based filtering and manual review, resulting in 105 papers meeting the inclusion criteria. The analysis reveals a shift from classroom instruction and physical drills toward immersive, simulation-based, and data-informed learning ecosystems that strengthen situational awareness, procedural accuracy, and decision-making under stress. However, the review identifies persistent gaps in evaluation metrics, cross-sector frameworks, and collaborative learning environments that limit adoption. The findings underscore that digital and immersive technologies can reconfigure education and training frameworks, enabling the formation of Resilient Operators endowed with adaptive cognition, continuous learning capacities, and responsiveness to natural hazard-induced technological risks.

Keywords: educational technologies; immersive learning; extended reality; digital twin; risk management; adaptive learning; professional training; risk awareness; workforce development; resilient operator

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1. Introduction

Resilience in critical infrastructures emerges as both a human and technical capability. Energy networks, transport systems, water and wastewater services, healthcare facilities, and communication networks constitute the functional backbone of contemporary societies of nations. Their continuous operation sustains economic stability, public safety, and social well-being. However, the growing interdependence and exposure of these systems to natural, technological, and hybrid hazards make them increasingly vulnerable to disruption. Climate change, cyber threats, supply-chain breakdowns, and geopolitical instability [1] now act as concurrent stressors, revealing that the capacity to preserve service continuity depends as much on human preparedness and organizational flexibility as on technological robustness. Ensuring the operational continuity and adaptability of CI has therefore become a strategic priority for governments, institutions, and operators worldwide [2].

Within this evolving landscape, Asset Management (AM) [3] has become a strategic function linking technical performance, safety, and sustainability. The digital transformation of infrastructure systems—driven by Artificial Intelligence (AI), the Internet of Things (IoT), automation, Big Data analytics, and Digital Twins (DTs)—has redefined how assets are designed, monitored, and maintained. Predictive maintenance, real-time sensing, and automated diagnostics have enhanced operational efficiency and situational awareness, yet they also demand new competencies that transcend traditional engineering expertise [4]. Professionals must now combine technical knowledge with systemic thinking, data literacy, and decision-making under uncertainty.

This shift exposes a growing skills gap within the infrastructure workforce. As organizations integrate digital technologies, they require personnel able to interpret complex information flows, coordinate across disciplines, and adapt to evolving operational scenarios. Consequently, education and continuous training are becoming pivotal for transforming technological innovation into resilient practice [5]. The workforce itself represents a critical asset: its learning capacity determines the ability of organizations to anticipate, absorb, and recover from disruption.

To address these needs, educational paradigms are moving beyond conventional instruction, embracing active and technology-supported approaches that mirror real operational contexts. Over the past two decades, methods such as experiential learning, problem-based learning, and design thinking [6] have gained prominence for fostering creativity, collaboration, and adaptive reasoning, skills essential in dynamic environments. These models converge toward the notion of "learning by doing" and "learning with understanding," in which knowledge is constructed through interaction, simulation, and reflection rather than passive transmission.

Within this pedagogical evolution, Educational Technologies (EdTech) [7] play an increasingly central role. Figure 1 shows that, according to Google search trends [8], interest in "critical infrastructure" has increased far more sharply than in "EdTech", highlighting a gap between concern for infrastructure resilience and attention to its educational tools.

EdTech encompasses the digital tools, platforms, and pedagogical models that enhance learning through technology, ranging from Learning Management Systems (LMS) and mobile learning to Artificial Intelligence-driven tutoring, serious games (SGs), and immersive environments such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). Together, these technologies enable interactive, experiential, and data-informed education. In the context of infrastructure management, they provide realistic, risk-free environments for practicing critical tasks, emergency response, inspection, coordination, and decision-making, thus bridging the gap between theoretical instruction and operational performance. These approaches align with recent policy frameworks promoting digital transformation in education [9].

The adoption of immersive and simulation-based learning has been accelerated by the convergence of technological and societal drivers. The digitalization of infrastructure systems provides the data backbone for realistic virtual training, while the growing complexity of risk scenarios requires safe and repeatable environments for practice. Extended Reality (XR) platforms [10], Digital Twins [11], and AI-based adaptive feedback mechanisms allow learners to engage in multi-scenario simulations that replicate the temporal, spatial, and cognitive demands of real operations. These technologies transform training from a one-off activity into an iterative process of experiential learning and reflection.

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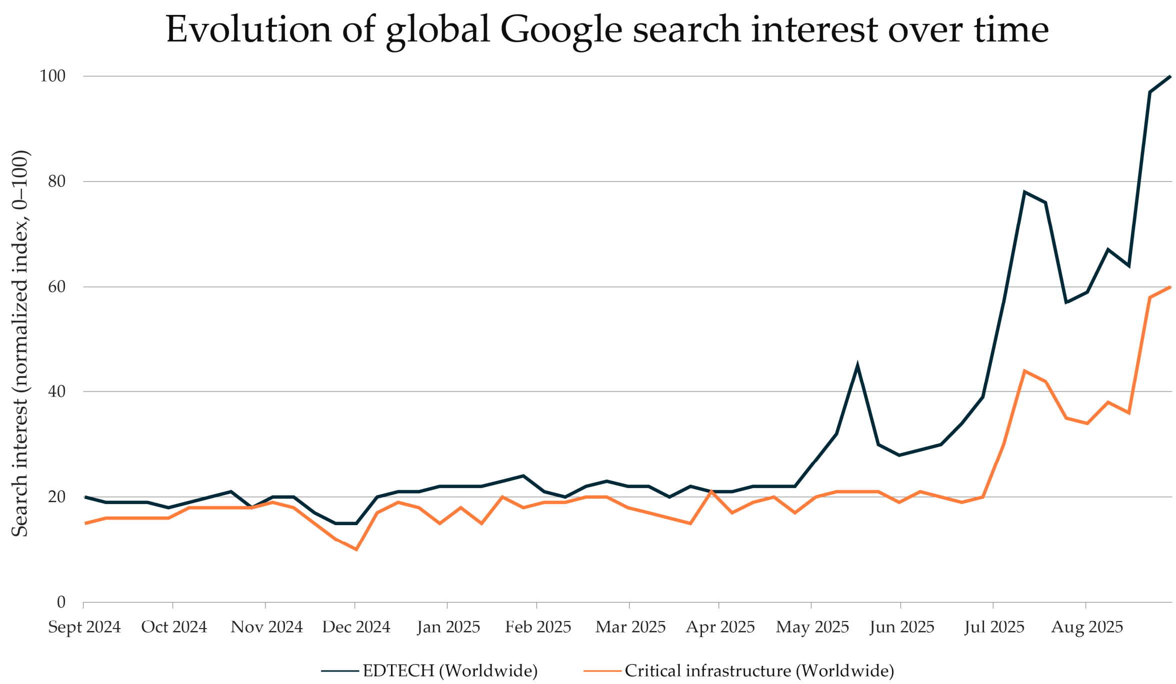

Figure 1. Evolution of global search interest in "EdTech" and "Critical Infrastructure" over time. (Image created by the authors using Google Trend Over Time).

At the same time, the global transition toward Industry 5.0 [12] and Construction 5.0 [13] has introduced a human-centric vision of technology, emphasizing collaboration between humans and intelligent systems. This paradigm reframes resilience as a co-produced quality of socio-technical systems, where human adaptability complements machine precision. Within this perspective emerges the concept of the Resilient Operator [14,15]: a professional who learns continuously, adapts under uncertainty, and interacts effectively with both digital and physical infrastructures. The Resilient Operator embodies the integration of technical expertise, cognitive flexibility, and emotional resilience required to manage complex systems safely and sustainably.

Despite growing recognition of these needs, systematic frameworks for integrating EdTech into resilience education remain limited. Many initiatives still rely on traditional drills or isolated simulations that fail to capture interdependencies among infrastructure networks or between stakeholders. Furthermore, there is a lack of standardized evaluation metrics and cross-sectoral coordination, which hinders comparability and large-scale implementation. As a result, the full potential of immersive and data-driven learning environments to strengthen organizational preparedness has yet to be realized.

In response to this challenge, various international programs have sought to bridge the gap between digital innovation and workforce development. Among these, the Italian Multi-Risk Science for Resilient Communities under a Changing Climate (RETURN) Project [16], funded under the National Recovery and Resilience Plan (NRRP), exemplifies how educational innovation can support governance and capacity building in risk management. Within the project's thematic cluster on Critical Infrastructure, specific attention is devoted to exploring how immersive technologies and digital representations can be used to design sustainable training pathways for infrastructure professionals. Such initiatives underscore the strategic role of education in promoting adaptive governance and multi-actor collaboration across public institutions, academia, and industry.

Significance of the Study

This review examines how research and applied initiatives address education and training for critical infrastructure across four interrelated dimensions:

1. The integration of educational technologies into professional training;
2. The evolution of pedagogical models in technical and engineering education;
3. The role of stakeholders and institutions in supporting adaptive learning ecosystems;
4. The development of competencies underpinning resilience and systemic awareness.

Beyond existing reviews on VR/XR, serious games, and disaster education, this study advances the literature in three keyways:

- Critical infrastructure perspective: it adopts an explicit CI and asset-management/workforce lens, focusing on operators, maintainers, and decision-makers, as well as on constraints imposed by operational contexts.
- Analytical framework: it introduces a six-dimensional coding scheme (technology, pedagogy, hazard, infrastructure domain, stakeholder, and implementation phase) that enables cross-domain comparison beyond modality- or interface-based classifications.
- Governance and transfer gaps: it synthesizes gaps related to operational transfer and governance, including limitations in evaluation metrics and validity evidence, scalability and deployment constraints, and challenges in cross-sector coordination and institutional accountability.

By synthesizing studies across technological, disciplinary, and geographical contexts, the review aims to inform the rethinking of education for critical infrastructure and to support future research and policy development. The paper is structured as follows: Section 2 describes the methodological approach; Section 3 presents the analyzed corpus; Section 4 examines educational and technological challenges; and Section 5 discusses emerging trends and future directions.

2. Methodological Approach to Research

This review follows a PRISMA-aligned [17], mixed-method systematic approach to examine how education, training, and capacity building are being applied to CI resilience and risk management. The objective is to identify and synthesize studies that connect scenario-based learning with immersive/interactive technologies, hazard contexts, and CI-relevant operational settings. No meta-analysis was planned because study designs, outcomes, and reporting formats are heterogeneous across sectors and disciplines. Two complementary strands guide the synthesis.

- Quantitative mapping, to capture distributional patterns by technology, sector, hazard, and geography;
- Qualitative synthesis, to interpret educational models, technological frameworks, and pedagogical paradigms.

2.1. Research Approach

Given the multidisciplinary nature of the topic, the review was designed around the following guiding questions:

- Technological integration: How are digital and immersive technologies integrated into CI education and training?
- CI sectors: Which CI domains apply these technologies, and with what objectives, methods, and outcomes?
- Hazard contexts: Which hazard scenarios are addressed, and how do these tools support preparedness and response?

- Stakeholders: Which stakeholder groups are targeted, and how are their learning needs differentiated?
- Pedagogical frameworks: Which learning frameworks underpin technology-enhanced CI resilience training?
- Skills and competencies: Which competencies are prioritized for CI workforce upskilling and reskilling?
- Gaps and directions: What gaps, limitations, and future research needs emerge across CI sectors?

These questions were translated into candidate search-term combinations. Terminology varies across CI sectors, education research, and technology-oriented disciplines, so term development was treated as an iterative validation step rather than a one-off selection. To validate and refine the keywords candidate set, a co-occurrence Social Network Analysis (SNA) was generated in VOSviewer 1.6.20 as shown in Figure 2. The SNA mapping was used to confirm that training/learning concepts, hazard/risk concepts, and technology concepts form connected clusters in the retrieved space, and to identify peripheral terms that tend to pull the search toward off-scope domains.

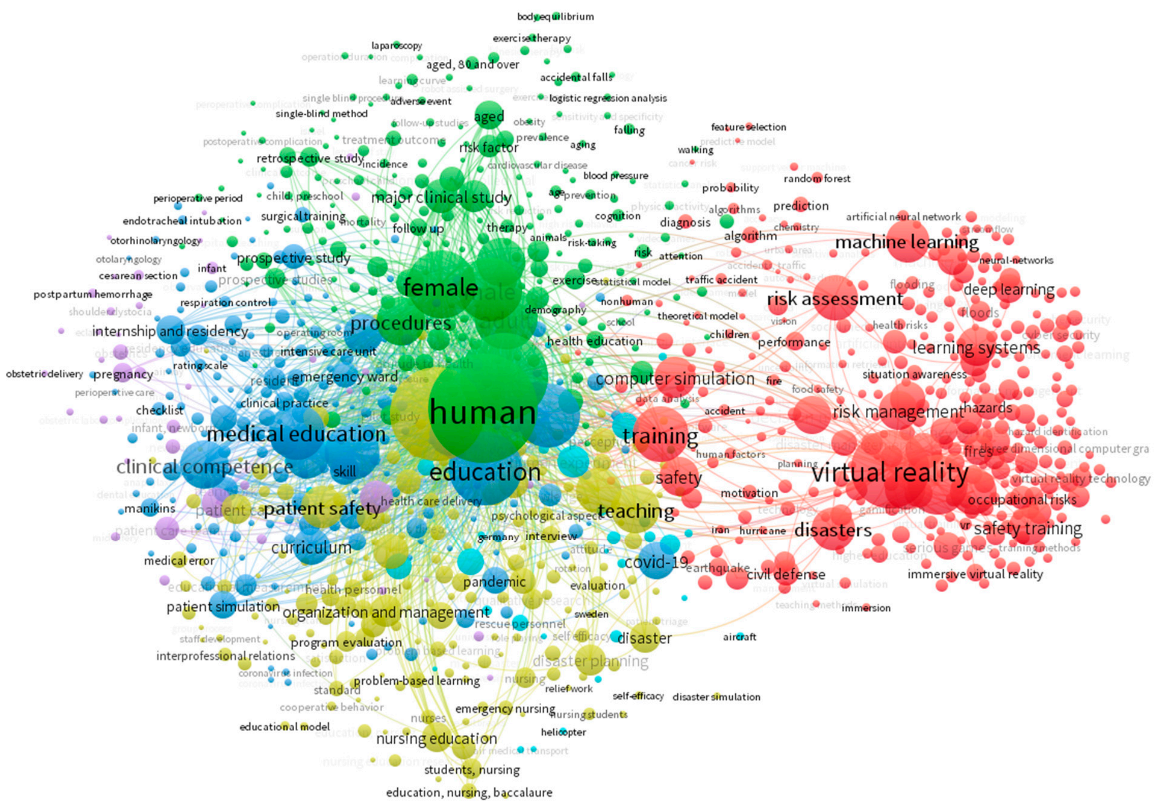

Figure 2. SNA of keyword co-occurrence from the initial search (Image created by the authors using VOSviewer).

Based on this validation step, the final keywords were consolidated into four conceptual domains that define the intended intersection for the review:

1. Scenario-based education and training (education, teaching, drills, exercises, preparedness, training, learning, awareness).
2. Immersive and interactive digital technologies (VR/AR/MR/XR, serious games, metaverse-related terms, simulators, simulation environments, digital twins, interactive/3D platforms).

3. Crisis, emergencies, and natural hazards (risk, safety, emergency, evacuation, flooding, earthquakes, storms, landslides, tsunamis, volcanism).
4. Critical infrastructure and contextual setting (CI sectors/assets and operational settings where training is situated).

These domains provide the conceptual bridge between the research questions and the operational query.

2.2. Data Sources and Query Strategy

Scopus served as the primary database for the systematic search because it supports reproducible, fielded query construction and consistent filter application aligned with the four-domain structure. Web of Science and Google Scholar were used only for verification: cross-checking records and supporting retrieval when a Scopus entry had no accessible article. They were not treated as independent identification streams and were not screened as separate pipelines.

The search query was designed to operationalize the four-domain model while limiting false positives. Given the breadth of the interdisciplinary fields examined, multiple test runs were conducted, leading to the following approach. Domains 1–3 are implemented in the TITLE field to anchor retrieval to studies that explicitly frame the work as training/education under hazard or crisis contexts using technology-mediated approaches. Domain 4 is implemented in the ABSTRACT field because CI relevance is often communicated through sector and asset language in abstracts even when the label "critical infrastructure" is absent. Figure 3 reports the PRISMA-consistent selection pathway from identification to inclusion for the Scopus search stream results.

The flow mentioned in PRISMA Chart (Figure 3) separates rule-based screening (Table 1 criteria applied as database filters) from manual screening approaches and eligibility assessment.

- Identification and rule-based screening: The Scopus retrieval yielded 5635 records from starting search query (Domain 1, 2, 3) 256 duplicates were removed by DOI (5379 remaining). Applying the abstract/context constraint (Domain 4) reduced the set to 2306 records (3073 excluded). Subject-area filtering excluded 22 records. Publication-year filtering excluded 469 records. Document-type and language filters excluded 128 non-article records and 66 non-English records, leaving 1621 records for manual screening. The full query is reported in Appendix A.
- Manual screening eligibility: Manual screening was applied to resolve ambiguities and reduce selection bias, detailed in Section 2.4. Exclusions at full-text stage occurred when one or more of the four core scope research question were not met (training focus, immersive/interactive technology, hazard/crisis context, CI contextual setting). Title–abstract screening excluded 992 records, leaving 629 full texts for eligibility assessment. Full-text screening excluded 524 records. The final corpus comprises 105 studies and is provided as Supplementary Material to support transparency at the corpus level (Table 2).

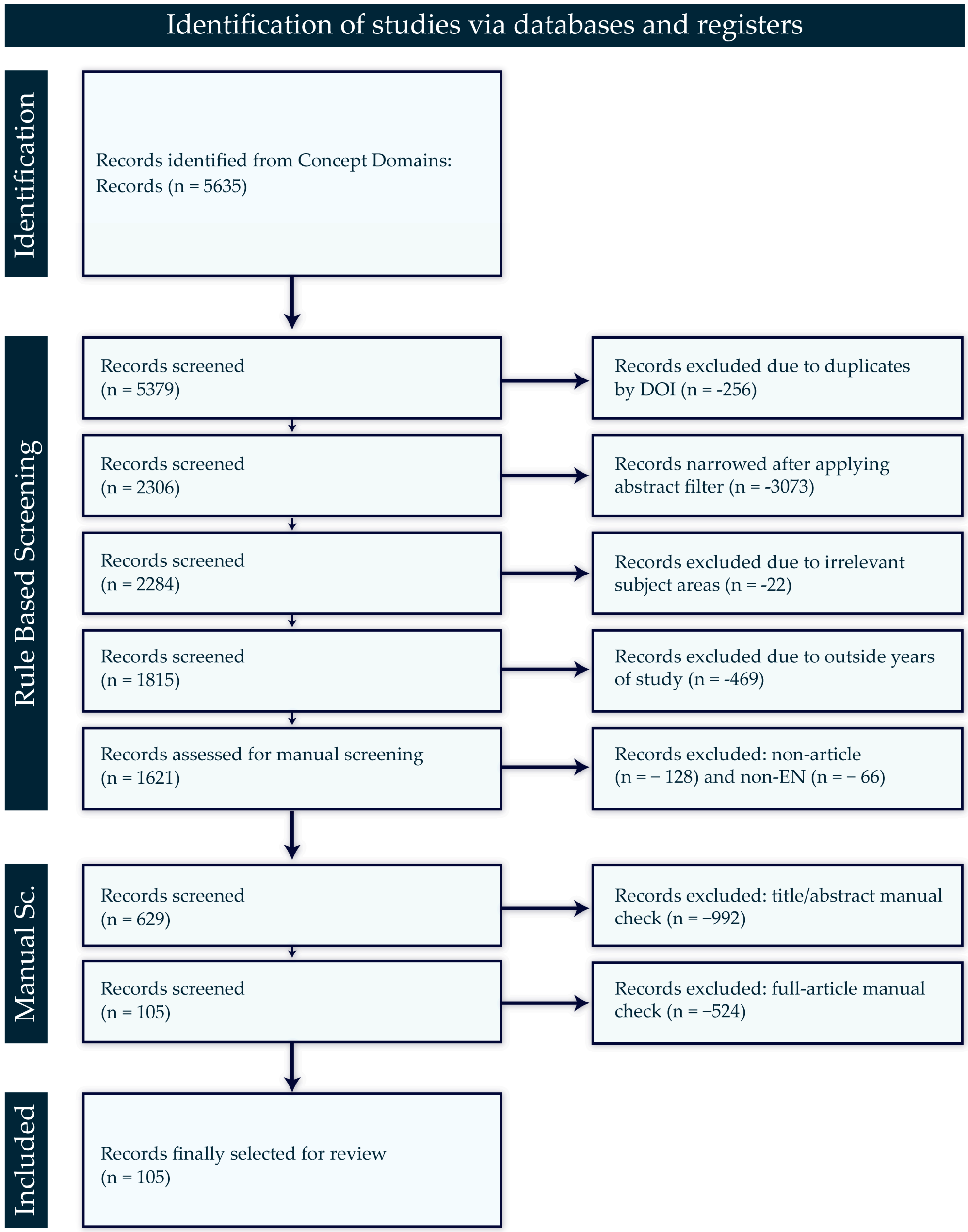

Figure 3. Overview of inclusion and exclusion criteria based on the PRISMA model.

Table 1. Domains and relevant keywords for search queries. * includes in the results all records that contain words beginning with the letters specified before the symbol.

Research Domains			
Domain 1	**Domain 2**	**Domain 3**	**Domain 4**
Scenario-based education, and training	Immersive and interactive digital technologies	Crisis, emergencies and natural hazards	Critical infrastructure and contextual setting
Search field(s)			
TITLE (…)	AND TITLE (…)	AND TITLE (…)	AND ABS (…)
“scenario based” OR training OR preparedness OR exercise OR education OR learning OR awareness OR teaching	immersive OR experien* OR interactive OR “virtual-reality-based” OR VR OR virtual OR cyber OR “web-based” OR “serious game” OR “Serious Games” OR “Serious Game” OR “augmented reality” OR “Mixed reality” OR “extended reality” OR “Virtual Reality” OR “situational awareness” OR metaverse OR hologram OR platform OR simulation OR simulations OR simulator	Crisis OR drought OR risk OR safety OR emergency OR flood* OR earthquake OR tsunami OR landslide OR hydro* OR fire OR evacuation OR hazard OR disaster OR volcan* OR tornado OR hurricane OR Cyclones	earthquake OR worldwide OR flood* OR hydro* OR landslide OR tsunami OR cyclones OR Hurricane OR volcano* OR Tornado OR sea OR school OR cit* OR factory OR industr* OR plant* OR airport OR station OR railway OR seaport OR bridge* OR tunnel OR buil* OR stadium* OR road OR subway OR metro* OR construction OR transport OR grid OR hydro* OR aqueduct OR dam OR canal OR gas OR pipeline OR off-shore OR infrastructure OR corridor OR highway OR urban OR oil OR nuclear OR power OR underpass OR overpass OR viaduct
Inclusion & Exclusion Criteria			
2015–2025 (PUBYEAR > 2014 AND PUBYEAR < 2026)			
(EXCLUDE (SUBJAREA, IMMU OR VETE OR DENT OR PHAR OR NEUR OR NURS))			
(LIMIT-TO (DOCTYPE, ar OR cp))			
(LIMIT-TO (LANGUAGE, English))			

Table 2. Overview of the included studies and their corresponding reference citations.

Authors	Year	Title	Document Type	Source Title	Reference
Aaboud, G.; Smouni, M.; Taibi, T.; Boudi, E.	2025	Virtual Reality Simulations for Effective Fire Safety Training in Passenger Trains	Article	International Journal of Advances in Soft Computing and its Applications	[18]
Akhmalludin, H.; Ayu, M.A.	2019	Mobile Based Augmented Reality to Improve Learning of Volcanology for High School Students	Conference paper	5th International Conference on Computing, Engineering, and Design (ICCED)	[19]
Alvaro, M.D.; Novak, R.; Barbosa, P.R.F.; Capelo, I.C.; Gallego, M.; Rodríguez-Sánchez, M.C.	2025	GUIDE2FR: A smart monitoring platform with a digital twin of a firefighter training tower for emergency scenarios	Article	Internet of Things (The Netherlands)	[20]
Asad, M.M.; Sherwani, F.; Rind, A.A.; Nawab, A.; Datoo, A.; Mahdi, M.	2024	Virtual Reality based Vestibule Training and Teaching Aid for Safety and Health Education in Pakistani Oil and Gas Industries: A Systematic Literature Review	Conference paper	IEEE 14th Symposium on Computer Applications and Industrial Electronics (ISCAIE)	[21]
Becu, N.; Amalric, M.; Anselme, B.; Beck, E.; Bertin, X.; Delay, E.; Long, N.; Manson, C.; Marilleau, N.; Pignon-Mussaud, C.; Rousseaux, F.	2016	Participatory simulation of coastal flooding: Building social learning on prevention measures with decision-makers	Conference paper	8th International Congress on Environmental Modelling and Software (iEMSs 2016)	[22]
Becu, N.; Amalric, M.; Anselme, B.; Beck, E.; Bertin, X.; Delay, E.; Long, N.; Marilleau, N.; Pignon-Mussaud, C.; Rousseaux, F.	2017	Participatory simulation to foster social learning on coastal flooding prevention	Article	Environmental Modelling and Software	[23]
Berg, T.A.; Kintziger, K.W.; Crumly, J.S.; Lawson, S.A.; Myers, C.R.; Stansberry, T.T.	2024	Development of a Proof-of-Concept Multi-Method Computer Simulation to Support Rural Healthcare Disaster Preparedness Planning	Article	International Journal of Disaster Risk Science	[24]
Bodzin, A.; Araujo-Junior, R.; Straw, K.; Huang, S.; Zalatan, B.; Semmens, K.; Anastasio, D.; Hammond, T.	2022	Flood Adventures: A Flood Preparedness Simulation Game	Conference paper	8th International Conference of the Immersive Learning Research Network (iLRN)	[25]
Calandra, D.; Pratticò, F.G.; Lupini, G.; Lamberti, F.	2023	Impact of Avatar Representation in a Virtual Reality-Based Multi-user Tunnel Fire Simulator for Training Purposes	Conference paper	Communications in Computer and Information Science	[26]
Calandra, D.; Pratticò, F.G.; Migliorini, M.; Verda, V.; Lamberti, F.	2021	A multi-role, multi-user, multi-technology virtual reality-based road tunnel fire simulator for training purposes	Conference paper	16th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications (VISIGRAPP 2021)	[27]
Capuano, N.; King, R.	2015	Adaptive Serious Games for Emergency Evacuation Training	Conference paper	International Conference on Intelligent Networking and Collaborative Systems (INCoS)	[28]
Carrozzino, M.A.; Giuliodori, G.; Tanca, C.; Evangelista, C.; Bergamasco, M.; Potel, M.	2023	Virtual Reality Training for Post-Earthquake Rescue Operators	Article	IEEE Computer Graphics and Applications	[29]

Carvalho, P.V.R.; Ranauro, D.O.; Mol, G.M.S.A.; Jatobá, A.; Legey, A.P.L.; de Abreu Mol, A.C.	2022	Using a Serious Game in public schools for training fire evacuation procedures	Article	International Journal of Serious Games	[30]
Chan, P.; van Gerven, T.; Dubois, J.-L.; Bernaerts, K.	2023	Study of motivation and engagement for chemical laboratory safety training with VR serious game	Article	Safety Science	[31]
Chaturvedi, P.; Arora, A.; Dutt, V.	2018	Learning in an interactive simulation tool against landslide risks: The role of strength and availability of experiential feedback	Article	Natural Hazards and Earth System Sciences	[32]
Chaturvedi, P.; Dutt, V.	2018	Interactive landslide simulator: Role of contextual feedback in learning against landslide risks	Conference paper	Lecture Notes in Computer Science	[33]
Chiou, Y.-M.; Barmaki, R.	2019	Learning tornado formation via collaborative mixed reality	Conference paper	IEEE Conference on Virtual Reality and 3D User Interfaces (VR)	[34]
Chiou, Y.M.; Shen, C.-C.	2022	Collaborative Learning with Augmented Reality Tornado Simulator	Conference paper	IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)	[35]
Chittaro, L.; Sioni, R.	2015	Serious games for emergency preparedness: Evaluation of an interactive vs. a non-interactive simulation of a terror attack	Article	Computers in Human Behavior	[36]
Congès, A.; Evain, A.; Benaben, F.; Chabiron, O.; Rebiere, S.	2020	Crisis Management Exercises in Virtual Reality	Conference paper	IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)	[37]
Constantinescu, R.; Robertson, R.; Lindsay, J.M.; Tonini, R.; Sandri, L.; Rouwet, D.; Smith, P.; Stewart, R.	2016	Application of the probabilistic model BET_UNREST during a volcanic unrest simulation exercise in Dominica, Lesser Antilles	Article	Geochemistry, Geophysics, Geosystems	[38]
Correia Pereira, T.; Aloise, D.; Rancourt, M.-È.	2025	HurricaneLog: A serious game for data collection and analysis of hurricane preparedness and response operations	Article	International Journal of Disaster Risk Reduction	[39]
de Andrew Ng, J.; Swee, D.W.J.; Fung, F.M.; Wong, L.C.; Peck, T.-G.	2025	Leveraging virtual reality to enhance laboratory safety and security inspection training	Article	Chemistry Teacher International	[40]
De Fino, M.; Tavolare, R.; Bernardini, G.; Quagliarini, E.; Fatiguso, F.	2023	Boosting urban community resilience to multi-hazard scenarios in open spaces: A virtual reality – serious game training prototype for heat wave protection and earthquake response	Article	Sustainable Cities and Society	[41]
De Lorenzis, F.; Pratticò, F.G.; Lamberti, F.	2022	HCP–VR: Training First Responders through a Virtual Reality Application for Hydrogeological Risk Management	Conference paper	Proceedings of the International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications	[42]
Demiray, B.Z.; Sermet, Y.; Yildirim, E.; Demir, I.	2025	FloodGame: An interactive 3D serious game on flood mitigation	Article	Environmental Modelling and Software	[43]

		for disaster awareness and education			
Dinh Thach, N.; Van Hung Nguyen, H.N.; Tuan, D.A.; Khanh, D.H.; Tam, L.V.	2024	Research and Design of Fire Alarm Systems using Virtual Reality Technology Enhance Safety Training in the Maritime	Article	Journal of Maritime Research	[44]
Egaji, O.A.; Asghar, I.; Dando, L.; Griffiths, M.G.; Dymond, E.	2022	User Evaluation of a Virtual Reality Application for Safety Training in Railway Level Crossing	Conference paper	Lecture Notes in Networks and Systems	[45]
Erten, B.; Oral, B.; Yakut, M.Z.	2022	The role of virtual and augmented reality in occupational health and safety training of employees in PV power systems and evaluation with a sustainability perspective	Article	Journal of Cleaner Production	[46]
Evangelista, A.; Manghisi, V.M.; De Giglio, V.; Mariconte, R.; Giliberti, C.; Uva, A.E.	2025	From knowledge to action: Assessing the effectiveness of immersive virtual reality training on safety behaviors in confined spaces using the Kirkpatrick model	Article	Safety Science	[47]
Feng, Z.; Gonzalez, V.A.; Amor, R.; Spearpoint, M.; Thomas, J.; Sacks, R.; Lovreglio, R.; Cabrera-Guerrero, G.	2020	An immersive virtual reality serious game to enhance earthquake behavioral responses and post-earthquake evacuation preparedness in buildings	Article	Advanced Engineering Informatics	[48]
Feng, Z.; Gonzalez, V.A.; Mutch, C.; Amor, R.; Cabrera-Guerrero, G.	2021	Instructional mechanisms in immersive virtual reality serious games: Earthquake emergency training for children	Article	Journal of Computer Assisted Learning	[49]
Feng, Z.; Gonzalez, V.A.; Mutch, C.; Amor, R.; Cabrera-Guerrero, G.	2023	Exploring spiral narratives with immediate feedback in immersive virtual reality serious games for earthquake emergency training	Article	Multimedia Tools and Applications	[50]
Feng, Z.; Gonzalez, V.A.; Mutch, C.; Amor, R.; Rahouti, A.; Baghouz, A.; Li, N.; Cabrera-Guerrero, G.	2020	Towards a customizable immersive virtual reality serious game for earthquake emergency training	Article	Advanced Engineering Informatics	[51]
Feng, Z.; Liu, C.; Gonzalez, V.A.; Lovreglio, R.; Nilsson, D.	2022	Prototyping an immersive virtual reality training system for urban-scale evacuation using 360-degree panoramas	Conference paper	IOP Conference Series: Earth and Environmental Science	[52]
Feng, Z.; Lovreglio, R.; Yiu, T.W.; Acosta, D.M.; Sun, B.; Li, N.	2024	Immersive virtual reality training for excavation safety and hazard identification	Article	Smart and Sustainable Built Environment	[53]
Fernández, A.; Munoz-La-Rivera, F.M.L.; Mora-Serrano, J.	2021	PREVENTION OF OCCUPATIONAL RISKS IN GEOTECHNICAL DRILLING WORKS THROUGH VIRTUAL REALITY TRAINING	Conference paper	WIT Transactions on the Built Environment	[54]
Fernández, A.; Munoz-La-Rivera, F.M.L.; Mora-Serrano, J.	2023	Virtual Reality Training for Occupational Risk Prevention: Application Case in Geotechnical Drilling Works	Article	International Journal of Computational Methods and Experimental Measurements	[55]

Fernández, S.Z.; Miron, D.L.; Couce-Casanova, A.C.; Diaz, F.F.	2025	Dual Hackathon Based on Immersive Simulation: A Multidisciplinary Approach for Engineering Training and Emergency Management	Article	IEEE Access	[56]
Gao, X.; Zhou, P.; Xiao, Q.; Peng, L.; Zhang, M.	2023	Research on the Effectiveness of Virtual Reality Technology for Locomotive Crew Driving and Emergency Skills Training	Article	Applied Sciences (Switzerland)	[57]
Gilligan, J.M.; Brady, C.; Camp, J.V.; Nay, J.J.; Sengupta, P.	2016	Participatory simulations of urban flooding for learning and decision support	Conference paper	Proceedings - Winter Simulation Conference	[58]
Gu, J.; Wang, J.; Guo, X.; Liu, G.; Qin, S.; Bi, Z.	2023	A Metaverse-Based Teaching Building Evacuation Training System With Deep Reinforcement Learning	Article	IEEE Transactions on Systems, Man, and Cybernetics: Systems	[59]
Hamed-Ahmed, M.H.; Fraga-Lamas, P.; Fernández-Caramés, T.M.	2024	Towards the Industrial Metaverse: A Game-Based VR Application for Fire Drill and Evacuation Training for Ships and Shipbuilding	Conference paper	WEB3D '24: Proceedings of the 29th International ACM Conference on 3D Web Technology	[60]
Jain, N.; Ernest, L.Y.C.; Fatt, C.C.; Teck, T.K.	2023	Extensible VR Emergency Preparedness Platform	Conference paper	AAAI Summer Symposium Series (SuSS 2023)	[61]
Jiang, M.; Zhou, G.; Zhang, Q.	2018	Fire-fighting Training System Based on Virtual Reality	Conference paper	IOP Conference Series: Earth and Environmental Science	[62]
Kaarlela, T.; Pieskä, S.; Pitkäaho, T.	2020	Digital twin and virtual reality for safety training	Conference paper	11th IEEE International Conference on Cognitive Infocommunications (CogInfoCom)	[63]
Keya, R.T.; Heldal, I.; Froland, T.H.; Székely-Keresztesi, O.; Székely, Z.; Kon, E.	2024	Emergency Preparedness Training Using Virtual Reality Games: Allowing Knowledge Transfer in the Digital Age	Conference paper	Proceedings of the European Conference on Knowledge Management, ECKM	[64]
Keya, R.T.; Heldal, I.; Patel, D.; Murano, P.; Wijkmark, C.H.	2025	Implementing Virtual Reality for Fire Evacuation Preparedness at Schools	Article	Computers	[65]
Kockár, S.; Hollá, K.; Dadová, A.; Gana, J.	2023	The use of mixed reality scenarios for training crisis managers and emergency responders in an ADR tanker accident	Conference paper	Transportation Research Procedia	[66]
Konstantakos, S.; Asparagkathos, S.; Mahmoud, M.; Rizou, S.; Quagliarini, E.; Bernardini, G.	2025	An Extended Reality-Based Framework for User Risk Training in Urban Built Environment	Conference paper	IEEE 14th Symposium on Computer Applications and Industrial Electronics (ISCAIE)	[67]
Krastev, G.; Georgiev, T.	2022	Simulator for Emergency Training on an Electrical Substation	Article	TEM Journal	[68]
Kwegyir-Afful, E.; Hassan, T.O.; Kantola, J.I.	2022	Simulation-based assessments of fire emergency preparedness and response in virtual reality	Article	International Journal of Occupational Safety and Ergonomics	[69]
Kwegyir-Afful, E.; Kantola, J.	2021	Simulation-Based Safety Training for Plant Maintenance in Virtual Reality	Conference paper	Advances in Intelligent Systems and Computing	[70]
Lacko, J.	2020	Health safety training for industry in virtual reality	Conference paper	Proceedings of the 30th International Conference on Cybernetics and Informatics	[71]

Lekea, I.K.; Stamatelos, D.G.; Raptis, P.	2021	Learning how to escape the unthinkable with virtual reality: The case of pilots' training on emergency procedures	Conference paper	IOP Conference Series: Materials Science and Engineering	[72]
Levy, J.; Liu, D.	2023	Extended Reality (XR) Environments for Flood Risk Management with 3D GIS and Open Source 3D Graphics Cross-Platform Game Engines: Advances in Immersive Sea Level Rise Planning Technologies for Student Learning and Community Engagement	Conference paper	Lecture Notes in Networks and Systems	[73]
Li, W.; Esmaeili, B.; Yu, L.-F.	2022	Simulating Wind Tower Construction Process for Virtual Construction Safety Training and Active Learning	Conference paper	IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)	[74]
Liang, H.; Ge, C.; Liang, F.; Sun, Y.	2020	VR-based training model for enhancing fire evacuee safety	Article	International Journal of Performability Engineering	[75]
Lovreglio, R.; Gonzalez, V.A.; Feng, Z.; Amor, R.; Spearpoint, M.; Thomas, J.; Trotter, M.; Sacks, R.	2018	Prototyping virtual reality serious games for building earthquake preparedness: The Auckland City Hospital case study	Article	Advanced Engineering Informatics	[76]
Lu, S.; Feng, Z.; Lovreglio, R.; Wang, F.; Yuan, X.	2024	Comparing the productive failure and directive instruction for declarative safety knowledge training using virtual reality	Article	Journal of Computer Assisted Learning	[77]
Makransky, G.; Klingenberg, S.	2022	Virtual reality enhances safety training in the maritime industry: An organizational training experiment with a non-WEIRD sample	Article	Journal of Computer Assisted Learning	[78]
Markopoulos, E.; Luimula, M.; Porramo, P.; Pisirici, T.; Kirjonen, A.	2020	Virtual Reality (VR) Safety Education for Ship Engine Training on Maintenance and Safety (ShipSEVR)	Conference paper	Advances in Intelligent Systems and Computing	[79]
Michel-Acosta, P.; Pepín-Ubrí, J.; Chaljub-Hasbun, J.	2024	Augmented reality about Tropical Cyclones in the Dominican Republic: evaluation of learning and cognitive load	Article	Journal of New Approaches in Educational Research	[80]
Mystakidis, S.; Salmas, J.; Papantzikos, G.; Christopoulos, A.; Stylios, C.; Agorgianitis, S.; Tselentis, D.	2022	Design, Development, and Evaluation of a Virtual Reality Serious Game for School Fire Preparedness Training	Article	Education Sciences	[81]
Nguyen, V.T.; Jung, K.; Dang, T.	2019	Vrescuer: A virtual reality application for disaster response training	Conference paper	IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)	[82]
Nilsen, E.; Safran, E.; Drake, P.; Sebok, B.	2020	Playing a serious game for earthquake preparedness: Effects of resource richness and avatar choice	Conference paper	Conference on Human Factors in Computing Systems - Proceedings	[83]
Novaliendry, D.; Syaputra, W.Z.; Samala, A.D.; Marta, R.	2025	Design of a Virtual Simulation for Tsunami Disaster Education and Mitigation at Teluk Penyu Beach, Cilacap	Article	Journal Europeen des Systemes Automatises	[84]

Ooi, S.; Kikuchi, A.; Goto, T.; Sano, M.	2021	Development and verification of mixed disaster training system in virtual reality based on experience learning	Conference paper	10th International Conference on Educational and Information Technology (ICEIT)	[85]
Paes, D.; Feng, Z.; King, M.; Khorrami Shad, H.; Sasikumar, P.; Pujoni, D.; Lovreglio, R.	2024	Optical see-through augmented reality fire safety training for building occupants	Article	Automation in Construction	[86]
Pallant, A.; Lee, H.-S.; Lord, T.; Lore, C.	2025	Framing Geohazard Learning as Risk Assessment Using a Computer Simulation: A Case of Flooding	Article	Journal of Science Education and Technology	[87]
Pedram, S.; Ogie, R.; Palmisano, S.; Farrelly, M.; Perez, P.	2021	Cost–benefit analysis of virtual reality-based training for emergency rescue workers: a socio-technical systems approach	Article	Virtual Reality	[88]
Pireddu, A.; Innocenti, A.; Lusuardi, L.M.; Santalucia, V.; Simeoni, C.	2025	The Impact and Effectiveness of Virtual Reality Applied to the Safety Training of Workers in Open-Cast Mining	Article	International Journal of Environmental Research and Public Health	[89]
Prasetya, S.P.; Hidayati, A.; Farid, J.A.; Listari, T.; Ardiansyah, R.; Chanthoeurn, D.	2024	Development of Augmented Reality Atlas Volcano Series Media in Social Sciences Learning	Article	TEM Journal	[90]
Querl, P.; Chandra, R.L.; Berkaoui, D.; Castermans, K.; Nacken, H.	2024	Does self-paced learning in mobile flood protection unit construction in virtual reality have advantages over traditional measures?	Article	Frontiers in Virtual Reality	[91]
Righi, A.W.; Wachs, P.; Saurin, T.A.; Manzolli, A.; Tovar, F.T.R.; Nara, F.Y.; Yamão, E.M.; Ribas, L.G.T.; Bório, H.F.; Carneiro, G.L.	2021	Computational Platform for Training Hydroelectric Power Plant Operators in Resilience Skills	Conference paper	Lecture Notes in Networks and Systems	[92]
Ríos, A.; Bonet, C.; Morales, J.L.; Alavedra, A.; París, A.; Guillén, M.	2017	Fireman Rescue: A Serious Game for fire fighting training	Conference paper	CEIG 2017: XXVII Spanish Computer Graphics Conference	[93]
Roofigari-Esfahan, N.; Polys, N.; Johnson, A.; Ogle, T.; Sandbrook, B.	2023	Immersive Cross-platform X3D Training: Elevating Construction Safety Education	Conference paper	Web3D '23: The 28th International ACM Conference on 3D Web Technology	[94]
Roofigari-Esfahan, N.; Porterfield, C.; Ogle, T.; Upthegrove, T.; Jeon, M.; Lee, S.W.	2022	Group-based VR Training to Improve Hazard Recognition, Evaluation, and Control for Highway Construction Workers	Conference paper	IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)	[95]
Rüppel, U.; Schatz, K.	2019	BIM-based virtual training environment for fire-fighters	Conference paper	International Conference on Computing in Civil and Building Engineering (ICCCBE 2010)	[96]
Sa'Don, N.F.; Sa Don, H.S.; Alias, R.A.; Nakanishi, H.	2023	Flood preparedness module for Malaysian Higher Education students via Metaverse Environment	Conference paper	IOP Conference Series: Earth and Environmental Science	[97]
Saklangıç, U.; Mertoglu, B.	2023	The Effect of Fire Training Given with Virtual Reality Applications on Individual Awareness	Article	Journal of Technical Education and Training	[98]
Samson, B.; Marooney, C.; Godefroy, S.; Sheth, S.	2020	Machine learning for fast eor flooding simulation	Conference paper	ECMOR XVII	[99]

Seo, H.J.; Park, G.M.; Son, M.; Hong, A.-J.	2021	Establishment of virtual-reality-based safety education and training system for safety engagement	Article	Education Sciences	[100]
Sermet, Y.; Demir, I.	2019	Flood action VR: A virtual reality framework for disaster awareness and emergency response training	Conference paper	ACM SIGGRAPH 2019 Posters	[101]
Sharma, S.; Devreaux, P.; Scribner, D.; Grynovicki, J.; Grazaitis, P.	2017	Megacity: A collaborative virtual reality environment for emergency response, training, and decision making	Conference paper	IS and T International Symposium on Electronic Imaging Science and Technology	[102]
Shiradkar, S.; Rabelo, L.; Alasim, F.; Nagadi, K.	2021	Virtual world as an interactive safety training platform	Article	Information (Switzerland)	[103]
Sookhanaphibarn, K.; Choensawat, W.; Paliyawan, P.; Thawonmas, R.	2016	Virtual reality system for fire evacuation training in a 3D virtual world	Conference paper	IEEE 5th Global Conference on Consumer Electronics (GCCE)	[104]
Speiser, K.; Teizer, J.	2024	FORMALIZING VIRTUAL CONSTRUCTION SAFETY TRAINING: A SCHEMATIC DATA FRAMEWORK ENABLING REAL-WORLD HAZARD SIMULATIONS USING BIM AND LOCATION TRACKING	Article	Journal of Information Technology in Construction	[105]
Stefan, H.; Mortimer, M.; Horan, B.; McMillan, S.	2024	How effective is virtual reality for electrical safety training? Evaluating trainees' reactions, learning, and training duration	Article	Journal of Safety Research	[106]
Takahashi, K.; Inomo, H.; Shiraki, W.; Isouchi, C.; Takahashi, M.	2017	Experience-based training in earthquake evacuation for school teachers	Article	Journal of Disaster Research	[107]
Tian, D.; Song, W.; Qu, T.; Zhou, B.; Lu, X.; Liu, Y.	2021	Constructions of earthquake scenarios based on virtual simulations	Conference paper	IOP Conference Series: Earth and Environmental Science	[108]
Tibaldi, A.; Bonali, F.L.; Vitello, F.; Delage, E.; Nomikou, P.; Antoniou, V.; Becciani, U.; van Wyk de Vries, B.V.W.; Krokos, M.; Whitworth, M.	2020	Real world–based immersive Virtual Reality for research, teaching and communication in volcanology	Article	Bulletin of Volcanology	[109]
Tsai, M.-H.; Chang, Y.-L.; Shiau, J.-S.; Wang, S.-M.	2020	Exploring the effects of a serious game-based learning package for disaster prevention education: The case of Battle of Flooding Protection	Article	International Journal of Disaster Risk Reduction	[110]
Van Hung Nguyen, H.N.; Anh, T.D.; Duc, T.H.; Tiep, T.D.; Van, T.L.; Anh, D.T.	2025	Research on High Voltage Electrical Safety Training Simulation Systems on Ships using Virtual Reality Technology	Conference paper	4th International Conference on Distributed Computing and Electrical Circuits and Electronics (ICDCECE)	[111]
Wan, J.; Zheng, Y.; Li, Y.; Mei, H.; Lin, L.; Kuang, L.	2020	Oil Depot Safety Inspection and Emergency Training System Based on Virtual Reality Technology	Conference paper	IOP Conference Series: Materials Science and Engineering	[112]
Wu, C.; Liu, J.	2025	Research on Risk Assessment and Simulation Training 3D Model in Fire Rescue Skill Training	Conference paper	International Conference on Electrical Drives, Power	[113]

				Electronics and Engineering (EDPEE)	
Xu, L.; Tang, Z.; Zhuang, D.; Peng, Z.	2025	Digital Twin-Oriented Train Derailment Accident Simulation and Its Applications on Railway Safety Training	Conference paper	Third International Conference on Rail Transportation	[114]
Xu, Z.; Liang, Y.; Campbell, A.G.; Dev, S.	2023	Climate Crisis in Virtual Environments: Exploration and Evaluation of Virtual Reality and Mixed Reality for Climate Change Education in Sea Level Rise Simulation	Conference paper	Lecture Notes in Networks and Systems	[115]
Yang, G.; Su, T.; Wang, X.; Xie, R.; Zhi, J.; Yan, X.	2022	Virtual Reality-based Emergency Robot Rescue Training Simulation System	Conference paper	ICETIS 2022 – 7th International Conference on Electronic Technology and Information Science	[116]
Ye, W.; He, N.; Wang, J.	2022	Research on Augmented Reality Technology in the Training of Pre-flight Safety Inspect Process	Conference paper	IEEE Asia-Pacific Conference on Image Processing, Electronics and Computers (IPEC)	[117]
Yin, W.; Hu, Q.; Liu, W.; Liu, J.; He, P.; Zhu, D.; Kornejady, A.	2024	Harnessing Game Engines and Digital Twins: Advancing Flood Education, Data Visualization, and Interactive Monitoring for Enhanced Hydrological Understanding	Article	Water (Switzerland)	[118]
Yu, Q.; Jiang, Z.; Hu, Z.; Li, A.; Long, G.; Liu, Y.	2020	Design and Accomplishment of Immersive Virtual Reality in Safety Training of Offshore Oil Platform Power System	Conference paper	IET Conference Proceedings	[119]
Yu, X.; Yu, P.; Wang, C.; Wang, D.; Shi, W.; Shou, W.; Wang, J.; Wang, X.	2022	Integrating Virtual Reality and Building Information Modeling for Improving Highway Tunnel Emergency Response Training	Article	Buildings	[120]
Zeng, J.; He, Y.; Wang, X.; Xu, Q.	2024	Research on Visual-Auditory Interactive Feedback Design in Virtual Reality for Electric Power Safety Training	Conference paper	Frontiers in Artificial Intelligence and Applications	[121]
Zhou, B.; Sun, G.; Zhang, X.; Xu, J.; Lai, J.; Du, X.; Hosokawa, M.; Hayashi, H.; Kimura, R.; Sakurada, Y.	2015	Development of web-based tabletop emergency earthquake exercise system	Article	Journal of Disaster Research	[122]

Table 1 translates the four conceptual domains into an operational Boolean structure and specifies the database filters applied at the identification stage (publication year, subject-area exclusions, document type, and language). Studies were selected according to the following criteria:

Inclusion criteria:

- Peer-reviewed journal articles and conference papers addressing education, training, or workforce development in CI-relevant sectors (e.g., energy, transport, water, health, ICT).
- Studies presenting or analyzing digital, immersive, or simulation technologies used in educational or operational training contexts.
- Contributions addressing resilience, risk management, safety, emergency management, or system reliability in explicit connection with learning/training.

- Empirical studies, methodological frameworks, or conceptual analyses that inform CI learning and training ecosystems.
- Training and education interventions aimed at operators, technical staff, decision-makers, emergency responders, or students in secondary, vocational, or higher education, where activities link to infrastructure operation, maintenance, governance, or hazard management.
- English-language publications from 2015–2025 (PUBYEAR > 2014 AND PUBYEAR < 2026, inclusive).

Exclusion criteria:

- Publications with a purely technical or engineering focus without educational or training implications.
- Papers not related to CI contexts or workforce development.
- Studies concerning medical, clinical, or COVID-related training.
- Studies from non-relevant subject areas (e.g., biomedical/clinical or unrelated computational fields), even when keywords overlap.
- Non–peer-reviewed materials (e.g., reports, theses, grey literature), duplicates, and non-English publications.

2.3. Screening and Bias Control

The screening and selection process involved multiple stages of validation to manage ambiguity, subjectivity, and potential bias inherent to interdisciplinary literature. Following the rule-based filtering steps described above, all remaining records underwent manual title–abstract screening and full-text assessment conducted by the three authors. During screening, several limitations of the rule-based procedure were identified and addressed through manual review:

- Implicit and heterogeneous treatment of critical infrastructure: Many studies addressed infrastructure assets, services, or operational contexts relevant to CI (e.g., transport, energy, water, or emergency systems) without explicitly using the term critical infrastructure in titles, abstracts, or keywords. This inconsistency reflects disciplinary differences and the absence of a unified CI vocabulary, and it limited the effectiveness of rule-based filters relying on explicit terminology.
- Terminological ambiguity across domains: Common terms such as training, bridge, or tunnel were frequently used in non-educational or unrelated technical contexts (e.g., machine-learning training or metaphorical usage), leading to false positives or exclusions in automated screening.
- Partial domain coverage in emerging areas: Some studies, particularly those related to emerging environments such as the metaverse, addressed only a subset of the predefined query domains, making strict rule-based inclusion difficult despite their conceptual relevance.

These issues were addressed through manual screening by flagging ambiguous records, verifying relevance through targeted full-text keyword searches and contextual reading, and applying author judgement to assess CI relevance and educational intent beyond metadata and query-domain completeness. Interpretative disagreements and borderline cases were resolved through structured author discussion until consensus was reached. No single reviewer made unilateral inclusion or exclusion decisions. This consensus-based approach was adopted in lieu of formal inter-rater reliability metrics, given the qualitative and interpretative nature of the review and the heterogeneity of study designs, objectives, and reporting styles across the corpus.

To avoid treating all included studies as having equal evidentiary weight, a robustness appraisal was applied during manual screening and data extraction. Only studies that clearly satisfied all four core criteria were retained: (i) scenario-based education and training; (ii) use of immersive or interactive digital technologies; (iii) focus on crises, emergencies, or natural hazards; and (iv) explicit critical infrastructure or contextual setting. This level of conceptual verification, robustness appraisal, and filtering relied exclusively on manual full-text assessment and author judgement and could not be achieved through rule-based screening alone.

Additional constraints arise from the restriction to peer-reviewed, English-language publications, which may underrepresent regional studies or grey literature and introduce language bias. This restriction was defined a priori because the review team lacked the resources and linguistic expertise to reliably translate and appraise full texts in other languages, and it was necessary to ensure consistency in study selection, data extraction, and risk-of-bias assessment. Further limitations stem from the rapid evolution of digital and immersive technologies, where practical implementation may outpace formal academic publication. These limitations should be considered when interpreting both the coverage and the distributional patterns reported in the Results section. To support consistency and transparency, collaborative extraction spreadsheets were used throughout screening. These shared instruments allowed the authors to jointly track inclusion decisions, flag ambiguities, and verify whether each record addressed all four query domains, while also enabling the subdivision of records according to the analytical dimensions later formalized in Section 2.5.

2.4. Data Extraction and Classification

Each included study was extracted using a structured matrix based on six analytical dimensions:

- Technology type (e.g., web-based, XR, digital twin, AI);
- Pedagogical model (e.g., experiential learning, problem-based learning, serious games, adaptive learning);
- Hazard typology (e.g., natural, technological, cyber, systemic);
- Infrastructure domain (e.g., transport, energy, water, health, communication);
- Stakeholder type (e.g., public authorities, industry operators, academia, civil protection);
- Implementation phase (planning, design, management, maintenance, emergency response).

Extraction and coding were conducted collaboratively by the three authors using shared spreadsheets. A codebook tab defined category meanings and decision rules to reduce coding drift. Ambiguous cases were logged in the sheet and resolved through discussion until consensus, then reflected in the final coded entry.

To address differences in evidentiary strength across heterogeneous study designs, the extraction matrix also recorded a set of robustness descriptors used to qualify interpretation rather than to exclude studies. These descriptors captured: study design and setting (prototype, lab study, field deployment), participant type and sample size (where reported), outcome type (learning/performance vs. usability/attitudes), evaluation structure (e.g., pre/post, comparator, triangulation), and evidence of operational or expert validation (where applicable). Results and claims are therefore discussed in line with what individual studies measured and validated.

2.5. Analytical Framework

To interpret the extracted evidence, a three-level analytical framework was applied:

- Descriptive analysis: mapping frequencies and distributions by technology, CI domain, hazard type, region, and stakeholder category.

- Thematic synthesis: identifying recurring patterns in educational approaches, instructional design, assessment practices, and technology deployment.
- Interpretative synthesis: connecting mapped patterns to resilience-oriented education needs and CI operational constraints, grounded in the extracted evidence and qualified by the robustness descriptors.

2.6. Use of Generative AI Tools

A generative AI tool (ChatGPT (GPT-5) by OpenAI) was used as an assistive aid under a verification-first rule, and never as a decision-maker. Inputs were limited to targeted questions and short excerpts needed to resolve specific screening ambiguities, and to author-written draft text for language editing; outputs were treated as provisional pointers or phrasing suggestions and were never accepted without author verification in the source paper.

Screening support (pointer-only)

During title–abstract triage and full-text reading, the tool was used to accelerate targeted retrieval of explicitly stated eligibility-relevant elements (e.g., infrastructure domain, hazard/risk context, stakeholder group, and whether a location term refers to a case-study setting rather than an author affiliation or institutional address). Inputs were limited to bibliographic metadata and/or text from candidate papers used for querying. Outputs were treated as provisional pointers only. Any element used to support screening or interpretation was verified by the authors directly in the source paper through keyword search and contextual reading. When outputs were ambiguous or inconsistent, the record was flagged and resolved through author judgement and consensus.

Writing support (language only)

During manuscript preparation, the tool was used for language editing and to propose alternative phrasings of author-written text derived from the extraction matrix, with the aim of improving clarity and consistency.

Explicit non-use.

The tool was not used to make inclusion or exclusion decisions, to assign study codes or analytical categories, to extract data without verification, to generate counts, or to produce tables or figures. Analytical decisions, synthesis logic, and conclusions were developed by the authors and checked against the extraction matrix and the source papers as needed.

3. Descriptive Overview of the Literature Corpus

This subsection presents a quantitative bibliometric snapshot of the reviewed corpus, covering publication types, temporal trends, geographic distribution, and key terms. It outlines the structure and evolution of research on education and training for critical infrastructure resilience and sets the empirical basis for subsequent analyses.

3.1. Typology of Results

The systematic review yielded 105 peer-reviewed studies from diverse geographical contexts, published in journals and conference proceedings. As detailed in Section 2.5, each study was manually classified by the authors across six analytical dimensions—interaction layer, simulation engine, hazard type, infrastructure domain, stakeholder group, and implementation phase. Figure 4 was then constructed by aggregating these author-assigned classifications and visualizing their interconnections as a Sankey diagram.

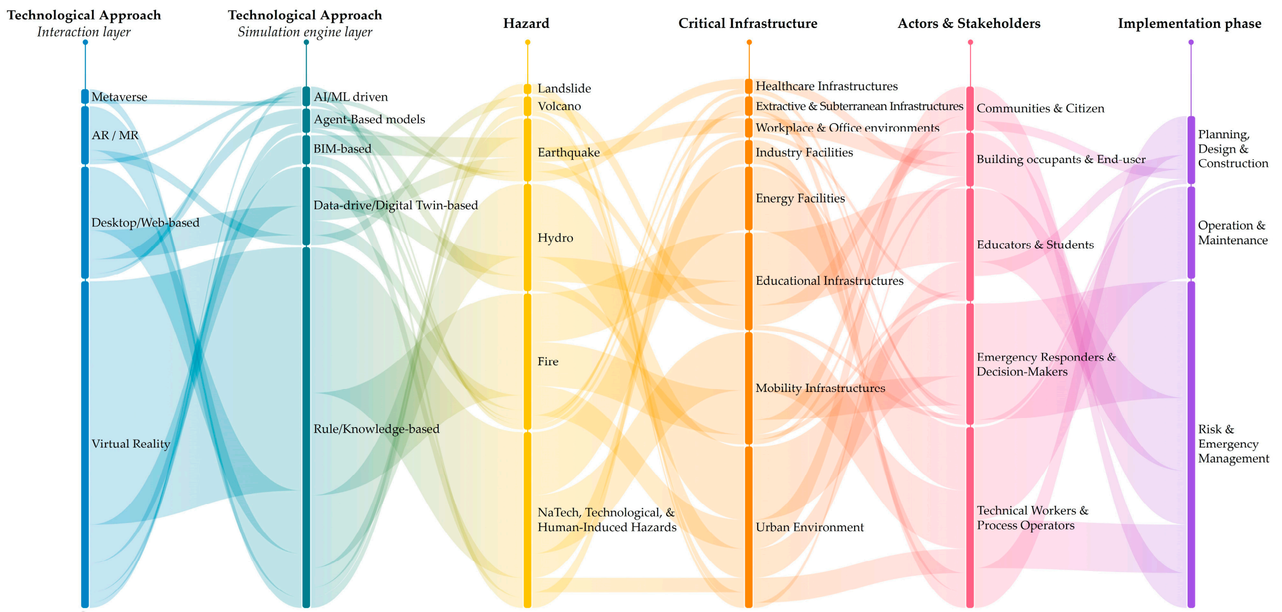

Figure 4. Multidimensional Sankey diagram of the reviewed corpus, showing the heterogeneous and cross-cutting connections between technological approaches, hazard types, critical infrastructures, stakeholder groups, and implementation phases. (Image created by the authors).

3.2. Year Distribution

The temporal distribution of publications between 2015 and 2025 is summarized in Figure 5, showing the annual number of studies and their classification by publication type. The solid line reports total output per year, while the stacked bars distinguish journal articles from conference papers.

Between 2015 and 2019, publication output is low and stable, ranging from three to five contributions per year, with conference papers prevailing over journal articles; in 2019, all contributions are conference papers. From 2020 onward, the volume increases sharply, rising to 13 publications in 2020, decreasing slightly in 2021 (11), peaking in 2022 (16), and remaining stable at 15 contributions per year from 2023 to 2025.

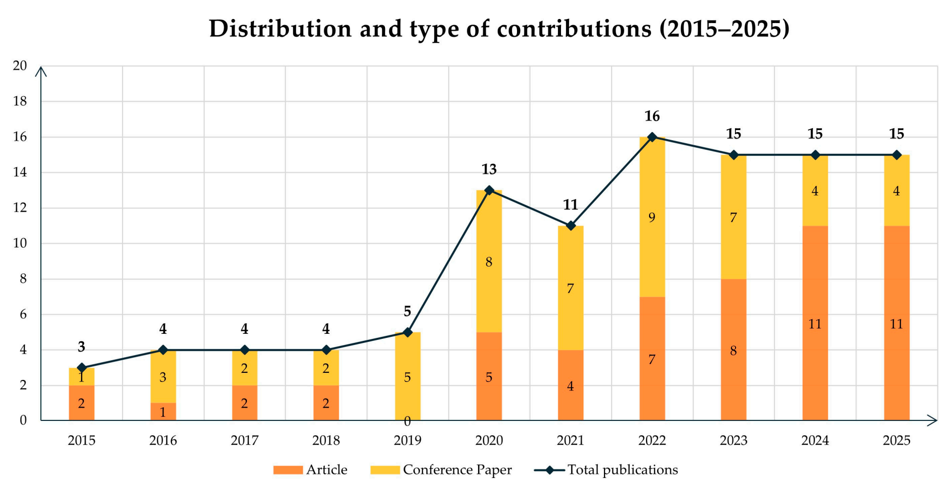

Figure 5. Distribution and type of contributions (2015–2025). The line indicates the total number of publications per year, while the stacked bars distinguish between journal articles and conference papers. (Image created by the authors).

https://doi.org/10.3390/su18063067

3.3. Geographical Perspectives

The geographical distribution of the reviewed studies, illustrated in Figure 6, identifies China, the United States, and Italy as the three main hubs of research on immersive learning for risk and resilience. Taken together, these countries account for nearly half of the corpus, indicating that scholarly activity is still strongly concentrated in a limited number of locations where technological capacity, institutional priorities, and hazard exposure converge.

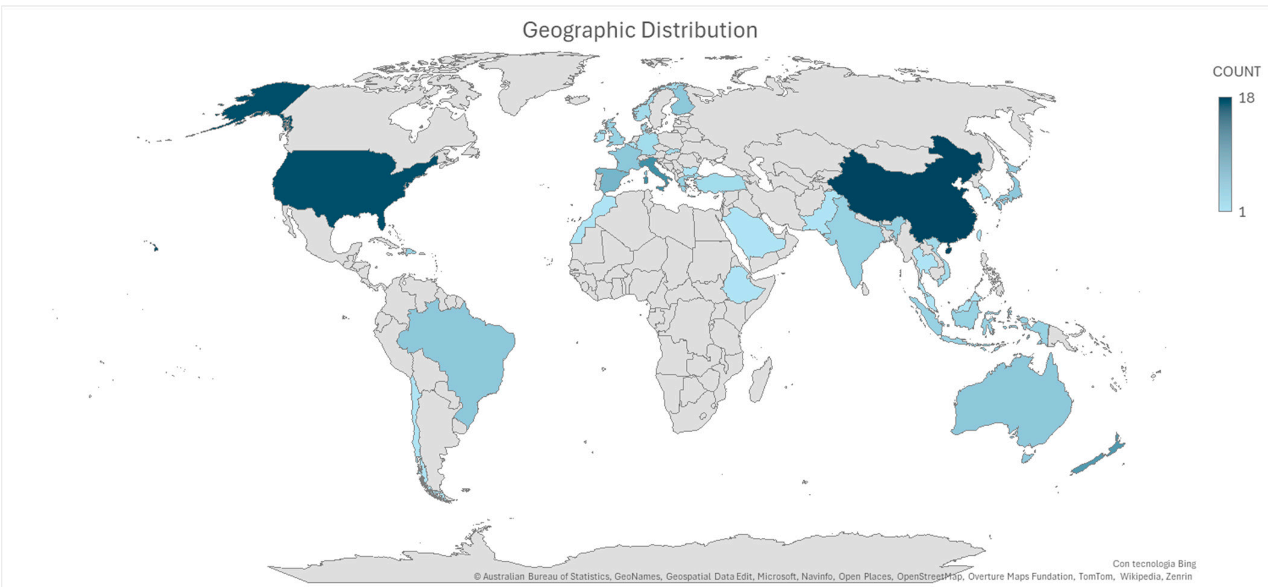

Figure 6. Geographic distribution of reviewed studies. (Image created by the authors using).

China leads this group, showing the highest concentration of studies focused on seismic, fire, and industrial hazards [46,53,57,59,62,75,77,83,108,112–114,116–121]. This prominence reflects both the country's high exposure to natural and technological risks and its strong investment in simulation technologies, serious games, and digital twins for safety and operational training. Chinese research tends to privilege procedural accuracy, system integration, and automation, aligning with the nation's industrial modernization and safety-management agendas.

The United States follows, contributing a robust body of work that emphasizes methodological innovation, data analytics, and human–computer interaction [24,25,35,43,58,59,73,74,82,87,94,95,99,101–103]. Rather than focusing on specific hazard types, U.S. studies explore adaptive learning, behavioral assessment, and AI-based personalization, positioning immersive training as part of broader educational technology ecosystems.

Italy stands out as the leading European contributor, distinguished by its integration of immersive technologies within multi-hazard and institutional frameworks [26–29,36,41,42,47,67,89]. Systems such as *BE-S²ECURe* [41] and *VRescue* [29] exemplify the shift from academic experimentation to operational training platforms embedded in civil protection and firefighting structures. This focus mirrors Italy's geological diversity and exposure to seismic, hydrogeological, and volcanic risks, as well as its coordinated national initiatives, such as the RETURN project, which foster sustained collaboration between academia, agencies, and industry. Beyond these three core contexts, additional contributions arise from Japan, New Zealand, Spain, France, and Finland, which emphasize urban resilience, collaborative response, and interoperability between virtual and physical training infrastructures.

3.4. Keywords

The selected publications were further examined through a Social Network Analysis (SNA) of keyword co-occurrences, with the aim of identifying major thematic clusters and interconnections between different research strands. The map shown in Figure 7 highlights the central position of the keyword Virtual Reality, which acts as a hub between terms related to immersive technologies (immersive virtual reality, augmented reality, serious game, simulation) and keywords that explicitly refer to safety and emergency training, such as training, emergency training, evaluation safety training, fire safety, and evacuation plan.

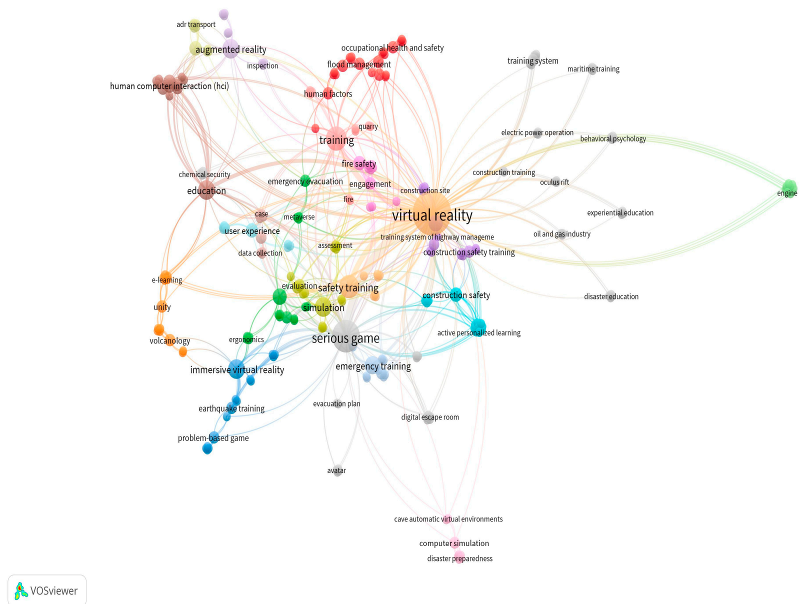

Figure 7. SNA of keyword co-occurrence in the selected papers. (Image created by the authors using VOSviewer).

Around this core, several recurring clusters can be distinguished: a first group oriented towards occupational safety and risk management (occupational safety and health, construction safety, electric power operation, oil and gas industry, earthquake training); a second cluster focused on educational dimensions and human factors (education, engineering education, disaster education, experiential education, e-learning, human–computer interaction (HCI), user experience, behavioral psychology); and a third group centered on game-based and experiential forms of training (serious game, digital escape room, problem-based game).

4. Results

This section presents a critical synthesis of the reviewed studies, organized according to the six analytical dimensions introduced in the methodological framework.

4.1. Technological Approaches

Training for critical infrastructure management increasingly relies on advanced learning technologies that support experiential and feedback-driven learning in safe yet realistic environments. To compare heterogeneous applications, the review adopts two orthogonal technological dimensions:

- Interaction Layer: describes how users engage with the system, ranging from non-immersive desktop and web-based applications to immersive VR, mobile AR/MR, and multi-user metaverse platforms.
- Simulation Engine Layer: defines the computational logic and data backbone of the system, including knowledge-based models, Building Information Modeling, digital twins, artificial intelligence, agent-based systems, and Internet of Things integration.

Together, these layers span a continuum from analytical, model-driven desktop simulations to adaptive, data-rich, and collaborative XR ecosystems. The following sections examine these interaction and simulation configurations in detail, clarifying how different levels of technological complexity relate to educational objectives and learning outcomes.

4.1.1. Interaction Layer

This section classifies the reviewed studies by immersion level and interaction mode. These factors condition user engagement, cognitive and sensory load, and experiential learning. As shown in Figure 8, interaction spans from non-immersive desktop systems to fully immersive and collaborative metaverse environments.

Figure 8. Reality–virtuality continuum. (Image created by the authors).

The concept of the reality-virtuality continuum, originally introduced by Milgram [92], defines this progression, encompassing immersive technologies such as Virtual Reality, Augmented Reality, and Mixed Reality, which merge physical and digital elements to create highly interactive and perceptually rich environments.

Within the field of critical infrastructure training, these systems allow users to perceive, manipulate, and respond to complex operational conditions through visual immersion, sensory feedback, and real-time interactivity. By combining realism, adaptability, and feedback-driven practice, XR technologies constitute the foundation for experiential learning, behavioral adaptation, and procedural accuracy in safety and resilience education. Figure 9 summarizes the distribution of the interaction layers across the analyzed studies through a twofold reading:

- A diachronic reading, showing the year-by-year evolution (2015–2025) of the different technological configurations, and
- An overall reading, reporting the totals for each layer through an integrated summary table.

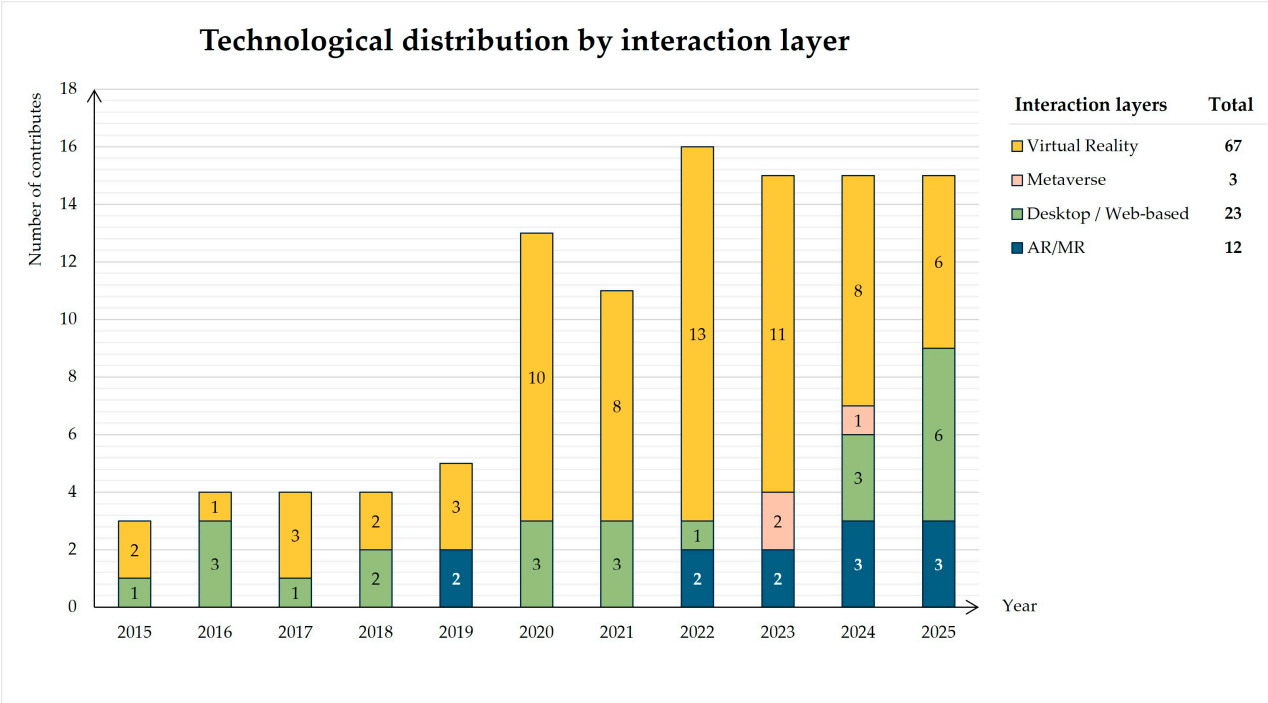

Figure 9. Temporal evolution of interaction-layer technologies in the reviewed studies (2015–2025). (Image created by the authors).

Desktop and web-based

At the lowest interaction level, desktop- and web-based simulations form the non-immersive analytical core of technology-enhanced learning for critical infrastructures. They provide interactive 2D or 3D environments accessed through standard computers or browsers, prioritizing strategic decision-making, coordination, and procedural rehearsal over sensory immersion, with interfaces designed for clarity and accessibility.

Desktop systems typically use dedicated rendering engines to deliver accurate 3D visualization and interactive control. An early example is the Virtual City Earthquake Simulation Platform by Tian et al. [108], which integrates detailed urban models and allows users to navigate scenarios, trigger seismic events, and observe cascading effects such as fires or landslides via mouse-and-keyboard interaction. These systems support analytical engagement observation, parameter adjustment, and impact interpretation making them suitable for planners and engineers involved in territorial risk assessment.

Similarly, Nilsen et al. [83] present a 2D desktop-based serious game designed for earthquake preparedness and behavioral training. The system adopts a simplified interface and rule-based logic to test decision-making and resource management under seismic scenarios, exemplifying low-cost, non-immersive learning environments oriented toward motivation and self-efficacy. In the healthcare sector, for example, Berg et al. [123] propose a multi-method platform for emergency preparedness in rural contexts, in which hybrid models based on system dynamics and discrete event simulation are exposed through desktop interfaces that allow users to configure scenarios, run simulations, and analyze performance indicators without any form of sensory immersion. In the energy sector, Righi et al. [123] developed a hydropower-plant training platform where a control-room interface supports diagnostic and anomaly management tasks. The *GUIDE2FR* platform [20] applies a similar principle for firefighting training: a digital twin of a training tower acts as a supervisory console through which instructors monitor real-time data, 3D maps, and sensor streams to plan and evaluate exercises. Along similar lines, Fernández et al. [56] present a "*dual hackathon*" for flood management that couples field exercises with non-immersive digital support using screens, drone feeds, and shared panels to enhance collective situational awareness.

Expanding the same paradigm into a distributed context, web-based applications allow users to engage collaboratively through standard browsers without installation or specialized hardware. A representative example is Zhou et al. [122], which developed the Web-Based Tabletop Earthquake Exercise System. The platform operates on a territorial and administrative scale, integrating 3D visualizations, GIS layers, and real-time decision panels accessible remotely. Participants, typically provincial and municipal decision-makers, interact by allocating resources, selecting response options, and assessing outcomes on shared maps. The browser-based, multi-user interface mirrors real command chains through dashboards and simulation playback, enabling large-scale, cross-agency training focused on collaborative situational awareness rather than sensory immersion. A related example is the *Virtual Safety World* by Shiradkar et al. [103], a non-immersive multi-user 3D platform that replaces slide-based fire-safety training with a shared, navigable environment using avatars and interactive tasks to rehearse procedures.

In the construction domain, the virtual construction safety framework proposed in [105] further exemplifies this approach, modeling risk logic in an independent, rule-based core that can be exposed through different desktop interfaces depending on the user profile. The control surfaces-sliders, layer selectors, parameter panels and scenario trees—are treated as modular "front ends" that can be reconfigured without modifying the underlying models [32,33,87]. This decoupling allows the same engine to support multiple educational uses: an exploratory mode for students, more constrained configurations for drills, and analytic runs for experts. Visualization pipelines rely on lightweight 2D/3D rendering (WebGL dashboards, Unity desktop builds) in which the camera position is fixed, and the emphasis is placed on the legible encoding of states and trends rather than on cinematic framing [43,118]. The design decision is clear: cognitive effort is directed towards reading controls and outputs, rather than towards spatial navigation. Volcanic-unrest and tsunami-preparedness scenarios are mediated through desktop and classroom displays, where BET_UNREST probability dashboards and split-screen evacuation video–inundation map composites serve as shared interaction surfaces for discussion and decision-making [38]. A subset of these platforms enriches the same technical stack with explicit serious game logic. Rule tables, mission graphs and scoring functions are implemented as discrete layers on top of the simulation, so that the GUI not only exposes parameters but also enforces progression rules, penalties and rewards [25,43,110]. From an engine perspective, this preserves a clean architecture: the model computes state transitions, while a rule manager interprets them into feedback (scores, status colors, end-of-round reports) [39,118]. The hazard domain changes across cases, but the pattern is stable: non-immersive systems are engineered as configurable, low-friction shells around a model, optimized for repeated use, batch comparison of scenarios and easy integration into classroom or workshop routines.

Augmented Reality—Mixed Reality

Augmented and Mixed Reality represent intermediate immersion by overlaying digital information onto the physical environment. This hybrid approach preserves real-world context while supporting interactive guidance, making it effective for maintenance, inspection, and operational training that require spatial awareness and physical interaction.

The reviewed literature reports several experimental applications of AR and MR technologies, often using *Microsoft HoloLens* or handheld mobile devices as interaction platforms [40,66,86,113,114,117]. Typical configurations include mobile AR modules coupled with 3D viewers for fire-rescue maneuvers [113], or pre-flight inspection systems that convert checklists and manuals into multimedia content anchored to aircraft components [117]. In both cases, virtual annotations, 3D models, and procedural sheets are displayed directly within the operator's field of view, enabling gesture or voice-based interaction while executing real tasks. This hybrid mode enhances memory, reduces procedural ambiguity, and standardizes execution without imposing full sensory isolation or overt gamification.

The *FightARs* platform [66] adopts a phygital configuration based on QR codes and physical targets to orchestrate training for hazardous-material incidents, allowing operators wearing a HoloLens 2 headset to visualize holograms, flowcharts, and risk indicators directly on vehicles and equipment. In the railway domain, the digital-twin-oriented derailment simulator [114] overlays 3D reconstructions of damaged rolling stock and infrastructure onto real accident sites, supporting emergency responders in inspection, hazard zoning, and rescue strategy planning while retaining full perception of the real environment.

Other optical see-through systems [86] combine transparent headsets with anchored annotations projected into the user's field of view, thereby preserving direct visual contact with equipment and enabling hands-free operation via gaze-based controls. These interactive mixed reality scenarios make it possible to recognize and manage hazards in controlled conditions, facilitating coordination and situational awareness without requiring full VR immersion, including in safety inspection contexts [40].

From a technical standpoint, the central challenge in AR/MR systems lies in content registration, stabilization, and consistency across users and devices. Marker-based mobile AR relies on fiducials and planar tracking to align meshes and labels with printed figures or surfaces, minimizing computational load [19,80,90]. In such cases, complexity is shifted from interaction design to computer-vision pipelines, allowing developers to standardize tracking while focusing on scenario logic and assessment. Collaborative AR/MR environments add synchronization and shared coordinate systems to this baseline: projection-based and optical see-through setups maintain a common world frame so that all participants perceive identical augmentations [34,35]. MR headsets contribute spatial mapping directly on-device, ensuring that holograms remain anchored to real-world geometry [66,114]. Broader XR frameworks distribute scenario data (3D assets, semantic tags, and state variables) through device-agnostic services consumed by AR tablets, MR headsets, or desktop viewers [67].

Virtual Reality

VR is the most mature and widely applied technology in the corpus [124]. By enabling first-person interaction with 3D environments and multisensory feedback, VR effectively reproduces complex and hazardous CI scenarios—such as fires, tunnel incidents, plant failures, and urban evacuations—where physical training is impractical or unsafe. The following sections examine these systems across three levels of immersion: (i) non-immersive, (ii) semi-immersive, and (iii) fully immersive, including hybrid setups that allow the same content to be accessed via desktop or head-mounted displays.

Non immersive systems

Non-immersive VR applications are typically desktop-based, displaying 3D scenes on monitors or projection screens. With low physical engagement but high accessibility, they suit classroom use and rapid training, using standard input devices to support exploration of simplified virtual environments.

Despite the absence of sensory immersion, such systems have proven effective for training procedural reasoning, hazard identification, and decision-making under time constraints [36]. In this low-immersion configuration, 3D environments rendered on desktop displays are often adapted from full VR engines but operate without head tracking. Virtual cameras follow predefined paths or fixed orbits around objects, while navigation relies on mouse and keyboard inputs. The virtual world thus becomes an artefact to be examined rather than a space to be inhabited. Rendering parameters such as pre-computed lighting, moderate texture sizes, and limited shader complexity, are optimized for stability across institutional computers. Interaction typically follows a GUI-first approach, employing ray-cast pointers, overlaid heads-up displays (HUDs), and contextual menus to prioritize scenario configuration and results interpretation while the engine manages geometric and physical computations [25,32,33,43,54,87,89,96]. This architecture allows game-engine assets and physics to be reused while maintaining the clarity and simplicity of traditional desktop-based simulations.

Within this framework, numerous training applications have been developed. Screen-based serious games remain common for procedural rehearsal and decision-making exercises, whether in educational settings [30] or in professional contexts such as firefighter training, exemplified by the Fireman Rescue simulation [93], emergency robot rescue training systems [116], and railway level-crossing safety applications [45]. Other examples include emergency preparedness scenarios based on large-scale virtual environments, such as the simulation of a terrorist attack in a train station [36], which demonstrated how interactivity alone can enhance risk perception and behavioral readiness even in non-immersive settings.

Multi-user virtual worlds represent a further evolution of this model, enabling participants to control first-person avatars in shared digital spaces used for evacuation and emergency practice [102,104]. Examples include the Second Life-based 3D platform for university evacuation training [104] and the Megacity CVE environment, which provides a non-immersive version for PC-based evacuation exercises [102]. Cross-platform implementations expand these capabilities, maintaining desktop clients as default access points for urban-risk training [21,55,68,72,85,112], or providing alternative interfaces for PCs and large-format displays [67,94].

Semi-immersive systems

Semi-immersive configurations sit between purely screen-based setups and fully immersive VR, using large-scale projections or enveloping displays to increase spatial presence while maintaining physical co-presence among participants.

These environments use a shared field of view instead of individual HMDs, often combining physical props and role differentiation to support coordination and decision-making. Cylindrical or panoramic theaters immerse trainees in common emergency scenarios under instructor control, enhancing shared situational awareness, while desktop VR alternatives offer lower cost, reduced motion sickness, and easier scalability [88]. A similar logic underpins group-based roadwork-safety platforms that use circular projection rooms (Cycloramas) to replicate highway contexts with moving vehicles, temporary delimitations, and ambient noise [95]. Participants collectively analyze hazards and mitigation strategies under instructor supervision, using simple selections or annotations that reinforce the character of a tabletop-style exercise enhanced by situated visualization.

A similar approach is used in CAVE systems, which project stereoscopic images on multiple walls to support collaborative, room-scale immersion. These environments allow free movement and are well suited to coordination and behavioral training; Figure 10 illustrates a five-wall hexagonal CAVE used for school fire preparedness with tracked participants and physical props [81].

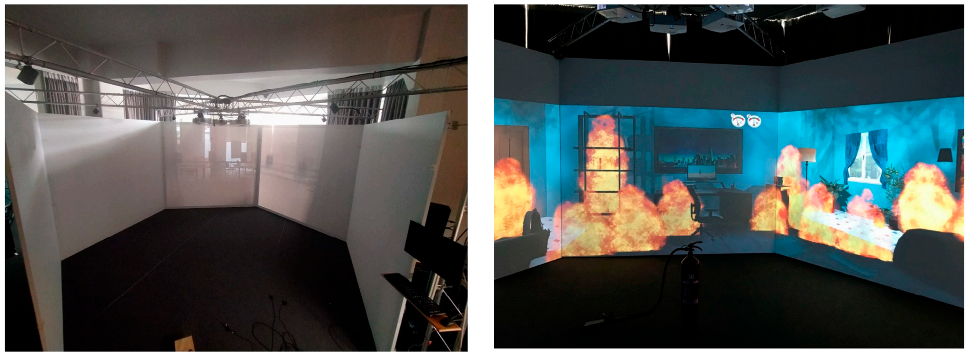

Figure 10. Example of a hexagonal CAVE-based application used in the study by Mystakidis et al. [81]. © 2022 The Author(s), distributed under the Creative Commons Attribution License (CC BY 4.0).

In open-pit mining, Unity-based simulations reproduce quarry topography, elevation changes, and ambient soundscapes while logging individual and group performance [89]. A comparable setup was applied to the seismic evacuation studies at Auckland City Hospital, where large-scale projections replaced HMDs to analyze collective evacuation behavior and support structured debriefing [76].

Lightweight variants also exist. A 360° panorama approach uses spherical images of urban environments as immersive backdrops enriched with interactive hotspots to display evacuation routes or alternative viewpoints [52]. The same panoramas can be viewed on a desktop, a panoramic screen, or through an HMD, maintaining visual consistency across devices while minimizing technical requirements.

Among the most accessible semi-immersive configurations are mobile VR systems that employ smartphone-based headsets such as *Google Cardboard*. These solutions provide an entry-level immersive experience that extends the reach of VR training to schools and community education. In earthquake-evacuation simulations, this approach enables students and teachers to experience virtual drills using low-cost devices, supporting awareness and preparedness without complex hardware requirements [107].

Fully immersive systems

Fully immersive VR most clearly separates users from the physical world by replacing it with a stereoscopic virtual environment viewed through head-mounted displays. Real-time head and hand tracking with 6DoF enables first-person navigation and object interaction, creating a strong sense of presence. Figure 11 summarizes the head-mounted devices used in fully immersive VR studies within the reviewed corpus.

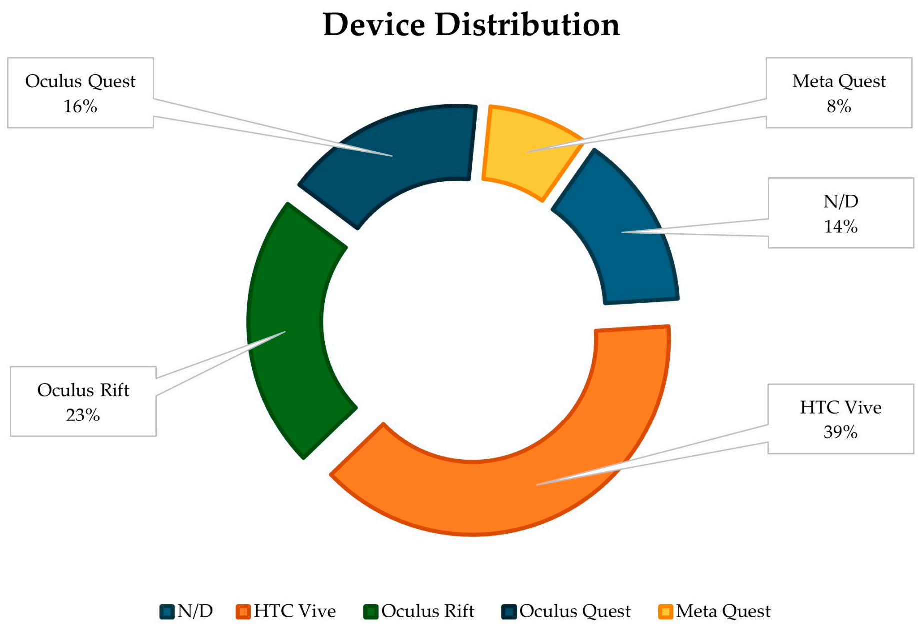

Figure 11. Distribution of devices in fully immersive VR studies with totally virtual environments. (Image created by the authors).

At the high-immersion end, most of the computational complexity lies in real-time interaction management. Tracking, physics, spatial audio, and controller input are orchestrated through event-driven architectures within Unity or Unreal engines [73,109,115]. Scenario designers use trigger volumes, state machines, and timelines to structure experiences: entering an area, completing an action, or exceeding a time limit advances the system state, driving cues, object behavior, or performance logging [25,84,91]. This approach transforms the engine into a runtime execution graph rather than a static scene, with implications for maintainability and adaptability.

Two main families of devices dominate this category. Tethered systems, such as the HTC Vive [26,27,29,37,42,47,51,57,62,63,69–71,75,77,98,119,121] or Oculus Rift [27,44,48–50,71,100,102,119,120], connect to high-performance workstations and often rely on external sensors, additional tracking systems, or locomotion devices. These configurations enable high-fidelity training environments that demand precise interaction and rich feedback. High-end models such as the HTC Vive Pro offer high-resolution displays (2880 × 1600), a 110° field of view, and integrated spatial audio, significantly improving realism and user engagement [121].

Standalone headsets, such as the Oculus Quest [28,53,61,65,74,78,82] and the Meta Quest 2 [31,41,42,50,106], combine computing power, inside-out tracking, and controllers within a single portable unit. These lightweight headsets are increasingly employed in educational and adaptive learning contexts, where portability and ease of deployment support repeated training cycles. In school-oriented simulations, HMD-based serious games use first-person navigation and immediate feedback to train students in evacuation and hazard recognition, fully contained within the headset environment [65,81]. Their versatility also makes them suitable for field-oriented or multi-hazard applications requiring mobility and minimal logistical constraints [41,82].

Both tethered and standalone devices provide wide fields of view, spatial audio, and low-latency response, generating a strong sense of presence and distinguishing them from desktop or semi-immersive projection systems. In the literature examined, even when specific head-mounted devices are not explicitly reported [18,64,79,111], a close reading of the studies and their accompanying visual documentation nevertheless reveals the presence of characteristics typical of fully immersive configurations.

Advanced tracking and feedback technologies further enhance embodiment. Motion-capture devices such as Kinect sensors, optical cameras, or inertial gloves are widely adopted to capture full-body movement and strengthen proprioceptive feedback [26,27,104,112]. In several applications, body-tracking systems translate natural gestures such as walking, running, or manipulating objects into virtual actions, allowing users to interact physically with the 3D environment. This gesture-based control, relying on nine-directional mapping and joint tracking, replaces conventional input devices and reinforces embodiment through movement-driven interaction [104].

Locomotion aids such as treadmills and walking-in-place systems expand navigation within confined spaces and create a more natural sense of motion. In emergency training for oil depots, HMDs combined with treadmills enable continuous navigation and walking-in-place, allowing participants to maintain spatial alignment with the virtual environment [112]. Comparable configurations in multi-technology tunnel-fire simulators employ locomotion platforms and tracking components to coordinate team exercises with differentiated roles; synchronized avatar rendering and alignment of head and hand tracking enhance spatial awareness and collective coordination [26,27]. To address the constraints of limited tracking areas, omnidirectional treadmills have also been introduced, achieving continuous locomotion without spatial drift, as demonstrated in hospital evacuation scenarios [76].

Haptic and force-feedback interfaces complement these tracking solutions by providing tactile responses when virtual tools or props are manipulated. The combination of haptic cues with guided locomotion has been shown to improve precision, confidence, and ergonomic control in industrial and confined-space training [47]. Fully immersive VR is extensively applied across the spectrum of critical-infrastructure hazards, encompassing seismic, hydro-meteorological, fire, technological, and multi-hazard contexts. In earthquake and fire preparedness [26,27,48,49,51,76,112], participants experience dynamic emergency scenarios within virtual hospitals, schools, and office buildings, rehearsing evacuation strategies, protective actions, and response coordination under simulated seismic shocks or fire conditions. Fully immersive simulations designed for first responders extend these capabilities to high-risk environments, allowing rescue teams to operate within photorealistic tunnels, industrial facilities, and collapsed structures while practicing coordination, victim search, and hazard mitigation [26,27,29].

Immersive applications addressing hydro-meteorological and slope-related hazards simulate flood evolution, water propagation, and landslide processes to train users in emergency decision-making, infrastructure monitoring, and evacuation planning under rapidly changing environmental conditions [32,33,73,87,110,118]. In the context of technological and NaTech risks, fully immersive environments reproduce industrial plants, refineries, and energy facilities to visualize cascading effects, equipment failures, or chemical releases triggered by natural events. These systems support scenario-based training for operators and safety managers, integrating process supervision, alarm handling, and critical-response procedures [47,82,112].

Training applications for maintenance and inspection further demonstrate the potential of immersive VR for continuous risk prevention. Users can perform virtual lock-out/tag-out procedures, interact with machinery, and rehearse diagnostic operations within data-driven replicas of real facilities, improving procedural accuracy and ergonomic awareness while reducing exposure to physical hazards [47,100,121]. Educational and reflective applications [28,49,50] extend these frameworks to classroom and institutional settings, illustrating how immersive systems foster adaptive learning, situational awareness, and long-term behavioral retention across the spectrum of critical infrastructure hazards.

Multiuser/Metaverse

At the most advanced end of the interaction spectrum, training systems evolve toward multi-user and metaverse-oriented configurations, in which participants can access a shared, persistent virtual environment. Unlike conventional single-user VR, these spaces are designed to host simultaneous interactions among multiple users, each represented by an avatar or an equivalent role interface, and to maintain continuity across sessions. The metaverse paradigm combines the immersive realism of XR with the connectivity of online platforms, creating social, collaborative, and data-rich ecosystems that can approximate the complexity of real operational networks. Within the domain of critical infrastructure training, these environments enable coordinated teamwork, inter-agency communication, and cooperative decision-making in high-risk or time-sensitive contexts. Users can collectively rehearse procedures, exchange information in real time, and visualize shared datasets or emergency scenarios from complementary perspectives.

Multi-user and metaverse-oriented platforms are defined by their ability to maintain a coherent shared state across distributed clients. Browser-based systems typically employ server-authoritative architectures that replicate avatars, interface states, and annotations to ensure that every participant experiences a consistent virtual environment, regardless of device or connection sequence [97]. Under these conditions, latency management, interpolation, and conflict resolution become critical design parameters, as even minor desynchronization can compromise collective situational awareness.

Alternative implementations adopt participatory-simulation logics, enabling shared interaction through desktops or tabletops rather than full avatar embodiment. In these systems, multiple clients connect to a common simulation kernel, and each parameter edit or scenario run is propagated using concurrency control or turn-taking protocols [22,23,58]. Here, the metaverse dimension lies primarily in the architecture: a single model instance is co-authored and explored by many users who negotiate scenarios and decisions over a common state. Immersive XR frameworks expand this topology by integrating HMD and AR clients, where distributed scene graphs and event buses synchronize object states, triggers, and visual cues across heterogeneous devices [56,67]. From a technological perspective, session topology, replication strategy, and network protocol design jointly determine whether collaboration remains stable under realistic training conditions.

Recent developments show a gradual convergence toward an industrial scale metaverse for safety and resilience training.

Distinctive features—shareable spaces, avatar-based roles, cross-session continuity, and coordinated multi-user participation—are increasingly embedded in immersive learning ecosystems [60]. Some systems extend this logic to operational contexts, providing shared virtual replicas of real facilities where participants visualize dynamic indicators, congestion levels, and evacuation routes updated in real time, ensuring continuity, co-presence, and shared data visibility [59].

In the context of emergency response, multi-user VR configurations also support collective practice in high-risk environments. The *VRescue* platform [29] exemplifies this approach, enabling simultaneous participation of rescuers and instructors within a photogrammetric reconstruction of a collapsed city. Similarly, the HCP–VR system [42] incorporates a cooperative mode where two first responders jointly perform high-capacity pumping operations within a flooded environment, illustrating how procedural collaboration and task coordination can be reproduced through lightweight multi-user architectures. Shared situational awareness, synchronous communication, and coordinated triage procedures are achieved in real time, demonstrating the transition from individual training to collaborative, metaverse-oriented ecosystems.

4.1.2. Simulation Engine Layer

The simulation backbone of the reviewed applications shows a progression from early rule-based frameworks to data-driven, adaptive, and cyber-physical systems. Over time, training tools evolved from scripted procedures to platforms integrating spatial models, agent-based dynamics, and real-time data, bringing simulations closer to operational environments. Figure 12 summarizes this evolution by illustrating the distribution of applications across simulation engine layers.

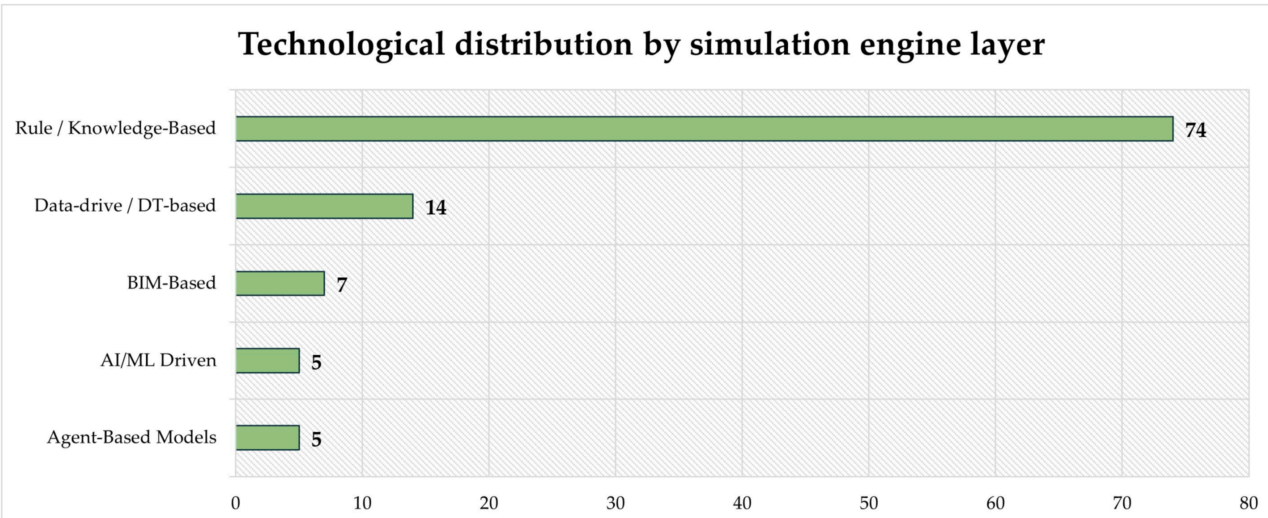

Figure 12. Technological distribution of the reviewed applications by simulation engine layer. (Image created by the authors).

Rule- and Knowledge-Based Systems

Early simulation environments in the corpus rely on rule- and knowledge-based architectures that formalize procedures through predefined logic and ontologies. A representative example is a virtual terror-attack simulation in a train station, where user actions trigger rule-based feedback and safety responses through explicit if–then relations [36]. At a larger scale, the Web-Based Tabletop Earthquake Exercise System models hierarchical decision chains across administrative levels, using rule-based algorithms to propagate the effects of resource allocation and response choices, reflecting real command structures rather than immersive interaction [122].

In more recent literature, analogous rule- and knowledge-based logics are adopted across numerous application domains, where simulators and serious games translate technical standards, Health, Safety and Environment (HSE) guidelines, and expert models into deterministic if–then structures. In the electrical power sector, training engines model high-voltage discharges, human–equipment contact, and operational decisions as procedural sequences aligned with safety norms and supported by explicit decision-making models [68,100,106,111,116,121]. In mining and quarry settings, content-driven courses based on analyses of real accidents organize the learning trajectory as cause–effect chains grounded in quarry HSE regulations [88,89]. In chemical laboratories, *WebVR platforms* and VR serious games encode frameworks such as RAMP and laboratory procedures into tasks for hazard identification, mitigation, and risk management [31,40], while in oil and gas and maritime domains, server-based VR environments and game engines aligned with SOLAS orchestrate safety inspection, emergency response, and mooring operations through procedural storylines with discrete success/failure conditions and scoring systems [21,60,78,79,112,119]. Related studies extend the same principle to fire safety and evacuation training [18,44,62,65,66,85,93,98], construction safety [53–55,77], healthcare and emergency preparedness [24,71], aircraft emergency procedures [72], photovoltaic and power-plant systems [46,52,123], and XR training for confined spaces [47,67], showing that rule- and knowledge-based logics remain central to the modeling of scenarios, outcomes, and performance metrics.

In pedestrian crossing training, for instance, the application for level crossings and foot crossings implements an explicit conditional rule logic, in which any movement beyond the barrier is classified as an unsafe crossing attempt, the correct use of the telephone to request permission to cross constitutes the only "safe" sequence, and a LED board returns a Pass/Fail outcome based on the child's choices [45].

Rule-based scripting remains a defining component of many subsequent serious-game frameworks, particularly those applied to behavioral and pedagogical studies. Conditional logic is used to alternate between immediate and delayed feedback in earthquake training [49], to vary resource availability and avatar roles in motivational experiments [26,27,83], and to guide teacher and student responses during school evacuation drills [30,61,75,81,86,103,107]. The same logic governs mission flow and scoring in professional rescue simulations such as *VRescue* [29]. More recent developments reformulate this rule-based structure into adaptive frameworks, such as the "spiral narrative" introduced in [50], where feedback loops and scenario restarts support reflection-in-action and incremental learning.

Across these implementations, rule-based systems evolved from static scripts to more adaptive narrative frameworks that combine behavioral control with pedagogical flexibility. Hazard-oriented applications still rely on finite-state logic and if–then rules to encode missions, scoring, and error conditions, ensuring predictable and verifiable scenario flows aligned with formal safety protocols [25,43,110].

Both desktop and VR-based serious games exploit this structure: while the graphical layer visualizes outcomes, the underlying controller functions as a rule interpreter that ensures procedural consistency [39,64,101]. Alongside these examples, the corpus also includes a set of studies that do not formally specify the logical architecture of the simulation engine, but where a close reading reveals that the training flow is nonetheless structured around procedures and scenarios derived from regulatory frameworks, operating plans, and expert models. This category includes, for instance, applications based on plant HSE procedures for maintenance activities in the power-generation sector [70], on evacuation times and routes [104], on risk scenarios in urban construction sites [95], on checklists for pre-flight safety inspection [117], on the construction sequence of wind towers modeled through mathematical procedural animation [74], on risk and emergency response procedures tested in a hackathon focusing on real flood scenarios [56], on safety pathways grounded in hazard recognition [94], and on simulated operations in gas power plants that follow codified EPR/HSE logics [69].

These contributions confirm the affinity with rule- and knowledge-based simulation engines, in which procedural knowledge is translated into chains of rules that structure task progression, feedback mechanisms, and the evaluation of user performance. Recent VR systems, such as HCP–VR [42], embed traditional rule-based logic within immersive simulators by using guided and evaluated modes to drive feedback, error detection, and task sequencing in civil protection training.

BIM-Based

As simulation technologies evolved, attention shifted from procedural logic to spatial realism. BIM integration supports detailed representations but requires simplification for real-time use, creating a risk of conflating geometric accuracy with behavioral validity. Where VR is tied to real infrastructure, BIM import or photogrammetric reconstruction adds another layer. Source models are cleaned, decimated and segmented; materials are remapped and colliders generated; non-essential detail is baked into textures [52,120].

Scripts retain links back to object IDs or metadata, so that scenario logic can still refer to functional categories (doors, exits, equipment) instead of to anonymous meshes. A comparison across approaches highlights three recurring "modes" through which BIM is mobilized for training. The first is BIM-as-virtual-world, where the model serves as the foundation of the virtual environment and simulations and agents are layered onto it; this is the case for fire-fighter training, which combines BIM, fire/smoke simulation, and gaming/VR technologies to create realistic scenarios without exposing trainees to risk [96]. The second is BIM-as-data-pipeline, where BIM's main value lies in coordinating a sequence of exports and reconfigurations—FBX/JSON/XML, hierarchies, and coordinate systems—so that the scene becomes directly usable in Unity [120]. The third is BIM-as-knowledge-of-hazards, where BIM explicitly encodes hazard zones and mitigation measures that can be queried at runtime and integrated with external data such as RTLS to quantify trainees' safety-related behavior [105]. This tripartite view is useful because it makes clear that the label "BIM-based" in practice covers very different roles (geometry, conversion logistics, hazard ontology). Instructional-design studies then exploit this infrastructure by swapping interaction rules self-paced exploration, guided sequences, productive—failure constraints over the same spatial content [77].

This approach is exemplified in the Auckland City Hospital studies [48,76], where BIM and VR are combined to create immersive serious games for safety training and emergency management. The BIM model, developed in Autodesk Revit and imported into Unity 3D, was used to simulate earthquake and structural-damage scenarios, allowing users to explore hospital spaces, identify evacuation routes, and experience realistic post-event conditions. In these applications, VR functions as a virtual behavioral laboratory, capable of replicating emergency dynamics in a safe environment and providing a situated, experiential form of learning.

The same logic underpins the Customizable VR-SG Framework [51], which demonstrates that once a digital building model is available, hazard conditions and training objectives can be rapidly reconfigured for different typologies (schools, offices, hospitals). A recurring critical issue emerges at this point: the more a system tries to "close the loop" between the model, the simulation, and performance outcomes (for instance by linking hazard zones and real trajectories in the *VirtualSafeConDM* framework [105]), the more it becomes sensitive to data quality and governance. Conversely, highly operational pipelines such as the tunnel workflow [120] show that fidelity is often achieved at the cost of strong tool dependence and ad hoc transformations that are not always repeatable or maintainable when the asset changes.

In parallel, BIM-based engines provide a structured way to reuse design-time information in interactive training. Pipelines that export Autodesk Revit or open format such as Industry Foundation Class (IFC) models to game engines perform a sequence of transformations: mesh decimation, collider generation, occlusion setup and material substitution [120]. Crucially, they also preserve identifiers and selected semantic attributes, so that the runtime system can address objects by type or function rather than by scene index.

Agent-Based Models

Agent-based modeling represents a further shift in simulation design by introducing collective behavior and crowd dynamics, moving beyond individual procedures to emergent system responses. In the corpus, BE-S2ECURe [41] combines physical hazard models with agent-based evacuation to examine how spatial layout and human behavior jointly shape resilience, linking architectural design with behavioral understanding. Sharma et al. [102] present a VR-based evacuation system using an agent-based simulation engine, where crowd dynamics emerge from interactions among autonomous agents with different roles and behaviors. Movement is guided by local rules and waypoint strategies rather than fixed procedural scripts.

Agent-based engines complement BIM by modeling behavior through local rules applied to autonomous agents that perceive and react to their environment. In flood-simulation platforms, agent-based modules govern individual responses while hydrodynamic models simulate environmental change, within architectures that separate spatial data, behavior rules, and user interaction [22,23,58].

AI & ML Driven Systems

Recent serious games use AI and machine learning to adapt training in real time based on user performance, adjusting difficulty and feedback to support effective learning. This principle is implemented in the Adaptive Serious Game for Emergency Evacuation [28], where an intelligent module monitors player behavior and modifies the scenario accordingly, ensuring that challenge and assistance remain balanced throughout the session. Similarly, in the VRescuer system [82], AI-assisted routing algorithms optimize rescue operations in complex urban environments by calculating efficient paths for rescuers and dynamically adapting to changing conditions within collapsed areas.

These systems shift training from fixed scripts to adaptive, machine-guided learning driven by user behavior. In many cases, AI and ML operate as embedded modules—such as classifiers or adaptive controllers—adjusting outputs or pacing at runtime without altering the visual environment, while raising issues of transparency and explainability [64,77].

At the opposite end of the spectrum, some systems use AI/ML as the core decision-making engine. One example applies deep reinforcement learning (rainbow DQN) to control dynamic evacuation guidance in a metaverse environment, minimizing total evacuation time [59]. Another integrates optimization and probabilistic risk assessment combining particle swarm optimization with fuzzy logic, Monte Carlo simulation, AHP, and Bayesian networks—to compute rescue paths and update risk indices during fire-response training [113].

Data-Driven and Digital-Twin Systems

The most advanced simulation environments adopt data-driven and digital-twin architectures, linking training simulations with datasets, sensors, or analytic modules to reflect real infrastructure behavior. An early precursor is the Virtual City Earthquake Simulation Platform [108], which integrates 3D urban data, hazard parameters, and interdependent infrastructure networks in a modular architecture that anticipates digital-twin principles for analyzing seismic impacts and cascading failures. Following the same trajectory, integrated XR–DT frameworks such as GUIDE2FR [20] combine digital twins with IoT sensing, live video, and machine-learning forecasting. The platform delivers a geolocated, web-based building twin updated from heterogeneous sensors, using semantic dashboards and ML-driven predictions to support real-time and predictive situational awareness rather than static visualization.

The result is a shift from static monitoring to predictive, near-real-time emergency management in scalable, containerized environments. Comparable architectures are also emerging in industrial and energy infrastructures, where XR and digital-twin systems are deployed in Oil & Gas and offshore operations [40,119]. These applications integrate BIM, GIS, and IoT data to support immersive maintenance, safety training, and predictive asset management. A related pattern synchronizes machine telemetry with human positioning in VR to test safety zones and stop conditions in automated production environments [63].

Similar data-driven training twins are reported in locomotive and transport contexts. Gao et al. [57] combine CAD-based mechanical models with a Unity3D 2022 engine to create an interactive training twin that links real-time fault diagnostics with immersive instruction and automated assessment. Likewise, the *EGCERSIS* engine [37] integrates a digital twin of a metro station with a decision-support core that processes sensor data and user actions in real time to drive adaptive crisis scenarios. *VirtualSafeConDM* [105] extends this approach by replaying real site states into VR, reconstructing scenes from as-built models and movement traces, dynamically updating hazard and protection zones, and logging interactions for post-training behavioral analysis.

Within this category, some platforms approach a genuine digital-twin configurations by coupling simulation cores with structured data and multiple client interfaces. Flood-education and monitoring platforms integrate terrain and infrastructure models, solver components and sensor streams via middleware that pushes updated state vectors to front-end viewers [118]. XR tools for sea-level rise and flood exploration ride on top of 3D GIS backbones: terrain meshes, building volumes and water-surface fields are stored once, then consumed by desktop, VR and AR clients through shared coordinate systems and asset registries [73,115]. Data-layer-centric VR preparedness games similarly treat scenario generation as a database problem: historical and drill-derived records parameterize environmental conditions (e.g., visibility, smoke, precipitation intensity/duration, time/location context) via secure/anonymous exchange frameworks, while ML is proposed to adapt tasks based on learner telemetry and feedback signals [64].

Data-driven logic also supports emergency-response twins that use photogrammetric models and AI-assisted routing as operational proxies. Systems such as *VRescue* [29] and *VRescuer* [82] link immersive training to performance data, route optimization, and environmental variability to provide continuous feedback and decision support. In derailment training, the digital twin couples physical and virtual systems through a shared data layer and service modules, using field data, physics constraints, and collision checks to validate rescue plans [114]. Probabilistic engines, such as the Bayesian *BET_UNREST* model, are integrated into volcanic-unrest exercises to update scenarios and inject forecast-based dynamics into training workflows [38].

At the architectural level, metaverse-labeled preparedness modules and urban-risk XR frameworks apply similar patterns: a central scenario model maintains roles, parameters, and object states, while browsers, headsets, and AR devices act as thin clients subscribing to updates and sending back interactions [67,97]. Tunnel-training engines that originate from BIM workflows are progressively extended with configuration files, event libraries, and sensor hooks, turning static design models into living operational surrogates [120]. Across these examples, the technological identity of digital-twin systems is defined less by visual style than by the degree of integration between data, solvers, and clients over time.

4.2. Pedagogical Approaches

Training for critical infrastructures extends beyond procedural repetition by using simulations as pedagogical tools for experiential, reflective, and adaptive learning. The reviewed studies show a progression from situated practice to game-based and adaptive learning frameworks that support sustained competence and resilience.

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4.2.1. Experiential and Context-Based Learning

Experiential learning underpins immersive education by building knowledge through situated action in realistic operational contexts, supporting decision-making under stress. In earthquake-related applications, for instance, Lovreglio et al. [76] and Feng et al. [48] demonstrate how context-based training enables users to understand spatial constraints, procedural dependencies, and interpersonal dynamics. Through embodied interaction and sensory feedback, learners construct meaning from experience, aligning with Kolb's [125] cycle of concrete experience, reflective observation, abstract conceptualization, and active experimentation. Across the corpus, systems operationalize this logic by positioning learners inside environments to be interpreted through direct action rather than passive observation. VR platforms use spatial scale, orientation, and visibility as instructional cues that guide perception and decision-making [73,109,115]. AR and MR applications apply spatial anchoring, simplified models, overlays, and labels, to real surfaces or physical training areas to connect abstract knowledge with tangible context [19,66,80,90]. This experiential grammar combines guided exploration, embedded visual cues, and structured autonomy, bridging the gap between knowing and doing [126,127] and building perceptual awareness, procedural fluency, and adaptive response.

4.2.2. Serious Games as Structured Learning Environments

Building on experiential learning, Serious Games integrate narrative, feedback, and interactive challenge into structured, self-contained learning environments that deliver rule-based, engaging, and measurable experiences.

Within this pedagogical spectrum, the application of psychological theories offers a meaningful way to structure motivation and behavioral engagement in serious games. Among these approaches, one study stands out for explicitly applying the Protection Motivation Theory (PMT) [128] to the design of an emergency-preparedness simulation in a train-station terror attack scenario [36]. The model's core variables—threat appraisal, coping appraisal, and self-efficacy—are operationalized through audiovisual cues, sequential challenges, and corrective recommendations, translating fear arousal and efficacy reinforcement into measurable learning outcomes. This example illustrates how psychological theories of risk perception and motivation can inform the structural logic of serious games, strengthening their educational coherence and behavioral impact. Beyond this case, a large share of the reviewed corpus employs Virtual Reality-based Serious Games (VR–SGs) [18,21,26–31,36,40,41,44–51,53–55,60–65,68–70,72,75–79,81–83,85,89,93,94,96,98,100,102,106,111,112,116,119–121].

The pedagogical architecture proposed by Gao et al. [57] represents a fully integrated approach to vocational learning. Their VR-based training system for locomotive crews combines structured instruction, autonomous practice, and automated evaluation, allowing trainees to progress from guided learning to independent problem solving. The multi-mode design—comprising teaching, practice, and assessment modules—translates experiential learning principles into a measurable performance framework, reinforcing procedural understanding through iterative feedback and adaptive evaluation.

Narrative architectures.

Narrative underpins serious-game pedagogy by structuring learning over time and emotion, with varied forms adapted to different training objectives and learner expertise.

- Linear narratives, common in early applications [48,49,76], guide users through a structured sequence of events, ideal for beginners or highly procedural scenarios.
- Adaptive and modular frameworks introduce variable hazards or spatial typologies for adaptive learning [28,41,51].

- Reflective storylines, exemplified by spiral or feedback-driven narratives, integrate reflection-in-action through iterative redo cycles [50].
- Mission-based storylines immerse participants in task-oriented operations, such as urban rescue and rescue or evacuation drills, emphasizing teamwork, situational awareness, and leadership [29,107]. Structure decision episodes allow learners to observe the consequences of their choices over a small number of scenes [25,39,101].

These structures sustain cognitive flow [129], balancing challenge and ability while transforming procedural rehearsal into narrative experience. They give temporal and emotional coherence to learning, turning each scenario into a story of discovery and reflection.

Problem-Based Gaming

At the cognitive level, most SGs implement the Problem-based Gaming (PBG) model [130], where learning emerges from the resolution of authentic, goal-oriented problems. This structure promotes iterative cycles of action → feedback → reflection → new action, directly mirroring the operational rhythm of crisis management in critical infrastructures. Applications such as Feng et al. [50] and Rahouti et al. [28] illustrate this logic through adaptive difficulty, branching scenarios, and time-bound objectives. Many of the reviewed serious games apply the same PBG principle by structuring tasks as short, repeatable problem cycles with clear goals and constraints. Mission graphs, rule tables and time-bound objectives guide users through well-defined action sequences that emphasize procedural clarity [25,43,110]. Immediate feedback occurs through scores, status changes, or corrective prompts, with refinement across multiple iterations [39,77,91]. These designs show how PBG facilitates sequencing, action–feedback loops, and strategic reasoning, making it a suitable pedagogical model across varied CI-related training tasks.

Interaction Design

Across immersion levels, most VR serious games use progressive scenarios within a storyline and a first-person perspective to enhance embodiment, often relying on teleportation for movement, particularly in non-immersive applications. Several studies highlight how first-person interaction and controlled navigation techniques reinforce the perception of presence and body ownership, even in semi-immersive or desktop-based applications [104]. Some studies [47,71] introduce a risk-based operational criterion: retain the first-person perspective (FPP) when fine control or an operational point of view is required (e.g., grasping a handrail, driving from the operator's seat), to leverage visuomotor coordination and the reading of occlusions; switch instead to the third-person perspective (TPP) when representing abrupt events, such as a fall, avoiding FPP for these sequences to prevent disorientation and motion sickness. In this logic, TPP functions as a "consequence view," clearly showing the error and its effects (worker ragdoll, information window) without compromising comfort; users judged it effective and more tolerable than experiencing the fall in first person [71]. In other words, FPP is useful for "doing," whereas TPP is for "showing" and raising awareness.

This relationship between embodiment and agency, highlighted in the alternation between FPP and TPP perspectives, is consistent across different simulation formats. Building on this, comparative research on emergency-preparedness simulations shows that interactive scenarios elicit higher emotional arousal, perceived threat, and self-efficacy than non-interactive ones, key variables of Protection Motivation Theory [36].

Non-Player Characters (NPCs), controlled by scripts or autonomous behaviors, add narrative, social realism, and behavioral complexity to immersive training, enabling interaction within dynamic virtual ecosystems that reflect the real critical-infrastructure contexts. NPCs are assigned context-specific roles depending on the training domain: in hospital simulations, they represent staff members, patients, and visitors, helping to create a credible and behaviorally rich environment [76] in post-earthquake operations, they act as victims or rescuers, generating realistic and dynamic contexts for team training and crowd management [29,41,82] in educational environments, they serve as instructors or peers who provide guidance and feedback [49] and in industrial or confined-space scenarios, they function as virtual supervisors assisting with procedural operations [47]. Through scripted routines, dialogue sequences, and programmed reactions, NPCs foster situational awareness, guide procedural learning, and encourage users to adapt their behavior under stress. From a technical standpoint, NPCs are modeled and animated through specialized tools such as Adobe Fuse CC for 3D human modeling and Adobe Mixamo for skeleton rigging and motion libraries. In Lovreglio et al. [76], for instance, NPC realism was enhanced using the *LipSync Pro* plugin for Unity, which synchronizes lip movements and facial expressions to speech, while simulating natural gestures such as blinking and head motion.

These elements enhance presence and emotional engagement, turning VR from static simulation into interactive narrative space. Within serious games, NPCs function as narrative guides and instructional agents, providing context and feedback through scripted social interactions that promote cognitive immersion and empathy. In doing so, they bridge procedural learning and human-centered experience, strengthening pedagogical realism across critical infrastructure domains.

Adaptivity and Inclusion

Adaptivity is an essential mechanism within SG design, ensuring that learners with diverse backgrounds and abilities remain engaged. Systems such as Feng et al. [51] integrate dynamic difficulty adjustment and personalized feedback to sustain learner motivation and inclusion, in line with Universal Design for Learning (UDL) principles [131]. Adaptive mechanisms in the corpus typically adjust pacing, difficulty and guidance in response to user performance. VR modules modulate task complexity or provide additional cues when timing, sequencing or error patterns indicate the need for support [77,91]. Desktop and serious-game systems implement similar logic through conditional task trees and adjustable parameter presets that offer easier or more demanding variants of the same core activity [43,110]. These approaches show how adaptivity can be integrated through the existing rule and analytics layers without requiring complex AI systems. This adaptive progression reflects the pedagogical principle of instructional scaffolding [132], as discussed by De Lorenzis et al. [42], whereby temporary guidance structures are provided and gradually withdrawn as competence and autonomy increase. A VR training platform incorporates adaptive guidance and assessment by analyzing task completion, accuracy, and response time to adjust instruction and feedback in real time. This ensures tailored learning for both novice and experienced operators within the same immersive framework [57].

Feedback and Debriefing

Feedback mechanisms are structural to SG pedagogy. Evidence from [49] indicates that post-game reflection results in the most significant learning gains, and complementary findings from [50,51] show that embedding feedback within gameplay loops enhances engagement and retention. The integration of PMT within interactive scenarios further supports this evidence: emotional activation, threat appraisal, and efficacy feedback jointly enhance motivation and knowledge retention, confirming the theoretical relevance of psychological models in the design of feedback-driven learning [36]. Structured debriefing modules, including action logs, replays, and performance dashboards, support self-analysis and instructor facilitation [25,80,101]. These tools close the learning loop, enabling metacognitive awareness and long-term retention-turning the SG from an exercise in reaction into a process of reflection.

4.2.3. Reflective and Adaptive Learning Dynamics

The convergence of experiential immersion and structured gaming produces a distinctive set of learning dynamics—cognitive, emotional, and collaborative—that define simulation-based education in critical infrastructure contexts.

Reflection and Metacognition

Reflection transforms experience into knowledge. Simulations designed for critical infrastructure training incorporate multiple feedback channels that encourage reflection-on-action [133] and reflection-in-action during the exercise itself. Debriefing sessions, replay functions, and instructor-mediated discussions [25,80,101] enable participants to connect cause and effect, transforming procedural performance into conceptual understanding. These metacognitive processes are not peripheral but central to resilience-oriented education: they cultivate self-awareness, judgment under pressure, and the ability to transfer lessons across contexts.

Emotional Engagement and Self-Efficacy

Emotional immersion amplifies cognitive impact. Several studies [50,76] show that affective activation, elicited by realistic visuals, sound design, and social presence, reinforces attention, motivation, and memory. Learners perceive themselves as competent actors within complex systems, strengthening self-efficacy and readiness for real emergencies. Comparable patterns appear across other immersive applications, where realism, proximity effects and perspective shifts reinforce engagement and perceived relevance. Semi-immersive and fully immersive simulations often elicit stronger attentional focus and a clearer sense of agency, which users associate with increased confidence in applying procedures or making decisions under pressure [73,101,115]. These findings suggest that emotional resonance—whether created through spatial immersion, narrative framing or multisensory cues—can meaningfully support self-efficacy within structured training environments.

Collaborative and Systemic Learning

As simulation platforms evolve toward multi-user and metaverse ecosystems, learning extends to the collective level. Teams operate within shared virtual environments to coordinate decisions and manage interdependencies among systems [26,27,29]. These configurations promote distributed situational awareness and collective intelligence, aligning with contemporary theories of social learning [127]. Collaboration becomes both the content and the method of training, reflecting the systemic nature of real-world resilience operations.

4.3. Hazards and Risks Addressed

Critical infrastructures operate under dynamic and uncertain conditions shaped by natural and anthropogenic hazards. These hazards act as initiating forces that drive disruption, influence decision-making, and define the conditions for failure, adaptation, and recovery, forming the basis of preparedness and response training.

In the literature, hazards are broadly classified into Sudden-Onset Disasters (SUODs) [134] and Slow-Onset Disasters (SLODs) [135]. SUODs, such as earthquakes, volcanic eruptions, flash floods, and industrial accidents, occur abruptly and often trigger cascading effects across interconnected systems. In contrast, SLODs, including droughts, sea-level rise, heatwaves and long-term environmental degradation, develop gradually over time. Over the past two decades, the increasing frequency and intensity of both categories of extreme events have underscored the need for systemic approaches to risk assessment, preparedness, and response.

Understanding hazard processes—how they unfold, what they affect, and when they escalate—is therefore essential for learners and practitioners operating within CI environments. This review adopts the UNDRR-ISC taxonomy and Hazard Information Profiles as a common basis for hazard descriptions [136], providing consistent terminology for triggers, footprints, and impact sequences, that support clear learning objectives. The Comprehensive School Safety Framework [137] reinforces this logic across education systems by linking hazard understanding to operational competencies.

Moreover, hazards differ in onset and complexity, influencing exposure, decision windows, and response options. The IPCC AR6 outlines how floods, droughts, storms, and heatwaves unfold on different timescales, shaping exposure and decision windows [138]. Compound and cascading risks such as storm-then-flood sequences require training to reflect real world escalation patterns [139]. Natural Hazard Triggering Technological Disasters (NaTech) events, where natural hazards trigger technological failures, and cascading interdependencies across systems [140] further complicate the operational landscape and must be explicitly incorporated into education and training frameworks.

As shown in Figure 13, NaTech, technological, and human-induced hazards are most frequently addressed, followed by fire and hydro-meteorological events; other hazards appear mainly in specialized studies. Each hazard is analyzed using the same framework to support comparability across studies and training contexts: (i) Objective (educational and operational aims), (ii) Applications (representative cases), (iii) Representation (models, simulations, and digital tools), and (iv) Limitations (constraints and transferability gaps).

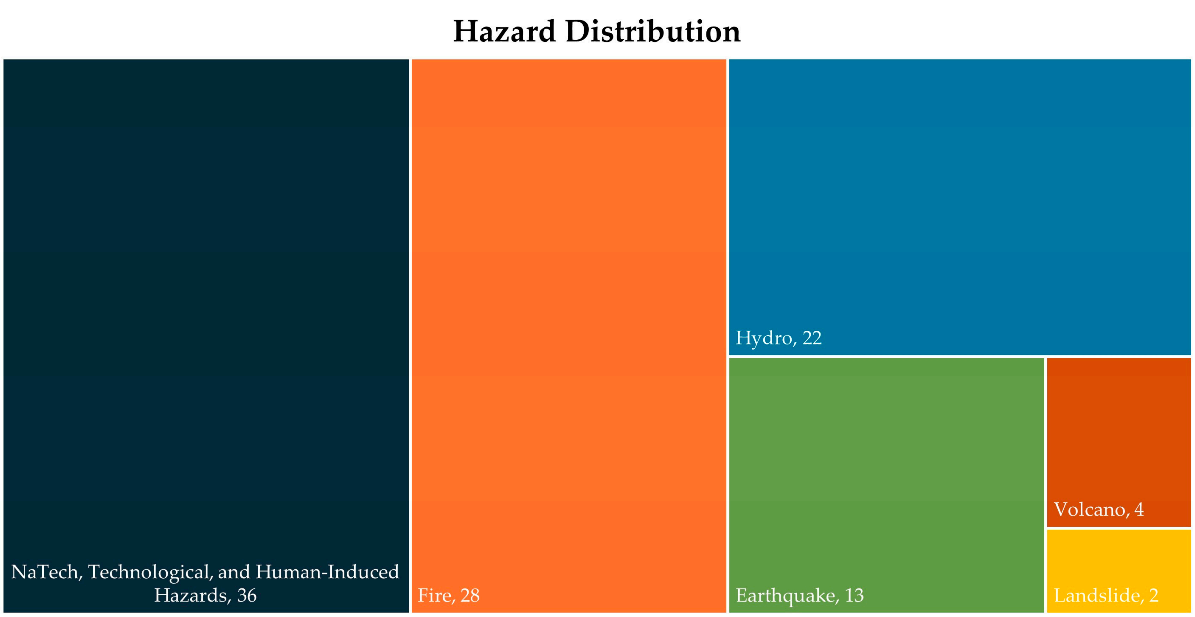

Figure 13. Distribution of hazard types across the selected papers. (Image created by the authors).

4.3.1. Hydro-Meteorological Events

Objectives

The reviewed tools address inland riverine and urban floods, coastal inundation from sea-level rise and storm surge, tsunamis, tropical cyclones and tornadoes [22,23,25,34,35,39,43,56,58,67,73,80,84,87,91,97,101,110,115,118]. A shared objective is to link rainfall, wind and water-level dynamics with concrete consequences for people, buildings and infrastructure, so that users can recognize risky situations and reason about protective options.

For inland floods the main goal is to teach learners to frame risk as a combination of hazard intensity, exposure and mitigation. School and university simulations guide students through riverine flooding cases where they design, test and justify mitigation strategies in a structured risk-assessment task [25,43,87,110]. Other tools target communities and planners and aim to support understanding of how defense portfolios and land-use choices shape inundation, damage and service disruption in specific catchments and cities [22,23,56,58,67,73,101,118]. Technical simulations seek procedural competence for constructing and deploying mobile flood barriers under time pressure [91].

For coastal flooding, sea-level rise, tsunamis and tropical cyclones the objective is to make low-frequency or slow-onset processes visible at familiar sites. Immersive sea-level rise applications aim to increase climate and coastal risk literacy by contrasting present and future water levels along real waterfronts [52,73,115]. Tsunami tools link inundation maps and evacuation scenarios to help users understand run-up limits, arrival times and safe areas [84]. Tropical cyclone and hurricane games focus on preparedness and response, training learners to interpret forecast products and plan resources ahead of landfall [39,80].

Applications

Several tools are embedded in formal education. Flood risk simulations for secondary schools position students as decision-makers who must choose measures and explain risk patterns in a river valley [87]. Serious games used with pupils, university students and the public expose users to inland flood scenarios where they allocate budgets to structural and non-structural measures and observe changes in losses and resilience indicators [25,43,110]. Sea-level rise and coastal flooding experiences support climate-change teaching and adaptation debates in higher education and outreach programs [73,115]. AR and MR tornado and tropical-cyclone applications are used in classroom activities to improve understanding of storm structure and evolution, with short in-app tests for basic knowledge [34,35,80]. Tsunami simulations appear in school lessons and evacuation drills, where they underpin practice on route choice and timing [84].

Professional and community applications target preparedness, planning and emergency management. Participatory simulations and serious games are used with planners, river-basin authorities and local officials to explore how different combinations of dikes, retention areas and zoning rules alter flood extents and exposed assets in urban and coastal settings [22,23,43,56,58,67,73,101,118]. Immersive digital-twin frameworks show flood propagation over detailed terrain and help technical staff rehearse monitoring and warning procedures using synthetic or replayed events [73,101,118]. In operational contexts, the HCP–VR system [42] provides an immersive training tool for Civil Protection teams, enabling first responders to perform high-capacity pumping and drainage operations during hydrogeological emergencies. VR training on mobile flood protection units is used with emergency services and volunteers to practice assembly and deployment sequences under varying hydraulic conditions [91].

Hurricane logistics games support humanitarian and civil-protection personnel in rehearsing pre-positioning and routing decisions under uncertain forecasts [39].

Representation of the hazard phenomena

Inland flood representations range from conceptual models to data-driven simulations. In school-centered tools, learners interact with a simplified 2D river valley where rainfall, land use and mitigation parameters can be adjusted; the model returns flood extent, depth and affected buildings for each configuration [87]. Web-based games such as *FloodGame* use stylized urban maps or simple 3D layouts and simulate flood waves and damage progression under different mitigation portfolios, with scores derived from economic losses and service disruption [25,43,110]. More technical frameworks import outputs from hydrodynamic models or monitoring networks into game engines, producing time-dependent water surfaces over high-resolution digital elevation models of rivers and cities [67,73,101,118].

Coastal flooding, sea-level rise and tsunamis are often represented through static or stepwise inundation layers anchored to real places. Sea-level rise simulations project future water levels and extreme events onto 360° panoramas or 3D reconstructions of specific coastlines, with scenario sliders for year or emission pathway [73,115]. Prototype systems for urban-scale tsunami evacuation similarly rely on 360° panoramas of real neighborhoods, arranged as a sequence of viewpoints and enriched with graphic overlays and immediate feedback to represent evacuation signage and the achievement of safe areas along escape routes [52]. Tsunami education tools use numerical inundation modeling to derive run-up and depth zones, which are then translated into maps and simple animations that guide evacuation strategies during tabletop exercises and combined drills [84]. Participatory coastal-flooding tools for decision-makers couple large-scale hydrodynamic models with interfaces that display flooded areas, protected zones and impacts under alternative protection strategies [22,23,67].

Atmospheric hazards are treated in a schematic but visually explicit way. AR and MR tornado applications render rotating storm structures and wind fields in the classroom, allowing inspection of supercell components and funnel evolution [34,35]. Tropical-cyclone AR overlays storm tracks, pressure fields and wind-intensity belts onto the learner's surroundings, linked to historical events in the Caribbean, and connects these patterns to potential impacts through micro-tasks [80]. HurricaneLog embeds hurricane hazard via stochastic tracks and impact categories derived from observational archives and forecast products, which players must interpret when planning logistics [39]. Here the focus is on path, intensity and forecast uncertainty rather than detailed damage mechanics.

Constraints

Most hydrometeorological tools use discrete scenarios and give limited access to the full probabilistic structure of hazards. Sea-level rise and tsunami simulations typically present one or a few water-level increments or inundation maps tied to selected scenarios, with little discussion of return periods or confidence ranges [73,84,115]. Many flood games compare mitigation strategies within a single event or a small set of synthetic storms and do not connect these to explicit design standards or safety levels [25,43,110]. Work that frames flooding as risk assessment does foreground likelihood and consequences but still relies on deterministic model runs once inputs are fixed [87].

Physical and data realism are uneven, especially in immersive applications. Digital-twin and XR frameworks integrate detailed topography and sometimes external models, yet they are usually presented as prototypes for limited areas, with calibration, validation and computational performance listed as open issues [67,73,101,118]. Many serious games simplify hydrometeorological processes to reduce learning barriers and hardware demands, which suits awareness-raising but restricts operational use [25,43,56,110].

The link to critical infrastructure performance remains partial. Several tools include roads, buildings and simple defenses but lack explicit modeling of interdependent networks or cumulative damage from repeated events [22,23,43,58,73,101,118]. Training on mobile flood barriers concentrates on local deployment and does not propagate barrier performance into system-scale consequences [91]. Participatory simulations highlight trade-offs between measures and residual flood risk but seldom extend to detailed models of transport, energy or water systems [22,23,56,67].

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4.3.2. Landslide

Objectives

The landslide studies focus on rainfall-induced slope failures and their consequences [32,33]. Their primary objective is to help learners understand how topography, soil properties, water content and mitigation measures combine to shape landslide risk. Users experiment with different interventions and see how these alter the likelihood and impact of slope failures.

A second objective is to test how feedback design affects learning about landslide risk. The tools systematically vary feedback strength, timing and contextual richness to examine how these factors influence users' mental models and decision quality when managing landslide-prone slopes [32,33]. Landslides serve as a domain where experiential and contextual learning principles can be evaluated in a controlled way.

Applications in training

Both simulations are used in controlled experiments with adult participants acting as generic decision-makers [32,33]. Users allocate mitigation resources across slopes, interpret feedback and update their strategies over repeated rounds. The applications sit between public-awareness tools and decision-support training: scenarios resemble situations faced by residents or local authorities responsible for slope management, but roles are not tied to specific institutions. Performance metrics and learning gains are central outcomes, which positions these studies as methodological references for future landslide-education tools.

Representation of the hazard phenomena

Landslides are represented with responsive but simplified hillslope models. Simulators describe slopes using a small set of variables (e.g., gradient, material strength, vegetation, hydrological state); mitigation and land-use choices adjust these variables and the stability margin [32,33]. Outputs indicate whether a landslide occurs and the severity of resulting damage, preserving key links between hydrological loading, strength, and failure while keeping decisions manageable.

Feedback context is a deliberate design variable. In decontextualized modes, consequences appear as scores or abstract indicators, with little spatial information. In contextual modes, the same physical behavior is embedded in simplified landscapes that show buildings, roads and people at risk; feedback includes visible damage to these elements after failures [32,33]. Comparing these modes allows analysis of whether contextual, visually rich feedback produces more robust understanding than abstract feedback using the same hazard engine.

Constraints

To support controlled experiments, these models simplify real-world landslide dynamics: slopes are schematic and homogeneous, excluding interactions among multiple slopes, long runout, and deep-seated failures [32,33]. Triggering relies on basic rainfall or groundwater thresholds, without modeling temporal rainfall structure, antecedent moisture, or complex geology, so the tools illustrate qualitative relations but cannot support site-specific assessment.

Stakeholder and institutional settings are also simplified: participants act as generic budget managers, without roles for infrastructure operators, emergency responders, or households. Zoning, warning systems, and evacuation protocols are not represented, limiting transfer to real governance contexts [32,33].

4.3.3. Earthquake

Objective

Among natural hazards affecting critical infrastructure, earthquakes are widely studied and simulated in education and professional training. Their potential to trigger cascading effects, including structural collapse, fire outbreaks, service interruptions, and socio-economic disruption, makes preparedness essential for system continuity and public safety. Seismic events are typically framed as foreshock, main shock, and aftershock stages; training applications mainly address the main shock and aftershock and pursue a dual educational objective.

- At the public level, it aims to familiarize citizens, students, and community members with the fundamental safety actions to adopt during a seismic event, such as following the "drop, hide, cover" guidelines, identifying evacuation routes, and managing panic in a safe, simulated environment [41]. School-based programs have repeatedly demonstrated that structured feedback and post-simulation reflection significantly improve understanding and knowledge retention among both students [49,51,83] and teachers [107] who must learn to manage the situation and guide others.
- At the professional level, training focuses on engineers, emergency responders, and utility operators, who rehearse critical procedures such as structural assessment, network shutdown, search and rescue, and post-event inspection under realistic but controlled conditions [29,48,82,108].

Applications

Across the reviewed corpus, numerous projects illustrate how earthquakes are translated into learning environments that merge simulation accuracy, interactivity, and experiential engagement. These include both analytical simulation systems [108,122] and immersive VR-SGs [29,41,48–50,82] developed for earthquake preparedness, infrastructure management, and post-event operations.

At the civic and educational level, immersive and participatory simulations have been employed to strengthen public awareness and school-based learning [49,51,83,107]. Repeated exposure to realistic earthquake scenarios has been shown to enhance risk perception, confidence, and recall of emergency procedures among students and teachers, as demonstrate in studies such as [41,49]. Interactive community drills and classroom-based VR activities promote a civil-protection culture by linking experiential learning with the behavioral standards defined by emergency authorities. The design and content of these programs often follow national civil-protection guidelines, ensuring coherence between institutional frameworks and public preparedness. The Auckland City Hospital simulations adopt the New Zealand Civil Defence guidelines as their behavioral framework [48,76], while the multi-hazard system developed in [41] integrates directives from the Italian Civil Protection Department and Ministry of Health, ensuring national coherence in emergency management procedures. Together, these initiatives demonstrate how immersive simulations operationalize institutional guidelines within participatory and educational settings, fostering consistent safety behaviors and a shared preparedness culture.

At an operational level, immersive environments have been adopted to train emergency responders in complex, multi-disaster urban contexts. Trainees are required to navigate blocked streets, debris, and dynamic obstacles while optimizing route selection and coordination under uncertainty [82]. In more advanced configurations, operators are immersed in virtual reconstructions of collapsed urban areas, performing triage and hazard recognition tasks [29]. These environments replace traditional static imagery and textual descriptions with interactive, sensory experiences that allow users to explore damaged sites and make real-time operational decisions.

A key example is the *VRescue* project, developed and tested at the Urban Search and Rescue Training Center of the Italian National Firefighters Corps in Pisa [29]. The facility combines a large-scale physical mock-up of collapsed structures with a virtual counterpart built from photogrammetric 3D models of real post-earthquake environments. Rescuers use the simulation to practice victim localization, triage, and coordinated intervention under realistic damage conditions similar to operational missions. By integrating virtual and physical modules, the initiative shows how immersive technologies can expand national training capacity while strengthening procedural accuracy, stress management, and decision-making under pressure.

At the strategic and institutional level, large-scale simulation environments have been developed to support decision-making and coordination among agencies during earthquake emergencies. These systems reproduce seismic events of varying magnitude and intensity to simulate ground shaking, structural collapse, and disruption of lifelines, allowing institutional decision-makers to plan and coordinate responses across multiple administrative levels and crisis tiers [122].

At a more systemic and multi-hazard level, dynamic modeling frameworks capture the earthquake as a complex process capable of triggering secondary hazards such as fires, explosions, or landslides, and propagating effects across interdependent infrastructure networks [108]. By integrating physical, functional, and spatial interconnections, these analytical tools provide a holistic view of cascading risks and support scenario-based training for large-scale disaster management.

Altogether, earthquake-related training applications illustrate a continuous progression from public education and civic preparedness to professional and institutional operation, integrating behavioral training, engineering knowledge, and decision-making under uncertainty. The simulated environments collectively cover the entire building-open space-city continuum: from office buildings [28,50,51], schools [49,107], and hospitals [48,76], to urban neighborhoods and open public areas [29,41,82,108,122].

Representation of the phenomenon

Traditional evacuation drills rarely reproduce the perceptual and emotional intensity of real emergencies, especially for earthquakes, where every occupant directly experiences shaking and threat. Immersive VR and Serious Games bridge this realism gap by recreating multisensory and cognitive stimuli within controlled settings. Participants can perceive stress conditions while receiving real-time and post-exercise feedback, enhancing learning outcomes and behavioral adaptation [49,51,83]. These environments are generally more engaging than static or animated materials, as users interact directly with virtual objects and perceive cause–effect relationships between their actions and environmental changes [48].

Representing earthquakes in simulation environments requires a careful balance between physical fidelity, perceptual realism, and computational efficiency. A persistent challenge lies in reproducing the perception of shaking, a defining feature of seismic events that is not naturally conveyed by standard immersive technologies. Most systems rely on indirect visual and auditory cues-swaying furniture, falling debris, shifting lighting, and synchronized audio feedback, to simulate motion and instability [76]. More advanced implementations incorporate physics-based particle systems that reproduce collapsing structures, dust, and vibration, creating a convincing perceptual experience. To enhance realism, some experiments have introduced motion and haptic feedback, including shake tables, vibration platforms, or controller-based tactile responses. While shake tables provide the highest physical fidelity, their cost, space requirements, and safety constraints limit their adoption. Portable haptic systems, on the other hand, offer low-cost, scalable alternatives that maintain comfort and usability [76].

Beyond perceptual realism, simulation research increasingly focuses on the computational modeling of structural damage. In the Auckland City Hospital simulation [76], damage visualization is implemented through custom C# scripting in Unity 3D, where the collapse of non-structural elements (e.g., ceiling tiles, light fixtures, and furniture) is triggered selectively during the main shock. This approach reduces computational load while maintaining frame-rate stability, delivering a realistic depiction of seismic effects without compromising performance. This mirrors a broader methodological trend in VR earthquake simulations: dynamic behaviors are scripted procedurally, while static damage states are precomputed or represented through simplified textures and animations. This hybrid solution, balancing visual realism and computational efficiency, is crucial for maintaining immersion without compromising usability, especially when training scenarios involve large-scale models (e.g., hospitals, multi-floor buildings, or schools). This hybrid approach balances realism and performance, maintaining immersion without compromising responsiveness, especially in large-scale environments such as hospitals, schools, or multi-story buildings. Analytical frameworks compute damage externally through quantitative models and import results as pre-processed data [108], whereas educational simulations often rely on simplified procedural logic sufficient for pedagogical realism [48,49,51].

The representation of structural damage also varies in degree of quantification and purpose. Quantitative models use detailed datasets describing event parameters such as magnitude, duration, and material properties, to produce context-specific damage estimations [108]. Qualitative representations, typical of educational simulations [48,49,51], portray plausible yet cognitively accessible scenarios, prioritizing clarity and behavioral learning over engineering precision. In both cases, designers intentionally avoid distressing imagery, such as injuries or fatalities, to respect ethical standards and protect user well-being, focusing instead on visual, auditory, and behavioral cues that foster situational awareness and reflection.

Particularly innovative is the emergence of multi-hazard simulation frameworks that combine seismic processes with concurrent environmental stressors. One notable example integrates earthquake and heatwave dynamics within a unified virtual environment, employing surface temperature analyses, debris-motion physics, and agent-based crowd modeling [41]. This approach demonstrates how concurrent hazards can amplify exposure and disrupt evacuation processes in urban spaces, providing a more comprehensive view of cascading risk conditions and interdependent human responses.

Constraints

Despite major advances, earthquake simulations continue to face technological and methodological constraints:

- Physical fidelity vs. interactivity. Realistic ground motion and structural deformation remain difficult to reproduce safely. Most systems simplify physics to preserve real-time performance, limiting the tactile realism of shaking.
- Partial sensory representation. Visual and auditory channels are well developed, but tactile, proprioceptive, and thermal cues are limited, reducing emotional engagement and behavioral transfer.
- Collaborative synchronization. Multi-user simulations suffer from latency, weak embodiment, and limited spatial audio, which undermine presence and coordination in team-based exercises [26,27].

- Validation and curricular integration. Few studies measure long-term retention or validate VR performance against real emergency behavior. Embedding immersive training into national curricula remains an ongoing challenge [49,51,107].

4.3.4. Volcano

Objectives

Volcano-related tools in the corpus pursue two main goals: conceptual volcanology learning for students and support to expert advisory processes in unrest. AR atlas and mobile applications replace static textbook images with manipulable 3D models of volcano types, internal structures and eruption styles, aiming to raise motivation and test performance in high-school geography and social science courses [19,90]. Immersive VR field trips reproduce access to remote or dangerous volcanic sites so that university students and researchers can practice mapping and measurement tasks in realistic outcrops without field travel [109]. A probabilistic event-tree model, BET_UNREST, targets scientific teams, seeking to familiarize them with structured probabilistic diagnosis of unrest and short-term eruption likelihood during crisis simulations [38].

Applications in training

AR volcano media are embedded in regular classroom sessions. The AR atlas projects Indonesian volcano objects on printed markers, with audio and short descriptions, evaluations with large student groups report higher cognitive scores and positive attitudes toward AR as a textbook supplement [90]. The ARGEO mobile app delivers similar content on smartphones, with labeled 3D volcanoes, brief videos and embedded quizzes used as pre/post tests of understanding [19]. Immersive volcanology VR is used in university teaching and outreach: students and non-specialists explore photogrammetric models of real volcanic landscapes in head-mounted displays, performing virtual field observations and measurements [109]. BET_UNREST is applied in a national volcanic-unrest exercise in Dominica, where scientific institutions and disaster agencies work through a staged crisis; one team runs the model, others interpret monitoring data and issue bulletins, exposing experts to probabilistic outputs in a realistic advisory workflow [38].

Representation of the hazard phenomena

School-oriented AR tools represent volcanism through generic yet detailed static 3D models. The AR atlas overlays textured cones, craters and flanks on markers and uses audio or labels to explain morphology and basic processes, without simulating ash, lava or gas dynamics over time [90]. The smartphone app provides rotatable models of stratovolcanoes and other types, plus simplified internal sections and short eruption animations, again with no explicit evolution of hazardous flows or plume dispersal [19]. The VR volcanology system represents hazard settings via high-resolution digital outcrop models built from drone imagery and structure-from-motion, imported into a game engine; users walk across cliffs and domes and record measurements, but eruptive behavior is absent, and risk is implicit in the landscape only [109]. BET_UNREST encodes volcanic activity as probabilities on an event tree, combining prior knowledge and multi-parameter monitoring to estimate the likelihood of different unrest states and eruption within defined windows, with outputs available as tables and graphs rather than visual hazard scenes [38].

Constraints

Existing volcano tools concentrate on conceptual and expert learning rather than explicit risk or critical-infrastructure management. AR applications do not link volcano types and eruptions to local evacuation plans, infrastructure exposure or long-term behavioral change, and their evaluations focus on short-term test gains in a single national school context [19,90]. The VR fieldwork system prioritizes geometric realism but omits dynamic eruptive phenomena and provides limited systematic evidence on learning outcomes across student cohorts [109]. *BET_UNREST* is evaluated in one exercise and depends on expert elicitation for priors and thresholds; participating scientists sometimes judged its probabilities difficult to reconcile with their own assessments, illustrating barriers to routine operational use [38]. Across these studies, infrastructural assets appear, if at all, as part of the surrounding landscape, and there is no explicit modeling of infrastructure performance or cascading effects under eruptions, which restricts direct application to critical-infrastructure-centered training.

4.3.5. Fire

Objective

In critical infrastructure, fire is a recurrent hazard that can quickly compromise space tenability and system operability through heat, smoke, and toxic gases. In training and education, it is treated as both an emergency and a systemic risk that can affect interdependent infrastructures such as energy, telecommunications, transport, and water, making it central to resilience education.

From a risk perspective, the literature consistently frames fire around three main vulnerability domains: (i) Operational continuity [24,26,44,60,66,88,96,112,116]; (ii) Occupant behavior and evacuation [18,20,26,27,30,37,59,62,64,65,75,81,85,86,93,96,98,102–104,120,141]; (iii) Energy escalation [61,69,111,113,116].

Accordingly, the educational objectives associated with this hazard can be summarized as follows:

- To enhance situational awareness and decision-making under time-critical, low-visibility conditions;
- To develop procedural discipline and inter-agency coordination across infrastructure sectors; and
- To strengthen behavioral and cognitive readiness through simulated exposure to realistic emergencies.

Within the analyzed corpus, approximately thirty studies directly or predominantly address fire, focusing on training and simulation applications. Events can be categorized by origin and operational domain using a hazard–exposure–vulnerability–consequence perspective, linking ignition mechanisms, exposure conditions, and infrastructural settings to risk profiles and training priorities.

Natural or wide-area fires occur under adverse climatic and meteorological conditions or within all-hazard and intentional security scenarios. Exposure involves dispersed populations and critical infrastructure networks; vulnerabilities relate to inter-agency coordination and service continuity; and consequences affect crowd dynamics and preparedness levels [24,93,102].

Cascading fires, secondary to primary natural hazard (e.g., post-earthquake) result from equipment failures, short circuits, or gas leaks in already compromised structures. Exposure occurs within damaged buildings where accessibility constraints and malfunctioning essential services amplify the consequences [85].

Technological fires are associated with system failures, operational errors, or electrical faults in highly complex assets. Exposure centers on high energy-density components and interdependent networks; vulnerabilities stem from operational complexity and interconnections; consequences include high-rise response optimization, chemical releases, and EPR scenarios in gas power plants and mines [69,88,113].

Beyond these typologies, practical applications span a wide range of infrastructural domains, each characterized by distinct operational conditions and training requirements.

Applications

Within the industrial and operational domain, fire-related training applications are analyzed across multiple sectors: maritime [44,60,111], railway [18,96], underground/tunnel [26,27,37,120], and hydrocarbon supply chains [66,112], all characterized by high energy releases and confined environments. Each presents specific challenges in ventilation, mobility, and emergency coordination.

Most contributions concern indoor fires in complex building systems, where ignition is often internal and exposure depends on occupancy load, compartmentation, and building program. Training scenarios address evacuation procedures, wayfinding under low visibility, and the reliability of fire-safety systems. Case studies include schools [30,64,65,81], universities [59,98,103,104], airports conceived as building systems, offices/civil and commercial buildings [62,75], and training towers [20].

The literature shows that virtual fire-safety training spans a continuum from individual awareness tools to complex operational simulations of multi-agent emergencies. Non-immersive applications include desktop simulations and online platforms that illustrate evacuation plans and behavioral guidance, focusing on route identification, exit recognition, hazard-source awareness, and safe handling of hazardous items/materials, mainly for occupants and visitors. Typically, low-cost and highly scalable solutions include web/virtual-world environments with assessments of knowledge, retention, and attention [103], desktop serious games for schools [30], and "hybrid" collaborative environments with a non-immersive option [102].

Most recent initiatives are oriented toward immersion, using XR and immersive Serious Games for procedural training, with evidence of increased sense of presence, motivation, and retention in educational and operational contexts [18,26,27,44,60,65,69,81,86,93,98,111]. Some approaches go further, proposing data-driven and model-integrated computing ecosystems that link information models, sensors, and simulation/optimization modules for data–rich scenarios, adaptive guidance, and coordinated drills in stations, tunnels, facilities, and depots [20,59,75,96,112,113,120]. By contrast, studies on synchronous multi-role exercises and joint decision-making in complex scenarios via multi-user collaborative platforms remain limited [26,27,60,102].

Representation of the phenomenon

The virtual representation of fire and smoke propagation follows a methodologically consolidated pipeline. Most mature studies—as shown in Figure 14—begin with Computational Fluid Dynamics (CFD) analysis, typically using the Fire Dynamics Simulator (FDS), to compute smoke, temperature, and velocity fields. These outputs are then resampled and imported into immersive environments for training delivery.

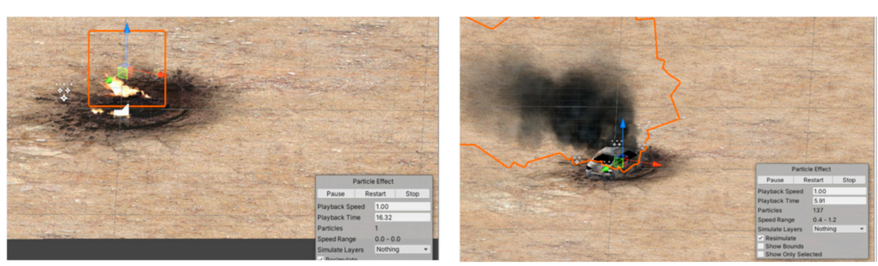

Figure 14. Representation of fire and smoke phenomena, adapted from Thach et al. [44].

In tunnel and roadway simulators, CFD data are rendered as volumetric smoke textures with opacity mapping and vertical stratification, reproducing visibility loss and hot-gas layering, while flames are depicted through parametric particle systems optimized for real-time performance [27]. In school-oriented serious games, FDS data are used to validate propagation times and directions, and custom scripts within Unity trigger the fire's progression according to the building's actual layout [81]. In industrial applications, the virtual rendering is often engine-driven, implemented through particle systems and shaders rather than full CFD coupling, to ensure stability and repeatability during procedural training [44,112]. At the opposite end, desktop and web-based solutions remain more scalable but less behaviorally accurate, while immersive XR systems enhance presence and motivation yet remain constrained by ergonomic and technical limits.

On top of this perceptual layer, an algorithmic intelligence increasingly supports operational decision-making:

- Evacuation algorithms integrate exposure to heat and toxic gases into pathfinding logic [75];
- Metaheuristics such as Particle Swarm Optimization (PSO) shorten evacuation time and path length [113];
- Deep Reinforcement Learning (DRL), combined with IoT sensors and Digital Twin data, enables adaptive guidance, re-routing occupants dynamically during evolving emergencies [59].

When realism and interoperability are key, simulations are anchored to Building Information Models and linked to Cyber-Physical Systems that ingest live or near-real-time sensor data [20,59,75,96,112,113,120]. This integration supports data-rich, adaptive scenarios, extending the role of fire simulation from training to operational decision support.

Constraints

Despite notable progress, fire simulation still faces several structural constraints that limit behavioral transfer and organizational adoption.

- Physical realism vs. interactivity. To ensure real-time performance, CFD fields (smoke, temperature, velocity) are precomputed and combustion rendered parametrically, which inevitably reduces thermofluid-dynamic accuracy [27,81].
- Partial sensory realism. Visual and auditory cues reproduce visibility and alarms, but other stimuli (heat, odor, breathing resistance) are absent, lowering perceived stress and limiting behavioral fidelity. Conversely, poor optimization can induce cybersickness and fatigue [81].
- Collaborative synchronization. In multi-user contexts, latency, avatar embodiment, and limited spatial audio undermine teamwork and coordinated decision-making [26,27].
- Validation and institutional integration. Few studies assess long-term retention or embed VR fire training in professional curricula, limiting adoption in formal education [65].

At the opposite end, desktop and web-based solutions offer scalability and measurability but lower behavioral fidelity than immersive environments, while XR and VR systems, though more effective in engagement and presence, remain constrained by these technological and ergonomic limitations [27,65,81].

4.3.6. NaTech, Technological, and Human-Induced Hazards

Objective

Natural Hazard Triggering Technological Disasters, technological hazards, and human-induced hazards form a continuum between natural and anthropogenic risk in critical infrastructures. Events often result from interacting natural triggers, technological vulnerabilities, and human or organizational factors in tightly coupled systems. NaTech events occur when environmental extremes (e.g., earthquakes, floods, storms) trigger failures in engineered structures and processes. Technological hazards arise from process instability, equipment aging, or supervision failures without external shocks. Human-induced hazards include unintentional errors, violations, and intentional acts such as sabotage or terrorism that exploit existing vulnerabilities.

Immersive simulation and extended reality (XR) are used to translate high-risk, low-frequency scenarios into controlled learning environments when real-world replication is unsafe or impractical. Across sectors such as open-pit mining, construction, process industries, transport, and power infrastructure, virtual settings recreate work sequences, near-misses, malfunctions, and critical conditions, allowing trainees to experience consequences without physical risk.

The overarching objective of these training programs is to develop a form of multidomain literacy that integrates physical understanding, procedural precision and cognitive resilience. This can be articulated along three interconnected dimensions:

- Cognitive dimension: fostering the understanding of interdependencies between natural events, technological systems and human behavior; enabling the recognition of recurrent hazards, critical process states and potential cascading effects, from the scale of the workplace to that of interconnected infrastructures.
- Affective and motivational dimension: strengthening risk awareness, engagement and safety commitment by leveraging presence, emotional arousal and experiential feedback, thereby overcoming the low attention and weak retention that often characterize traditional, lecture-based safety courses.
- Behavioral and procedural dimension: consolidating the ability to apply correct procedures, manage anomalies and emergencies, and make decisions under time pressure and stress, with particular attention to hybrid or intentional crisis conditions in which human choices critically influence system evolution.

Training therefore embeds human–machine interaction and digital supervision in operational readiness. Operators learn to execute tasks, interpret alarms, coordinate with automated systems, and anticipate failure propagation across interdependent networks. NaTech, technological, and human-induced scenarios are used in resilience education to connect protection and control engineering with the behavioral and organizational competencies needed for safe operation in complex environments.

Applications

In high-technology systems, risk is an intrinsic possibility arising from interactions among complex components, stringent procedures, and human limitations. XR safety applications therefore focus on training for complex operational and maintenance sequences and for coordinated inspection, maneuver, and emergency response management. Training systems for electrical safety [68,106,121] propose scenarios in which operators practice procedures such as switching, grounding, and verification of the absence of voltage, while in the case of training on low-voltage equipment, complete lock-out/tag-out sequences and testing of measuring instruments are also explicitly simulated [106]. In distribution networks and power generation, immersive platforms for substations and hydroelectric power plants [68,119,123] support operations such as switching, rapid start-up and shutdown of units, bus transfers, and fault management under critical operating conditions. Similar applications are developed for high-risk facilities such as offshore platforms and oil depots, where training integrates inspection tasks and identification of hidden troubles with multi-user exercises for response to fires and explosions [112,119]. In the energy sector and process industry, immersive scenarios for the maintenance of marine engines and generator sets [70,78,79] and for safety training in oil and gas facilities [21] strengthen competences related to HSE procedures, use of checklists, and operational countermeasures, in some cases recording a preference among participants for simulated training over traditional methods [70].

In construction and underground works, VR and VAR environments are used to anticipate high-risk site conditions where machinery co-presence, spatial constraints, and rapidly evolving operational phases create configurations that are difficult to control in situ. Safety training systems for open-pit quarries [89] and infrastructure excavations [53] reproduce cutting phases, block handling, and face management, enabling workers to confront scenarios of slope failures, falling blocks, diamond-wire breakage, run-overs, or entrapment in low-visibility areas before being exposed to real risk. A group of contributions focuses on geotechnical drilling works, developing environments in which high-power machines, operators, and danger zones are represented with sufficient detail to explore, under controlled conditions, the consequences of collisions, trips, falling rods, and run-over events [54,55]. Along the same line, applications for safety in road construction sites and work zones use VR group training to help workers recognize "caught-in-between" and "struck-by" situations, correctly interpret temporary signage, and coordinate movements with respect to road traffic and construction equipment [94,95,105]. The theme of working at height and in emerging energy contexts is addressed through simulations of wind tower erection [74] and maintenance of photovoltaic systems [46], in which participants practice access procedures, use of Personal protective equipment (PPE), management of electrical hazards, and organization of the work area. A further line of work concerns industrial confined spaces, such as tanks, silos, and service galleries, where immersive scenarios allow users to explore toxic or explosive atmospheres, oxygen deficiency, and risks associated with the presence of gases [47], while experimental studies on confined spaces based on productive failure theory analyze how animated incident sequences can act as feedback on procedural errors in PPE selection and in operational sequences [77].

Another group of applications focuses on emergency management and technological transport incidents. Digital twins oriented toward railway safety support training on derailments, level-crossing impacts, and service interruptions, enabling responders and decision-makers to coordinate evacuation, securing of the train, and restoration of traffic [45,114]. At subsystem scale, locomotive simulators couple mechanical models and real-time diagnostics to train drivers and technicians in handling pantograph failures, power losses, and circuit anomalies, linking the reading of on-board parameters to operational decisions under time constraints [57]. In the road transport of dangerous goods, mixed-reality and virtual scenarios reproduce complex accidents involving ADR tankers, releases of toxic or flammable substances, and electric vehicles, guiding crisis managers and first responders through phases of recognition, area delimitation, PPE selection, source control, and decontamination [66,112]. In industrial contexts, combinations of digital twins and VR are used to orchestrate multi-role exercises in hydroelectric power plants and robotized sites, in which load variations, instrument failures, and machinery accidents are integrated into sequences of alarm, diagnosis, and coordinated response among operators, supervisors, and automated systems [63,123]. Applications close to NaTech logic include fire scenarios in industrial plants and depots, where simulations of fire spread, evacuation, and isolation of energy sources are combined with inspection exercises and fire-fighting procedures, sometimes integrated with augmented reality components in the field [69,113,116]. In the aeronautical and defense domains, immersive simulators replicate in-flight emergencies and subsystem malfunctions—such as engine stall, smoke in the cockpit, or hydraulic failures—to train crews and student pilots to recognize early indicators, apply checklists, and maintain control of the aircraft under stress [72,117].

Finally, a set of applications explicitly explores the behavioral dimension and human-induced risks, linking serious game design to models of motivation, engagement, and risk protection. In simulations for laboratory and chemical process safety, users are required to identify hidden hazards, correct improper storage and handling practices, and understand security aspects related to the misuse of dangerous substances, with scoring systems, heat maps of overlooked areas, and interactive tags delivering additional information on risks [31,40]. Confined-space training based on the comparison between productive failure and direct instruction uses incident sequences (explosions, intoxications, falls, impacts from objects) as feedback on errors in PPE selection and procedural execution, showing how controlled phases of failure can strengthen recall of rules and understanding of consequences [77]. In extractive, energy, and manufacturing industries, immersive safety serious games integrate performance objectives with indicators of engagement, self-efficacy, and satisfaction, highlighting that perceived authenticity of the simulated context and the possibility to actively explore failure scenarios increase workers' willingness to adopt safe practices [71,89,100,106]. In parallel, studies on intentional attack or terrorism scenarios in urban transport contexts use models such as Protection Motivation Theory to analyze how interactivity, presence, and emotional involvement influence threat perception, feelings of vulnerability, and self-efficacy, showing that immersive simulation can strengthen the intention to adopt protective behaviors in crisis situations [36].

Representation of the Phenomenon

In this cluster, NaTech, technological, and human-induced risks are represented in virtual environments across three intertwined levels: spatial and infrastructural configuration, technical–industrial process evolution, and human actions within the scenario. At the spatial level, many studies reconstruct the physical context by means of CAD, BIM or digital twin models imported into game engines such as Unity, in order to reproduce open-pit mines, construction sites, substations, industrial plants, loading areas and depots [53,63,68,89,112,114]. In other cases, the environment is obtained from 360° photographs or video recordings of real locations, enriched with hotspots that activate hazard labels, examples of good practice, explanatory videos or hazard-recognition quizzes [40,52]. At this level, the simulation defines the "scene" in which hazards, equipment, paths and operational zones are laid out.

The process level concerns the states of operation and the transformations that lead from normal conditions to the onset of an accident. Hazards are often encoded as spatial and operational configurations derived from safety standards and accident statistics for excavation and quarry activities [53,89] and for infrastructural and energy construction sites [46,105]: absence of protective systems, proximity to edges or suspended loads, interference between machinery and workers, unsafe access routes.

Hazards are often encoded as spatial and operational configurations derived from standards and accident statistics: absence of protection systems, proximity to edges or suspended loads, interference between machinery and workers, unsafe access routes [46,53,89,105]. The transition to a critical situation is implemented as a discrete event triggered by user choices or procedural violations (entering forbidden areas, omitting checks, misusing devices), which in turn activate near-miss or explicit accident sequences, including falls, collisions, leaks of hazardous substances or emergency shutdowns [46,66,89]. In more automated contexts, risk is further formalized through dynamic safety volumes—such as cones or capsules attached to robots and machines—and through hazardous/protective zones whose intersection generates warning or collision events, allowing situations of safety, near-miss and accident to be systematically classified [53,63,105].

The human-induced dimension is made visible through avatars, roles and movement trajectories. Operators, technicians, apprentices and, in some cases, "intruders" are represented as characters that populate the scene and embody both correct conduct and unsafe practices, thereby making immediately perceptible the presence in maneuver zones, the use of inappropriate PPE or the non-compliance with procedures [21,45,78,89]. Users interact with the environment via controllers, pointers or gesture-based interfaces to inspect, select tools, confirm procedural steps and operate controls [46,53,117]. Risk perception is amplified by audio–visual and haptic stimuli—machinery or traffic noise, alarms, sirens, smoke, changes in lighting, controller vibrations—that simulate urgency, disorientation and stress typical of critical situations [106,116,121,123].

In the few cases that are more closely aligned with NaTech logic, extreme natural events appear mainly as initial conditions or narrative triggers: derailments attributed to environmental conditions, fires or explosions already in progress, industrial areas in a compromised state [66,112,114]. The representation therefore concentrates on the resulting scene of failure and emergency—the displaced train, the burning depot, the contaminated zone—and on the ensuing operations of isolation, rescue and securing, making the relationship between space, technical processes and human action manipulable within a controlled environment.

Constraints

Despite their pedagogical effectiveness, simulations of NaTech, technological, and human-induced scenarios show recurring constraints:

- Model coupling: integrating environmental triggers with industrial process models remains technically complex and data-intensive; most studies treat the natural hazard as a simplified narrative background and focus on downstream consequences, without fully representing the physical and organizational propagation chain.
- Emotional balance: portraying traumatic or violent events requires calibration to protect psychological safety without reducing pedagogical depth; few studies specify criteria, guidelines, or metrics to tune audio–visual intensity, induced stress, or emotional load by user profile.
- Behavioral validation: few studies test transfer to real-world behavior or long-term retention; evaluation mainly uses knowledge tests and immediate self-reports, with limited longitudinal evidence linking immersive training to changes in operational practice, near-miss indices, or accident rates.
- Systemic integration: multi-user coordination and modeling cross-infrastructure interdependencies remain limited, reducing realism in cross-sector crisis simulations; analyses often focus on a single plant or department, and rarely simulate impact chains spanning energy, transport, communications, and emergency services.

4.4. Critical Infrastructure Domains

In CI resilience, immersive and data-driven technologies are increasingly used across sectors, from energy and transport to healthcare and civil protection. Each domain has distinct operational logics, spatial configurations, and vulnerabilities, but the pedagogical aim is consistent: build systemic awareness and procedural competence where safety, service continuity, and coordination must coexist.

Within these domains, simulation does not merely replicate physical spaces; it operationalizes interdependence, between assets, processes, and human roles, turning infrastructures themselves into learning ecosystems. Training applications often mirror the operational structure of critical infrastructure systems, where interdependencies among assets, services, and actors shape crisis performance. Simulations therefore reproduce both the material configuration of infrastructures and their socio-technical hierarchies, enabling coordinated learning across organizational layers.

The urban built environment is treated as a socio-technical infrastructure that supports everyday functioning and community resilience. Figure 15 summarizes the distribution of reviewed studies across critical infrastructure domains, showing concentration in a limited set of sectors and a gradual expansion toward a wider range of socio-technical systems.

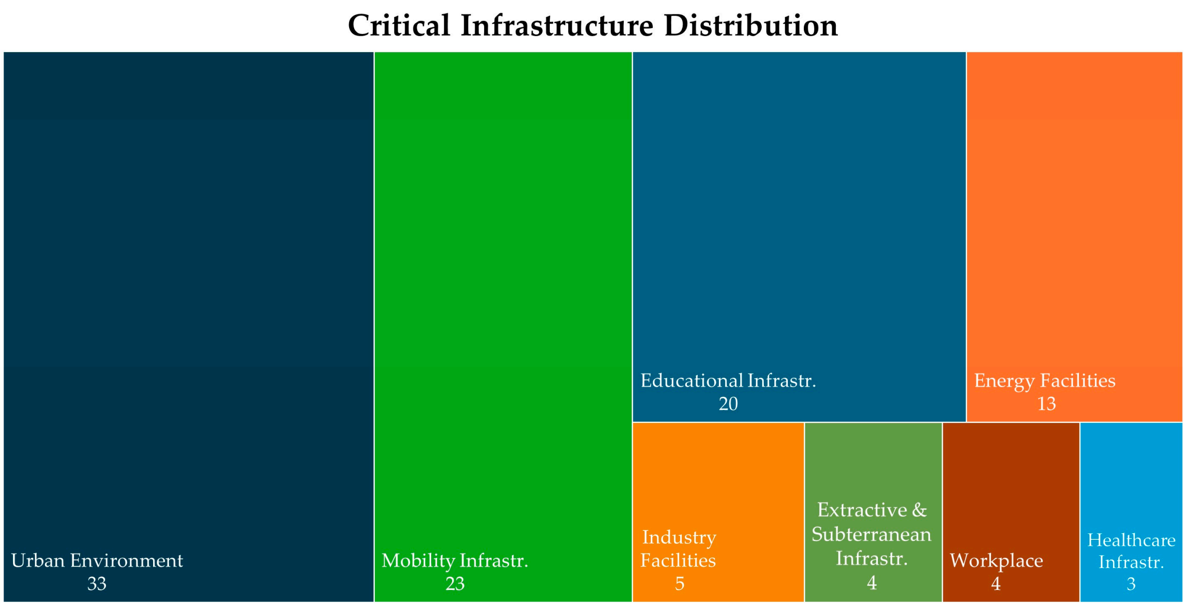

Figure 15. Critical Infrastructure distribution over selected papers. (Image created by the authors).

The following subsections outline how simulation-based and immersive approaches have been implemented across different types of infrastructures, emphasizing their contribution to safety, preparedness, and operational continuity.

4.4.1. Mobility Infrastructures

Mobility infrastructures, including multimodal transportation hubs, railways, tunnels, highways, and airports, form the connective tissue of contemporary societies, sustaining economic functionality and emergency accessibility. Their operational complexity arises from confined geometries, high user density, and continuous interdependence with energy, communication, and safety networks. The geometric continuity of elements (tracks, carriageways, tunnels) and the presence of nodes and specialized technical spaces (driver cabins, engine rooms, loading areas, construction sites) directly shape risk exposure. In these systems, even minor disruptions can cascade across sectors, compromising logistics, power distribution, or emergency coordination. Consequently, immersive and simulation-based environments have become key instruments for preparing operators, responders, and citizens to act coherently under uncertainty and time pressure. Beyond spatial description or visualization, these systems orchestrate interactions among heterogeneous actors (passengers, pedestrians, operators, emergency response teams, maintenance technicians) across the infrastructure life cycle, from design and construction to high-severity incident management (e.g., tunnel fires, derailments, air accidents, hazardous-material releases).

Across the reviewed corpus, mobility-related training consistently leverages virtual and mixed-reality environments to reproduce the spatial, procedural, and organizational dynamics of real transport systems. In this context, transportation hubs such as metro stations are increasingly modeled as digital twins to train coordinated crisis response in confined, high-density environments. The EGCERSIS project [37] exemplifies this approach by implementing a virtual-reality platform for crisis management in a metro station scenario, where fire, evacuation, and medical assistance procedures are enacted by multiple actors within an interactive digital twin connected to a decision-support system. This configuration demonstrates how immersive simulations can integrate spatial fidelity, real-time data, and procedural evaluation to enhance preparedness and coordination across interdependent transport networks.

In the railway domain, the studies reviewed outline a clear progression from the training of vulnerable users to the management of complex incident scenarios. These are critical linear systems in which the combination of track layout, civil works, track superstructure and mobile subsystems jointly determines both vulnerability and operational resilience. From an infrastructural standpoint, risk tends to concentrate in highly interactive nodes between networks, such as level crossings and pedestrian junctions on single- or double-track lines [45], as well as in internal corridor segments characterized by constrained geometries, specialized equipment and strong dependence on signaling logics and centralized control [18]. At a broader scale, the digital-twin model for derailment scenarios presented by Xu et al. [114] explicitly represents the railway system as a whole: the “incident subject” (the derailed trainset) and the “incident environment” (the infrastructure corridor and adjacent facilities) are modeled together, enabling the planning and testing of recovery operations within a high-fidelity reconstruction of real line segments. Expanding this modeling approach to the train itself, the locomotive crew VR training system [57] recreates the vehicle’s mechanical and control components in detail, integrating inspection, diagnostic, and emergency procedures within an interactive simulation that links the physical logic of the train to the cognitive performance of its operators.

Human-induced hazards have also been examined in this domain. The serious-game simulation of a terrorist attack in a train station [36] models evacuation behavior, risk perception, and protective decision-making within a confined public transport hub. The comparison between interactive and non-interactive conditions revealed that active engagement enhances perceived threat, emotional arousal, and self-efficacy, demonstrating how behavioral training and security preparedness can be effectively integrated into mobility-infrastructure simulations.

For underground and tunnel infrastructures, BIM–VR integration supports high-fidelity reconstructions of linear corridors, escape routes, and technical chambers. The BIM–VR motorway-tunnel emergency model [120] shows that encoding escape routes, SOS niches, and installations with semantic metadata is central to building plausible, reusable scenarios, although evaluation is qualitative and limited to a single case study. The *FrèjusVR* system [26,27] extends this logic through multi-user, multi-role training: firefighters, truck drivers, and civilians operate simultaneously in a shared digital replica of a road tunnel, rehearsing alarm activation, communication, and decision-making. The scenarios assess procedural timing and social coordination, showing that mutual avatar visibility increases collective situational awareness and perceived realism. At the urban scale, this perspective extends to metro systems, where the *VirtualSafeConDM* framework [105] models stations, platforms and adjacent work zones along an existing line as constrained underground corridors, using an as-built BIM model and RTLS data to represent the loading area as a logistical node in which interactions between machinery, materials and pedestrian routes can be systematically analyzed.

In road infrastructures, a similar training logic applies risk stems from the co-presence of moving vehicles, maintenance crews and variable environmental conditions. Mixed-Reality exercises for ADR tanker-truck accidents [66] highlight the specificity of roadside hazards and the need to train highly specialized operators. VR applications for hazard recognition in motorway work zones [55,95] reconstruct corridors and construction areas—as shown in Figure 16—to systematize hazard identification and decision-making. The *Immersive Cross—platform X3D* system [94] models a highway construction site as a linear roadside infrastructure with active traffic, multiple worker roles, heavy equipment, and varying weather and lighting conditions, delivering the same spatially coherent scenario across CAVE, HMD and screen-based platforms to support collective hazard recognition along the work corridor.

XR platforms for urban evacuation, by contrast, reinterpret transport networks within the built environment: the system based on 360° panoramas [52] adopts a lightweight and scalable pipeline to represent multi-site escape routes, at the cost of more limited interaction with the virtual environment. Other studies address specific operational issues, such as the management of hazardous-goods transport at the interface between industrial logistics and the public road network [66]. Across these cases, roads and tunnels are treated as infrastructures whose geometry, capacity and connectivity directly condition the feasibility of protective actions.

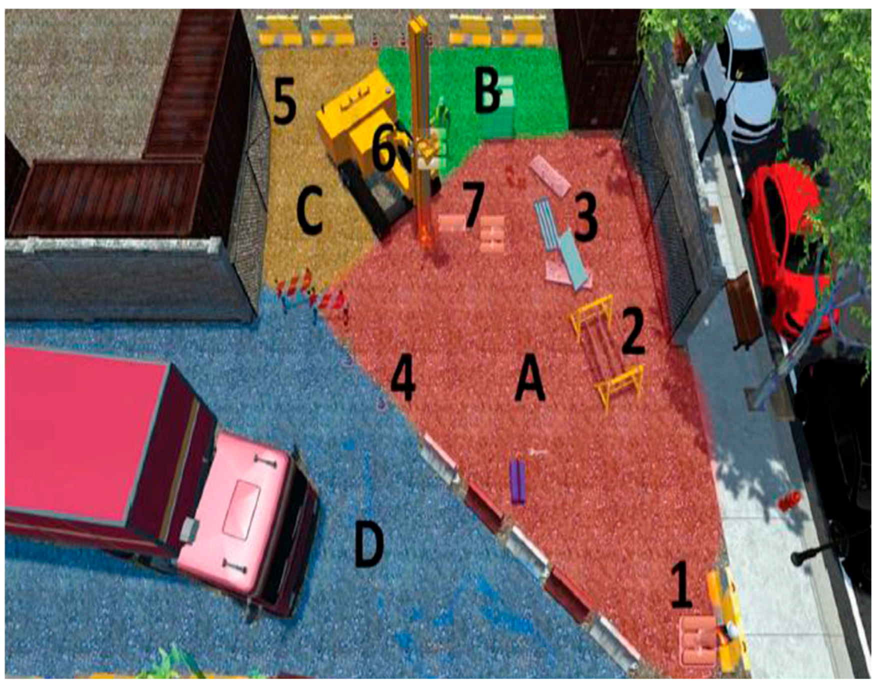

Figure 16. Work zone of the VR scenario. Reproduced from [55], © 2023 The Author(s), distributed under the Creative Commons Attribution License (CC BY 4.0).

In aviation infrastructures, immersive systems extend training to the coordination between airside and landside operational units. Simulations reproduce the hierarchical logic of emergency management-from incident detection to command-and-control decisions-while maintaining the spatial and temporal coherence required for realistic training. Case studies on pilot emergency-procedure training [72] and AR-based pre-flight inspection [117] show that simulated scenarios and digital overlays support procedural standardization and situational awareness, strengthening adherence to safety protocols among flight crews and maintenance personnel.

Maritime transport infrastructures including ports, shipping routes, and onboard technical spaces such as engine rooms extend mobility networks, coupling navigation, propulsion, and emergency management within highly confined industrial interiors. Engine rooms are critical subsystems, concentrating propulsion units, auxiliary systems, piping networks, and control panels in compact, evacuation-critical, operationally dense spaces. A VR training system [60] identifies the engine room and, in parallel, the galley as the highest fire-incidence areas; scenarios vary by severity and controllability and require trainees to locate the fire source, follow SOLAS procedures (alarm activation, communication with the bridge), and choose between local extinction and evacuation along predefined escape routes. *ShipSEVR* [79] models a platform supply vessel engine room as a high-fidelity technical space, integrating generator sets and auxiliary systems with plant schematics and VR-accessible digital documentation, shifting emphasis to maintenance procedures and safety practices.

A maritime VR setup [44] is coupled to shipboard fire-alarm hardware, modeling container-ship spaces (engine room, electric room, bridge) in Unity and linking alarm panels/HMI monitoring to the virtual scenario so trainees detect and localize fires and rehearse onboard response procedures. Electrical-safety training studies [111] extend this to high-voltage onboard electrical systems, reinforcing those technical interiors, mechanical and electrical, are key resilience nodes. Experimental evidence [78] in maritime safety training (e.g., dynamic risk assessment during mooring operations) reports VR simulators outperforming instructor-led training on motivation, perceived learning, and intentions for behavioral change, supporting immersive solutions for standardized, just-in-time training across global fleets.

4.4.2. Extractive and Subterranean Infrastructures

Extractive and subterranean infrastructures—underground mines and open-cast quarries—are inherently critical environments where unstable materials, mechanical operations, and constrained spaces create persistent risk. Work near ignition sources, handling weak or fragmented rock masses, and possible toxic gases make fires, collapses, and reduced visibility recurrent hazards. The contexts differ by setting: underground mining occurs in confined voids with ventilation networks and limited egress, while open-cast extraction takes place in exposed areas with excavation fronts, variable slopes, and continuous demands for stability and material-handling control.

Across the reviewed literature, workforce training in these domains centers on two principles: spatial continuity and operational coherence of the learning environment [88,89]. A quarry simulation for the marble sites of the Apuan Alps [89] applies these principles by reconstructing a real location as interconnected scenes linked by access ramps; yards, quarry faces, and drilling areas use realistic elevation data and include virtual machinery and operators. The environment reproduces instability, maneuvers in confined spaces, and human–machine interference, enabling participants to rehearse coordination and safety protocols in context. For underground mines, training for Australian rescue brigades uses a whole-of-mine model virtualizing about 50 km of galleries and roadways, embedding fire and smoke-release scenarios along a continuous drift network [88]. This large-scale simulation captures geometry and the sensory and operational constraints of underground response—darkness, visibility gradients, heat, noise—so teams can practice navigation, communication, and time-critical decision-making.

Another approach builds a high-fidelity environment from a laser-scanned point cloud of mine cavities at roughly 400 m depth, integrated into a Unity-based framework

[63]. It supports interactive training for emergency response to fires, explosions, haul-truck accidents, and co-worker injury, using realistic equipment and spatial configurations to train procedural execution, spatial reasoning, and team coordination together. Across applications, quarries, mines, and related infrastructures (trenches, drilling pads) are modeled as socio-technical systems: excavation volumes, functional areas, and safety perimeters are represented and manipulated in XR to reproduce gallery networks and open-pit morphologies (Figure 17). This supports navigation, hazard recognition, rescue training, and operational planning in underground and open-air industrial contexts. Combining accurate topography with contextual audio (wind, machinery, drilling, cutting) strengthens situational awareness and procedural learning, showing how XR can reproduce the perceptual and operational complexity of extraction sites. In several studies, high-fidelity reconstructions of tunnel and cavity networks [63] are coupled with process-simulation logics and robotic systems, turning the mine into a testbed for digital-twin concepts and advanced automation. These hybrid environments foreshadow later solutions in industrial and energy domains, where immersive technologies shift from spatial training tools to integrated platforms for simulating complex plants, hazardous processes, and control infrastructures.

(a) (b)

Figure 17. VR training for primary upstream cutting (SO1): safety-distance verification (**a**) and positioning of diamond wire guards before horizontal cutting (**b**). Reproduced from [89], © 2025 The Author(s), distributed under the Creative Commons Attribution License (CC BY 4.0).

4.4.3. Energy Facilities

Energy infrastructures are a core CI subset because failures cascade quickly across interdependent sectors: disrupted generation, conversion, or transmission can trigger blackouts and degrade communications, mobility and logistics, water services, and emergency response. These cascading risks coexist with internal technological hazards, including fire, explosion, and hazardous-substance release. In the corpus, this domain covers electrical power systems and substations, gas-fired power plants, onshore and offshore oil and gas (O&G) facilities, and renewable plants such as hydropower stations, wind towers, and photovoltaic farms. Configurations range from compact sites (e.g., gas plants centered on a few generators sets in one building) to distributed production chains spanning extraction, processing, storage, and transport across large territories. Despite this heterogeneity, the educational challenge is shared: training operators for complex, high-risk environments where spatial configuration, process control, and emergency procedures are tightly interwoven. Immersive and data-driven applications provide safe surrogates, allowing users to navigate plant layouts, distinguish safe from unsafe paths, and rehearse emergency, maintenance, and inspection procedures that are too dangerous or costly to replicate on site.

In the electrical power sector, immersive applications focus on substations, technical rooms, and live-line worksites, where high-voltage components require strict stepwise procedures. Substation simulators [68] recreate real high/medium-voltage facilities in 3D (bays, switching equipment, operator pathways), enabling rehearsal of circuit breaker, disconnector, and earthing-switch operations while visualizing the effects of wrong sequences. Low-voltage systems [106] cover end-to-end workflows from PPE selection and lock-out/tag-out to voltage verification, so learners internalize each step under realistic conditions. Comparisons of visual, textual, and auditory feedback indicate that multimodal cues improve comprehension, reduce cognitive load, and sustain motivation [121]. VR education further promotes safety adherence by simulating electric shock and fall accidents during elevated component replacement and flagging hazard points across the process [100]. Other platforms extend to risk prevention and robotics, using VR to test teleoperated interventions near energized equipment and to support safety-robot design and validation [116].

In gas power plants (GPPs), combustion, pressurized equipment, and confined environments create risks that demand high procedural accuracy. Immersive GPP simulations [69,70] reproduce end-to-end maintenance and emergency sequences: trainees identify leaks, execute shutdown procedures, and locate main gas valves under rapidly changing conditions, or perform routine maintenance (e.g., air-filter replacement) in line with plant HSE requirements [70]. One simulation models a conceptual gas-engine facility where a leak triggers a fire, requiring evacuation via the nearest exit and isolation of the fuel supply [69]. These scenarios enable repetitive, feedback-driven practice of critical actions while preserving physical safety; by visualizing links among process units, escape routes, and control devices, they strengthen spatial reasoning and adaptive behavior.

Moving from GPPs to oil and gas (O&G) infrastructures, the focus shifts from compact systems—few generation units in a single building—to distributed chains spanning extraction, processing, storage, and transport. GPP risk is largely governed by the fuel–combustion chamber–exhaust circuit and management of a confined high-energy volume; O&G systems involve large flammable inventories, extensive piping and tank networks, complex process units, and strong integration with logistics and transport. Evidence from Pakistani O&G industries [21] indicates this sector remains among those with the highest incidence of major accidents, while highlighting a still largely unmet need for VR safety-training solutions. In the corpus, onshore configurations (depots, terminals, process units connected to transport networks) and offshore configurations (platforms and marine units for onboard extraction, processing, and power generation) are treated together because they sit on the same infrastructural chain and share core hazards and plant logics. Despite differences in operational context, accessibility, and evacuation strategies, both rely on separation, compression, pumping, and storage of flammable fluids, with potentially explosive atmospheres, work at height, and confined spaces.

Across these infrastructures, risk is dominated by large volumes of flammable/explosive hydrocarbons, pressurized equipment, ATEX atmospheres, constrained access and egress, and systemic dependence on standardized operating procedures and a consolidated HSE culture. Within this framework, VR-based vestibule training is reported to have potential to reduce injuries and fatalities but faces economic and infrastructural barriers and organizational resistance to new technologies [21].

For onshore settings, an oil-depot system [112] reconstructs a high-risk node (tank farm, loading areas, piping networks, fire-fighting equipment) and uses separate inspection and emergency modules—illustrated by the O&G plant system-development interface in Figure 18—to let users explore infrastructural anomalies and fire/explosion scenarios along predefined routes and operational roles. Offshore, a platform power-system study [119] models the platform as an isolated micro-energy infrastructure, virtualizing the onboard substation and electrical equipment at real scale in a structured training environment where switching sequences, fault conditions, and operating states are controlled via programmable logic controllers (PLCs). In both cases, VR makes relationships among layout, risk-control devices, and intervention procedures explicit; the depot application emphasizes spatial and collaborative emergency response, while the platform scenario emphasizes detailed power-system and plant-behavior modeling.

Figure 18. System development interface of Oil and Gas plant. Reproduced from [112], © 2019 The Author(s), distributed under the Creative Commons Attribution License (CC BY 3.0).

Beyond plant and system levels, upstream and logistics segments are addressed through analytical and extended-reality approaches. Machine-learning pipelines calibrated on core-flooding experiments derive parameter distributions for enhanced-recovery models, supporting scenario analysis for reservoir development and production planning within the broader energy infrastructure [99]. MR accident scenarios for road tankers carrying dangerous goods train crisis managers and emergency responders where industrial supply chains intersect with public transport corridors [66]. Together, these works show that O&G infrastructures extend from the reservoir to the roadway, and that both high-fidelity simulation and interactive training support safer operation.

Within renewable-energy subdomains, energy infrastructures are treated as environmentally dependent, distributed systems with hybrid risk profiles: electrical and mechanical hazards typical of generation facilities combine with work-at-height exposure, difficult access, and variable weather. A hydropower-plant simulation [123] reconstructs a 132 MW reference facility (machine halls, control rooms, access routes) linked to hundreds of operational commands, training resilience skills from decision-making and coordination to managing operational constraints under grid disturbances. The plant is modeled as a continuous socio-technical system in which physical layout, supervisory systems, and power-grid constraints are simulated together to assess operators' ability to maintain performance under abnormal conditions. Other renewable configurations emphasize distinct spatial forms and task sequences. Wind-tower simulators [74] model vertical infrastructures with high fall and structural-collapse risk, guiding users through the sequential assembly process and emphasizing hazard recognition at each phase. Conversely, photovoltaic systems [46] are framed as diffuse infrastructures where electrical, fire, and height risks converge; based on field analyses, VR/AR gamified scenarios target workers involved in PV installation, maintenance, and cleaning, reproducing façades with photovoltaic panels, manlifts, lifelines, and anchor points, and structuring work into four stages (PPE selection, preparation, work at height, closure) with predefined performance thresholds and simulated incident outcomes triggered by repeated errors.

4.4.4. Industry Facilities

Industrial infrastructures are a core critical-infrastructure domain, where production lines, process units, laboratories, and control systems operate in high-density, interdependent configurations. Risks stem from hazardous substances, pressurized equipment, moving machinery, confined-space work, and high automation with reliance on standardized procedures. In the analyzed corpus, this domain spans manufacturing and process facilities (e.g., assembly lines, production departments, construction sites, proto-plant configurations) and chemical or research laboratories functioning as modular micro-plants with variable equipment and substances. Immersive applications make workspace geometry, operational sequences, and interaction points between people, equipment, and safety systems explicit, supporting training in hazard recognition, procedure execution, and incident management in complex techno-organizational settings. A VR occupational health and safety training system [71] recreates production and non-production factory areas using routine scenarios such as stair circulation, warehouse logistics with racks and forklift traffic, and safe interaction with industrial machinery and equipment.

For production facilities, an immersive VR platform for confined-space safety [47] models tanks, vessels, silos, manholes, and underground chambers as critical sub-infrastructures. It reconstructs enclosed volumes with limited access points, pipe connections, and level differences, embedding step-by-step procedures for entry and work. Confined spaces are treated as plant-network nodes where geometry, atmospheric conditions, and equipment jointly shape error margins, safe routes, and mitigation strategies.

For laboratories, some studies [31,40] treat the lab as a micro process infrastructure but with different logics. The inspection training system [40] divides the lab into 15 door-tagged scenes (entrance, PPE dressing, workbench, fume hood, storage), arranging "planted" hazards along an inspector's path and revealing them via interactive hotspots. The VR serious game [31] represents a single operational lab environment where benches, equipment, and protection devices frame tasks of risk identification, risk minimization, and safe experiment execution. Thus, [40] frames the lab as an inspection infrastructure of traversable nodes and links, while [31] frames it as a work infrastructure connecting actions, errors, and consequences within one experimental space.

Industrial plants also serve as incident settings for response training: a 3D simulation-based fire-rescue system [113] integrates rescue path planning and risk assessment and evaluates performance in scenarios including factory and chemical-plant fires.

4.4.5. Communication Infrastructures

Although less frequently addressed, communication and data infrastructures underpin the resilience of all other sectors. Immersive and simulated environments are applied to train operators in network recovery, data security, and cyber-physical continuity. AR-assisted inspection of hardware systems and VR-based command-center simulations allow staff to rehearse collaboration and crisis communication without interrupting live operations [39,58]. As these infrastructures become increasingly entangled with energy, transport, and safety systems, training approaches centered on situational awareness and data visualization will play a growing role in ensuring operational reliability [118].

Beyond their technical function, these infrastructures illustrate a new dimension of resilience: informational resilience [58,118], where the capacity to interpret, communicate, and restore data flow becomes as critical as maintaining physical assets. In this sense, immersive environments contribute not only to skill acquisition but also to the cognitive and organizational adaptation of digital ecosystems [39,118].

4.4.6. Healthcare Infrastructures

Healthcare facilities are among the most intricate and interdependent critical-infrastructure categories, where spatial layout, service continuity, and operational interconnection directly shape emergency performance. Auckland City Hospital, New Zealand's largest public hospital and a clinical research facility [48,76], exemplifies these dynamics under seismic stress and is used as a reference case for immersive training oriented to operational resilience and emergency management. Chosen for operational complexity, high occupant density, and essential functions, it comprises a multi-building complex integrating clinical wards, diagnostic and surgical units, administrative offices, and public areas (corridors, lobbies, waiting rooms). These components are linked by dense vertical and horizontal circulation networks that create overlapping zones of access, movement, and responsibility. Staff, patients, and visitors follow partially intersecting pathways, reflecting hospitals' dual role as care environments and logistical systems where controlled circulation and open accessibility must coexist. Under disruption, functional dependencies (e.g., between emergency exits, lift systems, and intensive care units) become critical. The hospital's compact morphology and high occupancy increase exposure to non-structural damage, while internal connectivity affects both risk propagation and evacuation efficiency. As a simulated setting, Auckland City Hospital provides a spatial and organizational model for analyzing healthcare-infrastructure resilience, showing how architectural form and functional interdependence shape performance during seismic and multi-hazard events.

Complementarily, ref. [24] models a rural healthcare system parametrically as an acute-care rural hospital (e.g., numbers of physicians and nurses, triage rooms, ER beds, inpatient wards) while integrating public-health and emergency-management subsystems; the main response variable is overall healthcare/hospital system performance. The approach also highlights VR's potential for interdisciplinary training by integrating medical, technical, and administrative perspectives within one virtual ecosystem.

4.4.7. Workplace and Office Environments

In office settings, immersive technologies are used to support both operational continuity and safety training, turning workplaces into testbeds for organizational and behavioral resilience. Offices form a distinct but increasingly relevant subset of critical and organizational infrastructures: while typically less exposed to physical hazards than industrial or transport systems, they concentrate people, digital assets, and service-continuity dependencies that are central to institutional and corporate resilience. Immersive and simulation-based applications mainly target evacuation dynamics, behavioral adaptation, and cognitive responses to emergency cues. Several studies simulate multi-floor layouts and dense occupancy to examine route choice, decision-making under alarms, and compliance with safety instructions, showing how cognitive load and spatial familiarity affect evacuation performance. Scenarios commonly model fire, smoke propagation, and earthquake evacuation [28,50,51], with attention to spatial perception, stress management, and real-time alert communication. More recent work deploys optical see-through AR in office corridors and circulation spaces to train occupants in core fire-safety tasks and compares outcomes with conventional video-based training [44]. Beyond evacuation, some studies extend to organizational resilience and human-factor assessment, linking safety training with workplace well-being, ergonomic design, and psychological readiness.

On the side of occupants and egress management, the training model [75] uses a multi-story building as a case study to analyze how internal configuration and the layout of escape routes influence path choice, evacuation times and perceived safety of participants in the event of fire. The BIM–VR environment [96] extends this logic to the firefighters' perspective, using information models of real buildings to allow crews to familiarize themselves in advance with geometries, systems, access points and critical areas of complex structures before field intervention. Taken together, these tools bridge the building and urban scales, showing how localized decisions—on exit placement, attack routes or rescue tactics—are tightly dependent on external accessibility, the road network and the location of emergency services.

4.4.8. Educational Infrastructures

Educational facilities, especially schools and universities, form a distinct critical-infrastructure class where safety management and knowledge dissemination intersect. In the literature, AR and mobile-AR applications overlay geological or meteorological content onto textbooks, classroom walls, or outdoor areas [19,34,35,80,90], converting standard lessons into situated risk explorations while keeping the school building as a stable spatial frame [19,34,35,80,90]. Other studies use school layouts, timetables, and assembly areas as the basis for evacuation drills and preparedness modules, combining physical exercises or metaverse sessions with simulation outputs so students and staff can understand circulation patterns, bottlenecks, and waiting zones [97].

Across educational settings, immersive environments are used to turn schools and campuses into laboratories for emergency preparedness, using different technological and pedagogical approaches. In public schools and primary education, VR serious games replicate typical school layouts and codified fire regulations, training pupils and teachers in evacuation procedures and emergency management through narratively structured scenarios [30,81]. At university level, virtual replicas of teaching and laboratory buildings, including campus-scale virtual worlds and metaverse-based evacuation systems, support repeated fire drills and testing of dynamic guidance strategies under realistic occupancy conditions [59,103,104]. More infrastructural approaches integrate digital twins of training towers and classroom blocks, multi-user preparedness platforms, and VR games embedded in learning-management systems, engaging students, teachers, safety professionals, and shared scenarios that can be monitored and adapted over time [20,61,64,65].

These studies show how schools can operate as learning-critical infrastructures, where architectural design, organizational routines, and educational objectives align to build a preparedness culture. Controlled studies further indicate that VR-based fire-safety programs can improve knowledge of safety measures and individual awareness among students and academic staff, supporting long-term internalization of emergency procedures [98]. Immersive technologies extend this by linking learning activities with resilience building across personal awareness, institutional readiness, and community safety.

4.4.9. Urban Environment

Urban and territorial infrastructures are central to resilience strategies, as cities concentrate critical assets, services, and populations within tightly interdependent systems. Accordingly, the reviewed literature is organized by the spatial and functional scale at which immersive and simulation-based environments support training, from territorial systems to task-specific settings.

At the territorial scale, immersive and simulation-based environments represent urban regions as interconnected socio-technical systems in which built form, hazard dynamics, and human behavior interact under emergency conditions. Seismic applications dominate this level, relying on synthetic or parametric virtual cities composed of administrative areas, functional districts, and lifeline infrastructures—including hospitals, schools, and emergency shelters—to support strategic reasoning and inter-agency coordination under large-scale earthquakes and cascading failures [29,41,82,83,108,122]. At this scale, learning objectives are predominantly strategic, focusing on system-wide situational awareness, policy-relevant decision-making, and coordination across institutional and infrastructural boundaries. At the metropolitan and mega-city scale, immersive environments model extensive urban systems characterized by high infrastructural density and systemic interdependence. Collaborative virtual platforms allow multi-user teams to explore crisis scenarios and to observe how decisions affecting individual assets propagate across interconnected networks, supporting training on complexity management and cross-sector coordination in large metropolitan contexts [102].

At the territorial–urban planning scale, immersive and simulation-based environments address hydro-meteorological and coastal hazards by representing cities as spatially extended configurations of river corridors, coastal zones, slope-side settlements, and flood-prone districts [25,32,33,43,52,67,73,84,87,101,109,115,118]. VR, desktop, and XR tools support planning-oriented decision-making by enabling reasoning about exposure, accessibility, and the continuity of essential services across urban areas, rather than at the level of individual buildings.

At the urban scale—where planning intentions, institutional coordination, and on-the-ground operations intersect—immersive and simulation-based environments become particularly diverse and articulated. Here, the city is framed as a multi-level critical infrastructure in which spatial configuration, circulation systems, institutional decisions, and human behavior jointly determine emergency outcomes. Participatory simulations enable residents, students, and decision-makers to modify protection measures, land-use options, and emergency routes and to observe how these changes propagate through the urban fabric, reinforcing an understanding of resilience as an emergent property of interconnected spatial and organizational choices [22,23,58]. Within this territorial–urban planning framework, the literature documents several cases in which specific existing urban contexts are modeled as immersive multi-hazard training scenarios. The historic center and river corridor of Senigallia are represented through an extended-reality framework that combines reusable typological scenarios with site-specific environments, enabling the joint training of citizens, technicians, and decision-makers in flood-risk management and related civil-protection measures [67]. The system integrates characteristic urban morphologies, riverfront conditions, and emergency-relevant public spaces, allowing users to explore alternative response options and protection strategies within a recognizable local setting. A closely related approach is adopted in a multidisciplinary "*dual hackathon*", in which a flood-affected urban territory is employed as a shared testbed for coordinating engineering analysis, risk communication, and operational decision-making during a joint exercise involving universities and local authorities [56]. In this case, the immersive environment functions less as a stand-alone simulator and more as a boundary object that supports collaboration across disciplinary and institutional perspectives. A similar logic underpins the experiential training system *MisasTer*, which situates participants in a coastal city exposed to a sequence of earthquake, tsunami, and fire events [85]. Drawing on the official disaster-prevention map, the virtual environment structures realistic evacuation routes and escape paths, allowing users to assess the correctness and feasibility of their decisions under time pressure and evolving hazard conditions. Across these cases, the urban scale is not treated as an abstract backdrop but as a concrete, recognizable environment in which spatial configuration, hazard progression, and social response are tightly coupled. Later immersive applications further emphasize the operational dimension of the urban scale by focusing on collapsed and damaged cityscapes during post-event conditions. Environments such as *VRescuer* [82] and *VRescue* [29] enable participants to navigate debris-filled streets and ruined structures during post-earthquake response activities, using high-resolution photogrammetry and physics-based simulation to support realistic interaction with disrupted urban fabrics and unstable structures.

At a more localized level, serious games and training modules foreground specific urban components and infrastructures as operational units. Flood- and water-protection systems—including levees, mobile barriers, pumps, and drainage elements—are modeled as manipulable components that learners must configure under time and resource constraints [91,110]. Data-driven and digital-twin platforms further link catchment-scale hydrological behavior with local assets such as embankments, channels, and sensor-equipped sites, enabling visualization of how interventions on individual structures affect neighborhood-scale conditions [118]. Parametric representations further reframe public squares as social and logistical nodes during emergencies through Built Environment Typologies (BETs) [142,143], which parameterize architectural form, spatial configuration, and functional attributes to create structured and replicable learning environments grounded in real-world morphological taxonomies [41]. Compared to indoor settings, outdoor spaces are typically represented in a more schematic manner due to their scale and spatial complexity; however, this abstraction supports a balance between realism and manageability and enables public spaces to function as parametric components of the city's resilience infrastructure [41,142,143].

At the most fine-grained level, immersive training environments focus on construction sites and task-specific operational settings, which are typically overlooked in larger-scale urban models. VR-based safety-training applications address excavations, geotechnical drilling works, and high-risk activities such as confined-space entry, treating trenches, underground utilities, temporary structures, and machinery as critical risk nodes within the urban environment [53,54,77]. At this scale, training objectives concentrate on procedural knowledge, equipment selection, and task-level hazard awareness, reframing infrastructures under construction as integral—rather than peripheral—components of built-environment resilience.

4.5. Actors and Stakeholders

The stakeholder segmentation reflects an effort to position educational technologies that addresses differing levels of expertise, responsibility, and operational risk as shown in Figure 19.

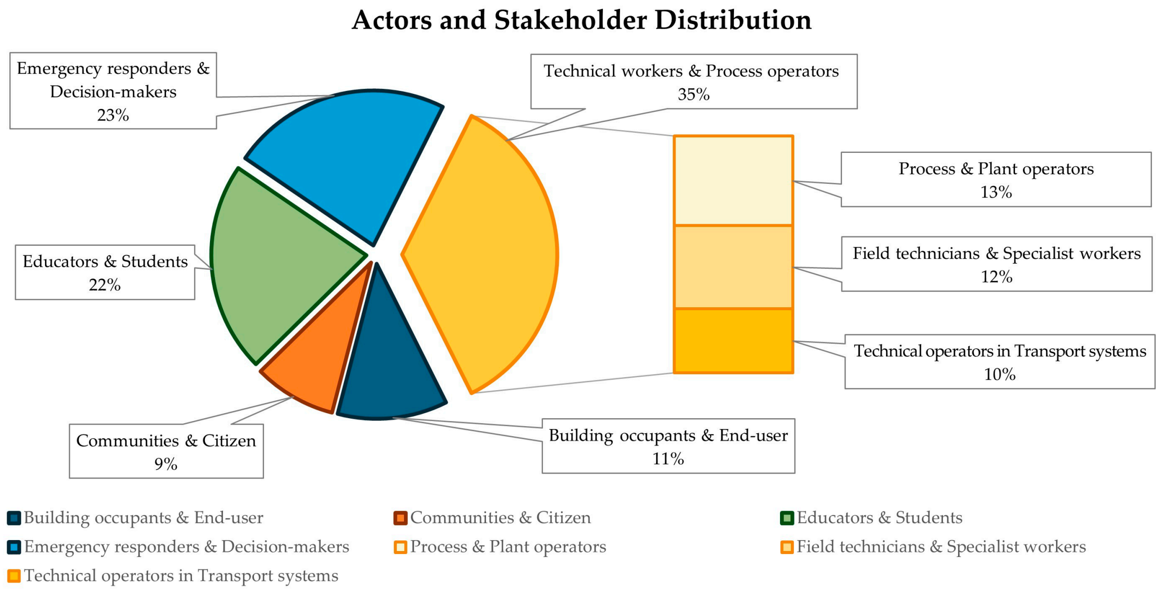

Figure 19. Actors and stakeholder distributions across the reviewed studies, including a detailed breakdown of the Technical Workers and Process Operators cluster. (Image created by the authors).

Within the analyzed literature, two main design logics recur. Some studies are infrastructure-centric [48,51,76], starting from the asset and distinguishing occupants and functional roles such as operators, visitors, maintenance staff, and managers. Others are user-centric [28,29,49,50,82,83,107], designing experiences for specific groups such as rescuers, technical workers, or students. Together, these approaches show how immersive technologies map human diversity within infrastructural systems, supporting an educational continuum from asset management professionals to citizens. A similar duality appears in hazard-focused studies. Many applications target school and university learners, embedding geohazards and hydrological risks into curricula or laboratory-style activities [19,25,34,35,43,73,80,84,87,90,97,110,115,118]. Others develop participatory simulations that involve residents, teachers, scientists, civil protection officers, and emergency responders in shared flood, landslide, tsunami, or hurricane scenarios, enabling evacuees, planners, and crisis managers to act within the same digital environment from distinct roles [22,23,32,33,38,39,56,58,64,67,101,118]. These studies extend stakeholder mapping beyond single institutions and link educational technologies to community risk governance. In addition, some studies adopt cooperative trainee-centered configurations, emphasizing situational awareness and peer communication, without specifying professional categories beyond the experimental participants [26].

4.5.1. Emergency Responders and Decision-Makers

In crisis and emergency management [37], immersive simulations target both operational responders and institutional decision-makers, reflecting the dual backbone of preparedness: tactical execution under stress and cross-level coordination and resource allocation.

At the operational level, *VRescue* [29] trains Urban Search and Rescue (USAR) teams, including debris navigation, victim triage, and use of professional equipment (GPS, dosimeters, radios). Comparable VR firefighting systems support orientation, team coordination, and equipment handling: a BIM-based environment [96] simulates fires, smoke, and explosions in complex facilities (airports, stations); a multi-scenario system [62] covers shopping malls, hospitals, dwellings, and entertainment venues with extinguishers, hydrants, fire doors, lifts, and escape routes; *Fireman Rescue* [93] logs actions, errors, and timings for debriefing and feedback, strengthening coordination, reaction time, situational awareness, and cognitive flexibility under stress.

Multi-role simulations such as *FrèjusVR* [26,27] assign distinct roles (firefighters, civilians, truck drivers) to practice collaboration, safe distancing, and procedure activation. Hydrogeological response is addressed by *HCP–VR* [42], which trains Civil Protection responders in high-capacity pumping through guided and evaluated modes integrating protocols and performance assessment. *EGCERSIS* [37] extends to coordinated multi-actor transport response via a metro-station digital twin with shared decision support for firefighters, police, and medical teams. *GUIDE2FR* [20] couples a digital twin of a training tower and nearby buildings with wireless beacons, cloud data management, and predictive air-quality models to support both responders and control-room operators during exercises.

At the strategic level, a web-based tabletop earthquake system [122] supports command structures, inter-agency communication, and resource allocation through hierarchical coordination and information exchange. In healthcare, a multi-method simulation for rural disaster preparedness [24] combines system-dynamics and discrete-event models of patient flows, capacity, and triage to test how policies and resources affect service performance under catastrophic scenarios.

Among the most advanced implementations, the *VRescue* training system, tested at the USAR Center in Pisa [29], exemplifies how immersive simulations are now being incorporated into institutional firefighter-training programs. Similarly, *Fireman Rescue* [93] and *GUIDE2FR* [20] are now embedded in stable training facilities and programmed for fire brigades and civil protection services.

Within hazard-focused transport and territorial settings, *Tunnel VR* uses BIM-based incident scenarios for lane closures, traffic control, and occupant guidance under fire and smoke [120], while mixed-reality ADR tanker training uses HoloLens overlays for stabilization, hazard identification, first aid, and logged performance [66]. *HurricaneLog* supports humanitarian logisticians and emergency managers in planning stocks, shelters, and fleets under uncertainty [39], and *Flood Action* VR stages multi-phase flood missions for emergency services and volunteers, assessed mainly through usability and perceived preparedness [101]. Institutional exercises include volcanic-unrest sessions around probabilistic *BET_UNREST* outputs for scientists and civil protection [38], and participatory flood simulations engaging municipal staff and elected representatives on prevention portfolios [22,23,58], with XR frameworks proposed for multi-profile urban risk training but limited pilots to date [67].

Across these settings, VR exposes control-room/field communication bottlenecks, detects stress even in experienced personnel, and shows response-time improvements after a few iterations. Data-driven tools (e.g., PSO-assisted routing and dynamic risk assessment) support responders in high-rise and industrial scenarios, improving efficiency and safety during fires and chemical releases [113]. The evidence base still needs longitudinal evaluations tied to real-world performance, outcome metrics beyond usability, and simulators designed to be age-inclusive and team-aware.

4.5.2. Technical Workers and Process Operators

Technical workers and process operators constitute the operational backbone of many critical infrastructures. Within the reviewed corpus, these profiles occupy an interface position between organizational and procedural prescriptions and material processes: they translate signals, constraints, and procedures into actions on the physical system and, precisely because of this proximity between decision and execution, they operate in contexts where error can rapidly escalate into major incidents. In this review, these profiles recur across three families: (i) technical "operations" staff, oriented toward running and controlling assets under ordinary conditions; (ii) safety-critical and operational HSE roles, focused on managing safety margins and operating under degraded conditions; and (iii) onsite or mobile technicians and specialists, active in dynamic contexts at the interface between infrastructure and its surrounding environment. This positioning generates a recurrent set of pressures, including tight time and protocol constraints, stringent safety requirements, exposure to operational stress, and the need to coordinate with co-workers, control rooms, and response teams. Against this backdrop, immersive training tends to support transversal capabilities, procedural accuracy, situational awareness, coordination, and stress management, and to be structured as drills that make recognition, response sequencing, and evacuation executable under time pressure [65,98], sometimes through cascading multi-hazard logics in which an initiating event, for example an earthquake, triggers subsequent threats within the same training flow [85]. In parallel, several contributions integrate performance metrics and indicators for analysis, after-action review, and preparedness assessment, thereby linking the exercise to reflective learning logics and decision support [37,64,67].

A first recurring family concerns technical "operations" staff, responsible for running and controlling assets under ordinary conditions. They are described as profiles required to internalize standardized procedures and to act promptly on high-consequence operational sequences, in settings where procedural deviations may have significant implications for service continuity and safety [21,71,112,119]. This family also includes technical roles in complex and constrained systems, such as substation personnel and electrical operators [68,121], railway crews [18,57], and shipboard technical operators [78,79,111], for whom competence is reflected in sequential mastery of procedures and the ability to maintain operational control in environments shaped by spatial and organizational constraints. By way of example, Figure 20 shows a VR interface providing operational instructions for handling the most common locomotive faults, in support of crew training [57]. Additional studies also include technical profiles in highly regulated contexts, such as pre-flight technical inspection roles [117] and operational emergency decision-making [72], where performance is defined by adherence to standardized routines and the management of operational choices under time pressure.

Figure 20. VR instructions on how to handle the most common faults in a locomotive for crew training. Reproduced from [57],

A second family comprises safety-critical and operational HSE roles, whose primary responsibility is to ensure that operations remain feasible under safe conditions by making explicit the constraints, margins, and boundary conditions that structure action. This dimension is visible in lock-out and isolation sequences [106] and, more broadly, in high-risk configurations that are difficult to reproduce through conventional training. In automated settings, for instance, action is constrained by interlocks, exclusion zones, and stop conditions that must be recognized and complied with when working in proximity to robots or semi-autonomous equipment [63]. A comparable need to operate within tight safety margins recurs in rare/high-consequence contexts, such as underground and otherwise constrained environments [88], and in confined-space work, where preparation revolves around entry, work, and rescue procedures [77] as well as pre-entry selection of PPE and appropriate tools [47]. Some applications also support operation under degraded conditions by rehearsing operational commands and abnormal procedures during grid disturbances and equipment faults [123]. Others are oriented toward preparedness through evacuation and mitigation [69] and multi-actor scenarios in which safety depends on role alignment and coordinated emergency management, such as tunnel-fire scenarios [26,27] and role-differentiated response platforms for highway tunnels [120]. In the maritime domain, fire preparedness is similarly framed through drill-oriented modules for crews [44,60], and comparable frameworks are extended to intentional crisis scenarios [36]. Continuity with field response is also reflected in contributions that include coordinated rescue actions during incidents in distribution environments [116].

A final family concerns onsite/mobile technicians and specialist workers operating at the interface between infrastructures and their surrounding environment in dynamic contexts, where risk emerges from interactions among people, machines, and evolving site configurations. This strand includes scenarios for construction, excavation, and roadwork settings [53,95], along with approaches that encode hazard zones and improve the traceability of unsafe proximities and procedural deviations during training [105]. Similar logics recur in geotechnical drilling worksites, structured around the coordinated actions of drillers and assistants near heavy machinery [54,70], and in open-pit quarrying, characterized by rapidly changing, equipment-dense conditions [89]. A parallel strand addresses electrical and maintenance trades on active worksites [100] and at-risk technical occupations, including wind-turbine servicing and crane/tower operations [74]. It also includes personnel involved in photovoltaic façade operations—covering tasks such as cleaning, maintenance, and repair—for whom role-specific decision-making is central under constrained operational conditions [46]. In protection services, immersive environments extend training to intervention and coordination tasks in multi-actor emergencies [93,96]. More marginally, some contributions connect these training ecosystems to risk-communication practices directed also at infrastructure users [45]. Finally, the corpus includes inspection and compliance profiles in laboratory contexts, where serious games and inspection environments support engagement and familiarity with standardized control practices [31,40].

4.5.3. Building Occupants and End-User

Building occupants are a heterogeneous and behaviorally influential stakeholder group in critical infrastructures, including people who work, study, or transit in hospitals, offices, and schools. During emergencies, their actions reflect the interplay of spatial configuration, functional hierarchies, and individual preparedness, shaping risk perception, cue interpretation, and decisions under stress. Training for both professionals and non-specialists is therefore needed to support safety and coordinated action in complex facilities.

Accordingly, the reviewed studies converge on two complementary strands: (i) behavioral research that uses immersive environments to observe and measure occupant responses under controlled conditions; and (ii) training applications that teach correct actions and translate simulated experience into preparedness. Within the behavioral strand, several contributions extend occupant analysis beyond public facilities to residential and mixed-use settings exposed to hydro-meteorological hazards. Interactive landslide simulations place participants in the role of householders selecting structural and behavioral measures, while a simplified model reports whether a landslide occurs and its severity; these designs are used to test how feedback timing and context shape risk judgments and mitigation preferences [32,33].

In parallel, behavioral work in complex public facilities is exemplified by a VR environment derived from a BIM-based reconstruction of a hospital section under an earthquake scenario [76]. Healthcare settings are particularly informative because they combine distinct occupant groups with different priorities and movement patterns (clinical staff, administrative staff, patients, visitors). Participants experience shaking cues, reduced visibility, and falling debris, enabling measurement of reaction times and evacuation choices in a controlled but realistic setting. In this role, VR functions as a behavioral observatory that produces empirical evidence relevant to emergency planning and spatial design.

Building on these observational foundations, the second strand shifts the focus from measurement to rehearsal. An immersive serious game based on the same hospital model asks users to perform protective actions (e.g., "drop, hide, cover"), identify hazards, and select safe routes, while receiving immediate performance feedback [48,76]. A similar training logic appears in confined transit infrastructures: the multi-user road-tunnel fire simulator *FréjusVR* trains civilian end-users to practice protective actions and evacuation under smoke and time pressure [26,27]. Moreover, within the same setting, avatar fidelity matters, as full-body representations tend to be preferred over minimal proxies and influence immersion and social presence during multi-player interaction.

To extend transferability across contexts, several studies propose configurable solutions that reuse scenario logic across offices and administrative complexes [51]. Likewise, extensible VR emergency-preparedness frameworks are framed as reusable structures that can be adapted across workplaces and commercial buildings and deployed alongside conventional drills [61]. In the same direction, iterative narrative design (spiral storytelling) is applied to office evacuation drills to promote reflection and correction, supporting longer-term behavioral retention [50].

When the focus moves to educational infrastructures, immersive and mobile VR are applied to classroom and corridor emergencies, training teachers and students for earthquake [49,107] and fire [59,61,103,104]. Complementing these scenario-based drills, a VR fire-evacuation training model formalizes route safety through an optimal escape-path formulation based on survivability constraints under high temperatures and harmful gases; it then compares user choices against safer alternatives and provides feedback [75]. Alongside VR, comparative evaluations examine how different delivery modes affect learning outcomes. Optical see-through AR fire-safety training for occupants has been compared with video instruction, reporting comparable knowledge acquisition and retention while yielding higher intrinsic motivation and better self-efficacy retention [86]. Similarly, in online settings, the Virtual Safety World reports knowledge gains comparable to slide-based training while increasing engagement (participants spend more time voluntarily), improving one-month retention, and sustaining attention via instrument-based measures [103].

At the same time, game design and adaptivity are treated as levers for sustaining attention and improving performance. Experiments test how mechanics such as resource richness and avatar customization influence motivation and concentration [83], while adaptive algorithms dynamically adjust task difficulty and feedback during training [28]. Consistent with this adaptive direction, metaverse-oriented evacuation training that updates guidance using real-time information (e.g., crowd distribution and hazard location) is reported to reduce evacuation time compared with static guidance [59].

Finally, several contributions scale occupant-facing learning and observation to neighborhoods and cities. Flood-risk simulations cast learners as floodplain residents comparing protection levels and land-use options while justifying their assessments, enabling analysis of how geohazard arguments are constructed [87]. Urban-scale tools built from 360-degree panoramas simulate city-center evacuation and sheltering, logging route choices and travel times under different layouts [52]. In addition, flood and tsunami preparedness games ask residents in low-lying neighborhoods to identify safe routes, decide when to leave, or allocate limited resources, treating these decisions as both training targets and behavioral evidence [25,43,110].

4.5.4. Educators and Students

Compared with building occupants who engage immersive systems mainly as end-users of infrastructure, educators and students represent learners and knowledge multipliers. Across the reviewed studies, their use of VR/AR and serious games follows two coherent educational narratives: (i) awareness and safety education that builds correct behaviors under stress; (ii) competency building that rehearses analytical and coordination work closer to professional CI practice.

This stream starts from a simple pedagogical premise: safe behavior improves when learners can rehearse procedures in realistic but controlled conditions, before physical drills or real operations. School-oriented tools therefore prioritize short, repeatable scenarios that translate emergency plans into embodied action. Low-cost mobile VR, including deployments on devices such as Google Cardboard, trains secondary-school students in earthquake self-evacuation and reports a 71% improvement in behavioral preparedness [107]. Immersive serious games built via BIM–Unity workflows and deployed on HMDs (e.g., Oculus Rift) simulate indoor earthquake and post-evacuation scenarios for children aged 11–15, allowing controlled comparison of instructional strategies. When tested against leaflet-based training, post-game assessment produced the strongest knowledge gains and self-efficacy improvements relative to prior instruction and immediate feedback conditions [49]. Virtual replicas of school buildings used in serious games allow pupils to practice route choices and consolidate basic rules (e.g., using emergency exits, following signage, avoiding lifts and hazardous areas) before drills [30]. Fire-safety VR and serious-game studies in secondary and technical education follow the same logic, reporting gains in awareness and perceived self-efficacy after exposure to incipient-fire and evacuation situations [30,65,81,98].

A second step in this narrative is the explicit inclusion of teachers as the actors who translate simulation experience into classroom routines and emergency leadership. VR is used not only for pupil learning but also to strengthen teachers' procedural role during prevention, initial response, and evacuation. *FSCHOOL*, evaluated with primary-school teachers, shows that simulations of prevention, initial extinguishing, and evacuation improve procedural knowledge, confidence, and motivation to guide students during emergencies [81]. Similar concerns emerge in higher education where gamified evacuation tools attract interest from students, academic staff, and fire-safety services, while practitioner feedback emphasizes the need for technical support and integration with learning platforms and existing emergency plans to avoid isolated one-off experiences [65]. This work also reinforces the teacher's facilitation role, including training educators to guide drills and manage leadership, coordination, and risk communication

[85,107]. Iterative "repeat-and-reflect" designs generalize this logic: a spiral-narrative framework applied to university staff and student shows how repeated scenario exposure with in-game feedback supports reflection-in-action, adaptive reasoning, and durable retention [50]. Beyond evacuation, this pathway extends into laboratories and research environments: VR inspection training supports safety and health inspectors, laboratory staff, and students in hazard recognition, chemical safety, and compliance, reducing disruption to real experiments [40].

Finally, the awareness narrative broadens beyond earthquakes and fires to geoscience and hydrometeorological risks, while keeping the same instructional arc (conceptual understanding → situated experience → guided debrief). AR volcanology atlases transform static diagrams into interactive 3D models on mobile devices, typically paired with worksheets that structure discussion of eruption styles and threats [19,90]. Tropical cyclone and tornado simulators combine handheld AR, desktop visualization, and mixed reality so students can vary storm parameters and connect track and intensity changes to learning objectives on atmospheric processes and warnings [8,34,35]. Tsunami and coastal-flood simulations embed local topography and landmarks, so learners traverse inundation in recognizable settings, strengthening links between concepts, place-based knowledge, and drills [25,84]. Evaluations in this group commonly assess knowledge, interest, and self-efficacy, with teachers responsible for briefing and debriefing.

This stream shifts from "*doing the right thing*" in a predefined emergency script to "*thinking and acting like a future practitioner*." The core narrative is professionalization: learners are placed in settings that require hazard recognition, evidence-based reasoning, documentation, and coordination, mirroring how CI risk is handled in practice. Multi-device platforms for highway work-zone safety, for example, move students from exploration to structured output by requiring hazard identification on complex sites and translation into technical reports and formal risk documentation [94]. Project-based formats such as flood-focused "*dual hackathons*" go further by assigning quasi-professional roles (e.g., designers, risk analysts, coordinators) and organizing negotiation of options with engineers and civil-protection representatives under lecturer/tutor facilitation [56]. In these settings, XR environments function as decision laboratories: learners compare interventions, reconcile perspectives, and rehearse coordination roles under time and information constraints.

Hazard modules at university level apply the same competence narrative through domain-specific analytical work. Sea-level-rise and flood-risk learning units built on game engines and 3D GIS require students in geography, civil engineering, and environmental sciences to interrogate model outputs, combine measures, and justify adaptation choices [73,115,118]. Real-world-based immersive VR for volcanology supports observation and communication practice through high-resolution outcrop models and landscapes, enabling field-like learning without logistical constraints [109]. Flood-preparedness metaverse scenarios and serious games position learners as crisis coordinators or community leaders who interpret alerts and organize actions, with outcomes typically captured via perceived usefulness, presence, and preparedness measures [64,97,110]. Across these deployments, the emphasis is on analytical and communicative competence, though studies note that implementations are usually course-embedded and rarely include practicing CI operators or emergency staff [64,97,110].

4.5.5. Citizen and Communities

Beyond workforce and formal education, several studies position immersive learning as a civic tool for risk awareness and participatory resilience. Public-education simulations and civil-protection campaigns use VR to translate technical scenarios into accessible narratives that support safe action during crises. These interventions target collective learning and social cognition, helping communities understand their infrastructural surroundings, rehearse emergency behavior, and build trust in institutional response systems.

In mobility infrastructures, citizen-facing VR also addresses everyday safety. A railway level-crossing VR training application [45] supports pedestrians, especially students, in practicing safe crossing behavior, and evaluates the experience using the System Usability Scale and sense-of-presence measures. This framing links procedural practice to community-based resilience education and shared responsibility between institutions and the public. A related stream tackles intentional events: a serious-game scenario of a terrorist attack in a train station [36] engages citizens with emergency dynamics and protective decision-making, extending preparedness to human-induced hazards.

Several contributions aim to scale participation through lightweight or co-designed formats. An urban-evacuation VR training system based on 360° panoramas [52] represents multi-site escape routes through a streamlined pipeline, with more limited interaction in the virtual environment. A *dual hackathon* convenes student teams, civil protection organizations, and local stakeholders to co-design emergency-training concepts [56]. XR frameworks for flood action and urban risk propose multi-profile environments for training in the urban built environment [67], where residents, volunteers, and responders access role-specific views; however, pilots remain small and evidence on long-term effects on citizen–institution relations is limited [22,23,56,58,67,101].

Within hazard-focused applications, several serious games and simulations treat citizens and local communities as the primary users. *FloodGame* and *Flood Adventures* ask players to manage households or small communities exposed to river flooding, test combinations of structural and behavioral measures, and observe impacts through animated scenarios and scores [25,43]. Landslide and flood risk simulators have participants adjust slope or defense parameters and justify their choices, allowing researchers to identify misconceptions and shifts in perceived effectiveness of measures [32,33,87]. These tools support awareness and reasoning but usually remain outside concrete local plans or formal feedback channels. Participatory platforms on coastal and urban flooding embed model outputs in territorial and policy contexts. Residents, association members, and community representatives explore sea-level-rise or pluvial-flood scenarios, review inundation maps, and deliberate structural and non-structural measures, making visible tensions between development, safety, and equity, and the roles of trust, experience, and responsibility in shaping preferences [22,23,58].

4.6. Implementation Phase

After identifying who learns in resilience-oriented systems, it is also important to clarify when and where learning occurs. This section examines how educational technologies are applied across the critical-infrastructure lifecycle, from planning and design to operations, emergency response, and recovery. As shown in Figure 21, applications are unevenly distributed, clustering in phases where decision-making, coordination, and procedural compliance are most critical, highlighting how timing shapes learning objectives, scenarios, and simulation fidelity.

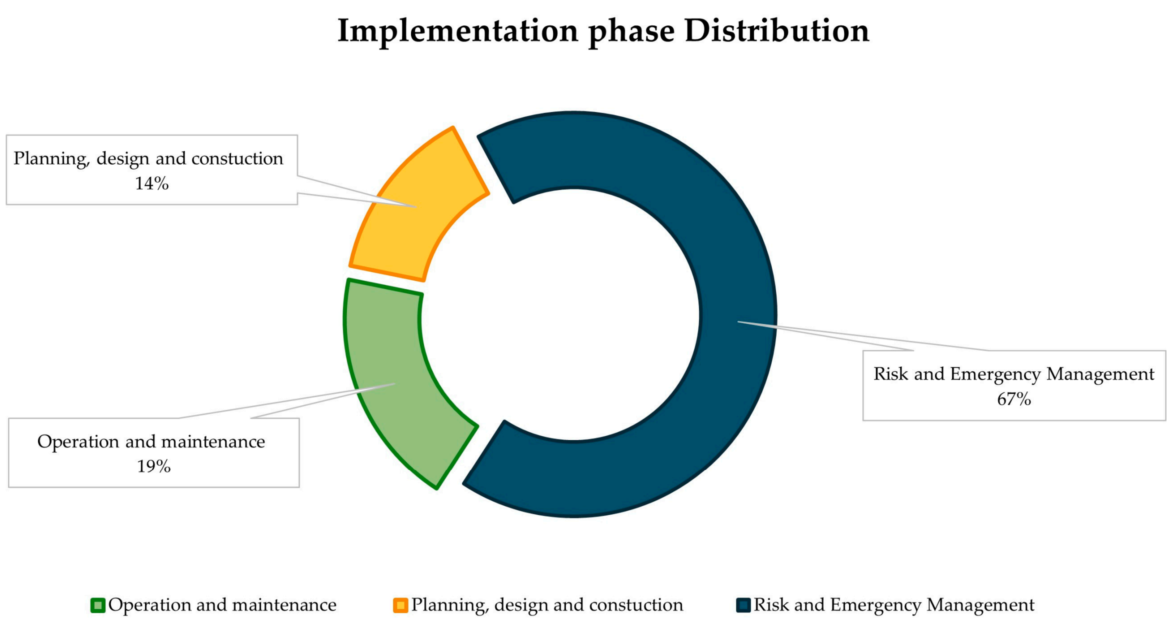

Figure 21. Implementation phase distribution. (Image created by the authors).

4.6.1. Planning, Design and Construction

During planning, design, and construction, critical infrastructures exist as evolving systems—dynamic worksites where geometry, activity sequencing, and the co-presence of workers and equipment shape risk. In this phase, XR and BIM-VR do not simply depict the finished asset but are used to train personnel before site entry and to test alternative spatial layouts, construction phases, and procedures.

A first group of applications addresses geotechnical works and excavations, treated as temporary underground micro-infrastructures where excavation geometry, access, and machinery interactions define risk. In excavation safety simulations [53], real sites are reproduced in Unity with accurate terrain, depth, width, and textures, while drilling simulations [54] emphasize the machine–environment relationship by segmenting the workspace into functional and risk zones, each linked to specific incidents and access rules. These studies show how VR makes construction-site "risk geography" explicit, allowing workers to experience hazardous configurations and correct practices before real exposure.

A second line of work focuses on complex vertical infrastructures, where construction sequencing is closely linked to risk. Wind-tower construction, for example, is modeled as a sequence of phases—from foundation works to the assembly of tower sections, nacelle, hub, and blades—within immersive VR environments that require trainees to identify hazards at each stage and systematically relate layout and operations to risk assessment [74].

Similarly, road and metro work zones are repurposed as VR training scenarios [94,95,102,105], using field-observed risk configurations to support exercises in hazard recognition, selection of control measures, and evaluation of layout alternatives prior to on-site implementation. From a methodological perspective, comparative studies on VR-based safety training [77] indicate that learning outcomes at this stage depend not only on environmental realism but also on instructional design—specifically how tasks, feedback, and errors are structured—shaping both knowledge acquisition and its transfer into practice.

4.6.2. Operation and Maintenance

Operation and maintenance (O&M) are the longest and most knowledge-intensive phases of the infrastructure lifecycle, during which digital and immersive technologies are increasingly leveraged to support safety, efficiency, and decision support under both routine and abnormal conditions. In this phase, training is oriented toward continuous monitoring, inspection, preventive actions, and the management of anomalies under operational constraints; accordingly, XR/VR and digital-twin environments can be understood as controlled, repeatable platforms for training and validation that allow users to rehearse procedures, visualize system status, and anticipate failures without disrupting live operations [31,70,71,78,89,111,119].

Across the reviewed applications, immersive systems operationalize procedural knowledge and interface literacy through sector-specific configurations. In flood protection, VR tutorials for mobile flood protection units guide trainees through the full assembly sequence of demountable barriers, enabling repetition and providing feedback on time and errors in ways that mirror real deployment along rivers or dikes [91]. Flood-oriented digital twins and XR dashboards, in turn, train users to operate observation and decision interfaces by loading scenarios, adjusting inputs (e.g., sea-level or rainfall parameters), interpreting outputs (e.g., water levels and inundation extents), and checking the status of defenses within 3D GIS scenes [73,115,118]. In geoscience practice, VR supports analytical work in field and volcanic-unrest exercises by having learners and junior experts inspect virtual outcrops, interpret monitoring time series, and propose alert levels using probabilistic tools, thereby reflecting core steps of operational surveillance [38,109].

Comparable approaches emerge for the management of technological and structural assets. In electrical substations, gas plants, and industrial facilities, immersive simulators reproduce inspection and maintenance tasks within realistic plant layouts [70,100,106,111,121]. In these contexts, operators rehearse isolation and lock-out/tag-out (LOTO) procedures [106], circuit testing and associated operating routines [121], and controlled shutdown/emergency sequences [111,121]; in parallel, data-driven modules record actions and errors to support feedback, assessment, and where applicable certification [106,111,121]. Across open-cast mining [89], maritime transport [78], offshore systems [68], chemical laboratories [31], and aviation [117], VR/AR safety courses similarly guide workers through inspection routines and standardized safety checks [46,63,71,100,119] as well as emergency responses [78,117,119], strengthening hazard recognition, engagement, and procedural compliance [46,47]. Within laboratory settings, web-based VR inspection modules enable standardized hazard-identification walkthroughs that can be completed remotely and revisited for refresher learning, with embedded quizzes and usage analytics supporting assessment and targeted reinforcement [40]. Beyond scenario fidelity, controlled comparisons of instructional designs in VR indicate that pedagogically grounded approaches can materially affect learning outcomes: productive-failure VR training has been shown to outperform directive-instruction designs in declarative safety knowledge acquisition and retention for confined-space preparation tasks [77]. Complementarily, evidence syntheses on VR/AR-based safety training underline the effectiveness of these approaches for procedural learning and risk awareness, while calling for more standardized evaluation frameworks and stable integration into organizational training programs [46,47].

In transport systems, VR training for locomotive crews enables operators to rehearse diagnostic procedures and emergency management within interactive digital-twin environments [57]. Fire-related XR systems such as GUIDE2FR support the coupling of routine inspection with emergency preparedness by allowing users to monitor sensors, verify alarms, and switch between normal and alert modes within the same digital twin [20]; similarly, tunnel-maintenance simulators operationalize this continuity in tunnel settings [27,120]. Taken together, these examples point to a functional convergence between maintenance training and safety rehearsal, whereby the same virtual infrastructure supports both preventive management and rapid response.

More advanced configurations incorporate real-time data streams into training environments, moving toward cyber-physical continuity. Digital twins of oil depots and hydropower plants synchronize IoT sensors, alarms, and control parameters with interactive 3D models [112,123]; in learning-factory contexts, digital twins of robot cells and production lines are coupled with VR-based operator training [63], providing immediate feedback on equipment status and supporting predictive-maintenance strategies [63,112,123]. In such settings, immersive interfaces enable multi-scale understanding—from component to system level—thereby reducing the cognitive gap between monitoring dashboards and physical assets.

4.6.3. Risk and Emergency Management.

Many applications use XR and serious games to rehearse how people manage risk before and during emergencies [144–146]. Overall, the reviewed contributions address three complementary functions of risk and emergency management: (i) individual preparedness and behavior (awareness, drills, and procedures), (ii) coordinated professional and multi-agency response, and (iii) data- and analytics-enabled decision support to guide choices and priorities during scenarios.

Alongside SG-driven by scripted logics, a more recent line shifts the focus toward data-driven and digital-twin platforms, where situational awareness is supported by monitoring, historical records, and forecasting to inform operational decisions during events [20]. Complementarily, some studies operate at a planning scale and compare alternative disaster-preparedness strategies in terms of expected effectiveness and health-related impacts [24], while others embed intelligence directly into wayfinding by contrasting dynamic and static guidance to optimize evacuation time and safety [59]. Related VR preparedness framework's structure training around data layers (historical data and drill records) and anticipate behavior analytics and adaptive strategies, positioned between operational training and data-centric architectures [64].

Flood and tsunami games train household- and neighborhood-level protection: players decide where to place barriers, which shelters to use, and when to evacuate while water levels evolve, then see how these choices affect damage and safety through scores and feedback screens [25,43,110]. Landslide and flood simulators train risk assessment itself, asking users to set land use and protection levels, observe resulting losses, and adjust strategies across multiple runs, which reveals how feedback shifts mitigation preferences [32,33,87]. Tsunami and coastal tools train evacuation planning by combining virtual walkthroughs of local terrain with drills, so schools and disaster authorities can test and refine routes and timing against simulated inundation [84].

Comparable approaches are evident in earthquake and fire training, where XR environments aim to enhance situational awareness, decision-making under stress, and multi-agency coordination. Earthquake scenarios reproduce the temporal progression of shocks and aftershocks, training users to take protective actions, manage panic, and execute evacuation protocols under dynamic conditions [41,51,83,85,107]. Fire simulations, in turn, focus on tenability management and evacuation under visibility loss, requiring participants to assess routes, follow alarm cues, and cooperate within time-critical situations [60,66,88]. Some drills also couple evacuation with immediate mitigation actions, such as isolating the hazard source as part of the response sequence [69]. Within this stream, drills for occupants and students alternate operational tasks (detecting the fire, selecting escape routes, using extinguishers, and managing distance and time) [65] with more procedural and organizational sequences (roles, evacuation order, collective protocols, and meeting points) [30,81]. Evaluation encompasses both awareness/competence indicators and scenario performance [61,98,103], as well as comparisons across training modalities (e.g., AR versus video) in terms of retention, motivation, and self-efficacy [86], with variants deployed in existing buildings and, in some cases, extended to support search-and-rescue tasks [75,104]. Analogous approaches also appear in transport, where immersive environments train procedural chains and command decisions in constrained spaces, from onboard-fire management with containment and passenger evacuation [18] to naval fire drills up to the muster area [60], and simulators that also support fire-brigade organization and commanding decision-making [44]. A similar emphasis on decision-making under stress is observed in other high-criticality domains such as aviation, where gamified formats are used to train emergency procedures and crisis management under time pressure and elevated cognitive load [72].

Similar behavioral frameworks have also been applied to human-induced crises, such as the simulation of a terrorist attack [36], which extends preparedness training to intentional emergencies through interactive scenario design.

Across these hazards, the emphasis shifts from individual awareness to collective and procedural preparedness, reflecting how immersive drills can operationalize safety principles across diverse emergency types. More "ex ante", some applications treat risk reduction as a behavioral objective by training safe practices at critical infrastructure points (e.g., for vulnerable users such as pedestrians) as part of accident-prevention campaigns [45].

Other studies focus on preparedness and response at community and professional level. Sea-level-rise and cyclone experiences train residents and students to interpret place-based flooding and storm impacts and to link them to local responsibilities and plans [19,73,90,115,124]. At an urban scale, contributions range from frameworks oriented to behavioral preparedness metrics (decision timing, errors, and pre/post awareness) for flood and evacuation scenarios [67] to place-based tsunami drills that train signage interpretation and route choice before real events [52]. In parallel, collaborative multi-hazard environments extend preparedness to intentional crises and support what-if exploration and decision strategies in complex city scenarios [102], while civil-protection initiatives combine emergency simulation and hackathons to develop solutions for communication, coordination, and response support [56]. Metaverse-style flood modules and participatory simulations train groups of students, citizens, technicians, and decision-makers to compare portfolios of measures and debate trade-offs between cost and protection while viewing the same model outputs [23,58,73,97,125]. Mixed-reality ADR-accident scenarios, tunnel and urban-evacuation VR, and flood-action frameworks train professional teams in coordinated response: they practice containment, route guidance, alarm strategies, and division of roles around hazardous transport and urban flooding, followed by structured debriefing in exercise or hackathon formats [52,56,66,101,120].

In tunnel contexts, *FrejusVR* provides a multi-actor example that couples the user perspective (shelter choice, SOS use, evaluating whether to attempt fire suppression, and obstacle negotiation) with the responder perspective (intervention and evacuation management), making explicit the transition from individual preparedness to coordinated response within the same scenario [26,27]. At a more systemic scale, highway-tunnel platforms train differentiated roles (control-room operators, emergency teams, drivers transporting dangerous goods, and passengers) and introduce longitudinal assessments that go beyond immediate post-tests [120]. At the professional level, some simulations go beyond procedural rehearsal and integrate operational metrics and decision components typical of response, such as fire-rescue training that measures performance (time, path, extinguishing coverage, injury rate) and updates risk estimates to guide choices during action [113]. In parallel, incident-oriented digital-twin approaches support verification and optimization of rescue plans before real execution, using the same scene for event analysis and for safety training of response teams [114]. Related patterns recur in firefighter training on real buildings for preparedness and intervention [96], complex scenarios that require multi-agency coordination and rapid decision-making [93], industrial contexts such as oil depots that combine preventive inspection with multi-role drills and penalties for errors and delays [112], and systems that introduce automation/robotics to guide action and support personnel assessment [116], as well as low-frequency/high-risk events in constrained environments such as mines [88]. Architectures for emergency-preparedness games, including *HurricaneLog* and VR training frameworks, package these patterns into reusable designs, but evaluation still focuses mainly on usability and short-term competence rather than performance in real incidents [39,64,67]. Moreover, some contributions embed emergency modules within continuous workforce H&S programs, where critical scenarios become part of recurring training that integrates crisis management and decision-making beyond episodic drills [21].

5. Discussion

The results presented in Section 4 highlight how the convergence of educational, technological, and infrastructural dimensions is reshaping the way resilience and risk management are conceived within the field of critical infrastructures. Rather than treating training technologies, pedagogical strategies, and operational contexts as separate domains, the reviewed literature increasingly frames them as interdependent components of a single socio-technical system, in which learning, simulation, and infrastructure operations co-evolve. Accordingly, this review deliberately addresses a broad and hybrid domain, at the intersection of technological tools and methods, pedagogical and learning-oriented approaches, and the organizational actors and processes operating within critical infrastructure systems. The analytical emphasis is placed on conceptual mapping and synthesis across these dimensions, rather than on a fine-grained comparison of the performance of individual tools or applications. This choice reflects the maturity and heterogeneity of the field, where variability in contexts, hazards, and learning objectives limits the transferability of isolated performance metrics, while cross-cutting patterns and design logics offer greater explanatory value.

From a technological perspective, the literature delineates a clear continuum of increasing sophistication: from analytical, model-driven desktop simulations toward adaptive, data-enriched, and collaborative XR ecosystems capable of embedding human learning within digital representations of operational infrastructures. In this trajectory, multi-user and metaverse-oriented systems represent a qualitative shift—from individual, experience-centered training to collective simulation environments in which knowledge is constructed through coordination, negotiation, and shared situational awareness, rather than through isolated task performance. What emerges is a transition from stand-alone training applications toward integrated learning ecosystems, where simulation engines, data flows, and human interaction coalesce into dynamic environments for experiential and adaptive learning. In these configurations, the boundaries between education, operation, and governance become increasingly blurred: training is no longer a discrete preparatory activity, but an ongoing process that mirrors and supports the evolving complexity of infrastructure management.

Across the reviewed studies, this integration can be interpreted through a layered architecture. An interaction layer—ranging from desktop and web-based interfaces to immersive VR, AR/MR, and multi-user platforms—shapes embodiment, attention, and coordination among participants. Beneath it, a simulation and analytics layer encodes hazard dynamics, asset behavior, and feedback logic through a heterogeneous set of approaches, including rule- and knowledge-based models, physics-based components, GIS- and BIM-linked spatial representations, agent-based engines, and, more recently, data-driven and digital-twin–oriented pipelines.

The synthesis across these technological layers reveals a consistent evolution from static, rule-based simulations toward adaptive, data-driven, and multi-user architectures that increasingly approximate the logic of cyber-physical systems. While rule- and knowledge-based engines remain essential where procedural consistency, transparency, and formal verification are required, they are progressively complemented by agent-based, AI-enhanced, and digital-twin frameworks capable of reproducing feedback loops between environment, infrastructure, and human behavior. This progression mirrors the digital transformation of critical infrastructures themselves: as assets become sensorized and interconnected, their virtual counterparts evolve from training simulators into living laboratories for operational learning.

Within this layered and increasingly integrated landscape, the treatment of hazards emerges as a critical axis along which the limits and potentials of immersive training systems become most evident. Hazards are not merely scenario backdrops but function as organizing principles that shape simulation design, data requirements, interaction modalities, and learning outcomes. The way hazards are abstracted, parameterized, and coupled with infrastructure behavior and human decision-making fundamentally constrains and enables what can be learned, by whom, and under which conditions.

Importantly, the literature shows that hazard representation rarely aims at comprehensive physical completeness. Instead, it involves selective modeling choices that balance realism, computational tractability, and pedagogical intent. In immersive and multi-user settings, hazards are often designed as adaptive stressors that evolve in response to user actions and organizational roles, rather than as fully deterministic phenomena. This reframing positions hazards not only as organizing principles but also as mediators between technological architectures and learning processes, translating analytical models into experiential challenges that expose infrastructure interdependencies, vulnerabilities, and coordination demands.

Taken together, these findings indicate that the development of immersive and simulation-based training systems does not follow a linear trajectory toward ever-greater realism or technological integration. Instead, the field is structured by recurring design tensions, in which advances along one dimension—such as hazard fidelity, geometric and semantic richness, immersion, or technological integration—entail trade-offs along others, including scalability, behavioral validity, pedagogical controllability, and transferability. To make these structural tensions explicit, the following sections organize the discussion around a set of key trade-offs that recurrently shape the design, implementation, and effectiveness of immersive training for critical infrastructures.

5.1. Trade-Off

Hazard fidelity vs. real-time interaction and scalability

Across the reviewed literature, hazard representation emerges as a foundational design choice that exposes a persistent trade-off between physical hazard fidelity and real-time interaction in immersive and multi-user training systems. High-fidelity, physics-based models—such as simulations of fire and smoke propagation, flood dynamics, or seismic damage—offer strong analytical plausibility but often impose computational constraints that limit temporal resolution, interactivity, and scalability, requiring simplifications or partial decoupling from user actions.

To preserve responsiveness and support collaborative participation, many systems adopt simplified, rule-based, or hybrid hazard models. While these approaches enable real-time interaction and adaptive scenario evolution, they risk reducing hazards to scripted processes, potentially limiting exposure to uncertainty, non-linearity, and cascading effects. Importantly, the review indicates that this tension does not concern "realism" as a single dimension. Physical realism, associated with detailed hazard dynamics and damage outputs, is the most affected by real-time constraints, whereas decision realism—time pressure, degraded information, constrained resources, and interface-mediated action—can be effectively staged even with simplified physics. By contrast, system realism, understood as the representation of interdependencies and cascading failures across infrastructure networks, remains the least developed layer, as it requires explicit coupling between hazard evolution and network or service models.

As a result, hazard fidelity in immersive training is rarely maximized in absolute terms but selectively negotiated in relation to learning objectives, user roles, and system constraints. Effective systems manage this trade-off by treating hazards not as fully deterministic phenomena, but as adaptive stressors that privilege decision salience and behavioral relevance over exhaustive physical completeness. Making this distinction explicit helps avoid conflating technical or visual realism with educational effectiveness in simulation-based training for critical infrastructures.

Geometric and semantic richness vs. behavioral validity

Across the reviewed literature, the growing reliance on GIS-, BIM-, and digital-twin–based representations highlight a central trade-off between geometric and semantic richness and behavioral validity in immersive training for critical infrastructures. Depending on infrastructure typology and lifecycle stage—from design-phase or hypothetical models to existing assets—different strategies are adopted to represent geometry, materials, and semantics within simulation environments. These choices are tightly coupled to hazard modeling, as spatial configuration and asset semantics directly shape hazard propagation, exposure, and response.

BIM-based approaches are widely used in hazard-oriented training scenarios grounded in real facilities, as they enable detailed representations of architectural layout, materials, evacuation routes, and safety systems that mediate the interaction between hazards and occupants. However, transferring BIM data into real-time training environments rarely involves preserving the full information content of the original models. Instead, BIM representations are typically reduced to selective, fit-for-purpose semantic subsets—such as object identifiers, categories, and limited properties—while attributes essential for hazard simulation, including parameters for fire and smoke propagation, crowd dynamics, or operational constraints, require additional mappings or simplifications. This reduction creates a recurring risk of conflating geometric accuracy with behavioral validity.

In practice, BIM functions less as a comprehensive digital twin and more as a semantic backbone that supports hazard-driven interaction and scenario control. Accordingly, it should be understood as a fit-for-purpose semantic substrate rather than an automatically complete representation. Claims of "liveness" in BIM- or twin-enabled training systems depend on explicit governance mechanisms, including model versioning, export consistency, controlled attribute loss, and validation metrics. Without such governance, visually credible simulations risk becoming semantically impoverished, where hazard response procedures are correct within the simulation engine but only weakly aligned with real-world operational practice.

Despite broad consensus on the pedagogical value of BIM–XR integration for hazard training, technical challenges persist. Large GIS and BIM datasets pose conversion and performance constraints, reinforcing that training-oriented spatial models do not require engineering-level completeness but must balance perceptual credibility, computational efficiency, and behavioral relevance. When this balance is achieved, BIM-based representations enable powerful hazard-centered scenario scripting, allowing safety elements to be queried collectively and evacuation or response procedures to be dynamically assessed as hazard conditions evolve.

Individual immersion vs. collective coordination

Across the reviewed literature, interaction modalities span a continuum from non-immersive desktop and web-based interfaces to fully embodied and collaborative XR and metaverse environments. Each configuration reflects a different balance between accessibility, realism, and coordination demands. While higher levels of visual immersion can enhance presence and engagement, the review consistently indicates that learning transfer depends less on sensory realism per se than on cognitive immersion—that is, the capacity to reason, decide, and act under uncertainty within meaningful constraints.

In this respect, multi-user and networked environments represent a qualitative shift in training design. By enabling collective rehearsal, inter-agency coordination, and distributed situational awareness, they move immersive training beyond individual experiential learning toward shared sense-making across roles and organizational boundaries. However, this shift also introduces new coordination challenges, including role asymmetries, communication overhead, and increased cognitive load, which must be explicitly managed through scenario design and facilitation.

Across the corpus, learning gains are most consistently associated with active interactivity rather than passive exposure to realistic scenes. Studies comparing interactive and observational versions of the same scenarios report higher emotional engagement, perceived threat, and self-efficacy when learners retain control over actions and receive feedback, aligning educational outcomes with behavioral involvement rather than with "watching" realism. Interactivity thus emerges as a primary pedagogical driver, on par with or exceeding the role of visual immersion.

Design choices that regulate how users act within scenarios function as key pedagogical levers in managing this trade-off. Navigation constraints, task monitoring, and guided feedback shape both individual experience and collective coordination. Teleportation is commonly adopted in large-scale environments to reduce disorientation and support accessibility, while free locomotion is favored in smaller, task-focused settings where fine-grained behavioral tracking is required. These choices directly influence what can be measured, coordinated, and learned, underscoring that the effectiveness of immersive training depends not on immersion alone, but on how interaction and coordination are deliberately orchestrated.

Technological integration vs. pedagogical controllability

As immersive training systems for critical infrastructures evolve toward increasingly integrated architectures, a central trade-off emerges between technological integration and pedagogical controllability. The convergence of XR interfaces, hazard simulators, spatial models derived from BIM and GIS, and analytics or digital-twin-oriented pipelines enable richer, more operationally grounded training environments. At the same time, this integration complicates the ability to define, monitor, and assess learning processes in a transparent and reproducible manner.

Highly integrated systems privilege dynamic coupling and emergence over prescriptive control. Adaptive hazard behavior, real-time data flows, and multi-user interaction generate scenarios whose evolution depends on feedback loops between environment, infrastructure, and human action. While such complexity enhances ecological validity and supports learning under uncertainty, it reduces experimental and pedagogical control: learning objectives become harder to isolate, task boundaries blur, and performance indicators are more difficult to standardize across sessions, roles, or organizational contexts.

The reviewed literature suggests that this loss of controllability is not simply a technical limitation but a pedagogical design choice. As scenario openness increases, scripted tasks and predefined success criteria are often replaced by facilitation-driven learning, debriefing, and reflection. These approaches are well suited to developing adaptive reasoning, judgment, and coordination skills, yet they complicate attribution of learning outcomes to specific design elements and challenge conventional assessment practices.

Design levers at the interaction and orchestration level play a critical role in managing this trade-off. Constraints on navigation, role assignment, information availability, and system responsiveness can be deliberately used to reintroduce pedagogical structure within technologically complex environments. Similarly, event logging, replay functions, and analytics dashboards can partially restore observability of learner behavior, provided that they are aligned with explicit learning objectives rather than driven solely by technological affordances.

Overall, the literature indicates that increasing technological integration does not automatically enhance educational effectiveness. Effective immersive training systems selectively integrate technologies while preserving sufficient pedagogical controllability to support feedback, assessment, and the learning loop. Making this trade-off explicit is essential to ensure that technological sophistication remains a means to support learning and competence development, rather than an end in itself.

Scenario specificity vs. transferability and generalization

Across the reviewed literature, immersive training systems for critical infrastructures are often designed around highly specific scenarios, assets, and organizational contexts. This specificity enhances contextual relevance and perceived realism, allowing learners to engage with familiar environments, procedures, and hazard profiles. Scenario grounding in real facilities, localized risks, and institution-specific workflows supports situated learning and can increase motivation, credibility, and immediate applicability.

At the same time, strong scenario specificity limits transferability and generalization. Training systems tightly coupled to a single asset, location, or organizational configuration are difficult to reuse across contexts, roles, or institutions, and their learning outcomes may not readily extend beyond the trained scenario. This tension is particularly salient in critical infrastructure domains, where preparedness depends not only on mastering known procedures but also on adapting to unfamiliar conditions, evolving hazards, and cross-sector coordination.

The literature highlights different strategies for negotiating this trade-off. Some studies prioritize generalizable competencies—such as decision-making under uncertainty, communication protocols, or coordination patterns—by abstracting spatial detail or hazard dynamics. Others retain high contextual fidelity while seeking transfer at a higher level, for example through role-based learning objectives, scenario variation, or parameterized hazard conditions. However, the more training scenarios are tailored to specific assets or procedures, the greater the effort required to maintain, adapt, and validate them for new contexts.

This trade-off also intersects with issues of scalability and institutional adoption. Scenario-specific systems tend to rely on bespoke data, expert configuration, and localized validation, which constrains deployment beyond pilot settings. Conversely, more generic or modular training environments may sacrifice contextual richness but support broader dissemination and longitudinal use across organizations and stakeholder groups. As a result, transferability is not an inherent property of immersive training systems, but an outcome of deliberate design choices concerning abstraction, parameterization, and learning objectives.

Overall, the reviewed studies suggest that effective immersive training does not maximize either specificity or generalization in isolation. Instead, it selectively anchors scenarios in concrete operational contexts while designing for transfer at the level of competencies, coordination patterns, and decision strategies. Making this trade-off explicit is essential to align immersive training systems with long-term resilience goals, workforce development, and cross-institutional learning in critical infrastructure domains.

Infrastructure and Maintenance Costs vs. Innovation Pace

Across the reviewed literature, immersive training systems for critical infrastructures are often presented as technologically advanced and rapidly evolving, reflecting the fast pace of innovation in XR platforms, simulation engines, data integration, and analytics. Continuous advances in hardware, software frameworks, and interaction paradigms enable increasingly sophisticated training experiences, but they also introduce a persistent trade-off between innovation pace and the infrastructural and maintenance costs required to sustain these systems over time.

Highly innovative training environments tend to rely on complex technical stacks, including specialized hardware, proprietary software components, custom integration pipelines, and expert configuration. While these choices support cutting-edge functionality, they increase dependency on specific platforms and skill sets, raising costs related to system upkeep, updates, and troubleshooting. Several studies implicitly acknowledge that maintaining operational continuity—ensuring compatibility across hardware generations, software versions, and data sources—can become as demanding as initial system development.

Conversely, approaches that prioritize infrastructural stability and maintainability often adopt more conservative technological choices, favoring mature platforms, standardized components, and modular architectures. While such strategies may limit access to the latest interaction modalities or simulation capabilities, they support scalability, longevity, and institutional adoption, particularly in organizations with constrained budgets or limited technical support. In these contexts, slower innovation cycles can enable more reliable integration with training programs, curricula, and organizational processes.

This trade-off is especially salient for immersive training conceived not as one-off demonstrations but as long-term institutional capabilities. Rapid innovation without corresponding investment in maintenance, documentation, and staff training risks producing systems that are technologically impressive yet short-lived, remaining confined to pilot projects or research prototypes. By contrast, sustainable training infrastructures require deliberate decisions about when to adopt new technologies, how to manage upgrades, and how to balance experimentation with operational reliability.

Overall, the literature suggests that the educational value of immersive training depends not only on technological novelty but also on the capacity to sustain and evolve systems over time. Making the trade-off between infrastructure and maintenance costs and innovation pace explicit is essential to align immersive training initiatives with long-term resilience strategies, workforce development, and organizational capacity building in critical infrastructure domains.

5.2. Boundary Conditions and Transfer-to-Practice Limitations

The reviewed literature highlights constraints that still prevent the full realization of ecosystem-level resilience learning and, crucially, limit transfer to practice. Cultural and institutional barriers remain among the most critical: immersive and simulation-based tools are still frequently perceived as experimental or peripheral and thus treated as addons rather than as integral components of curriculum design, competence management, and organizational learning. Integration into formal curricula, competence frameworks, and regulatory pathways remains fragmentary, weakening continuity between pilot studies and operational adoption. In professional settings, experienced staff may express skepticism toward game-like interfaces or "edutainment" aesthetics, while public agencies and academic institutions often lack the procurement capacity, staffing stability, and governance structures needed to sustain training ecosystems beyond the duration of funded projects. Notably, these limitations cluster along two dimensions of our coding framework—stakeholders and implementation phase—indicating that the field often optimizes interaction and scenario design at prototype stage while under-addressing the institutional conditions required for operational transfer.

Methodological limitations further constrain progress and comparability. Evaluation practices frequently stop at usability, acceptability, or short-term knowledge gains, whereas fewer studies validate learning in terms of behavior, longitudinal retention, or transferability to real-world performance. Consequently, training impacts are rarely linked to operationally meaningful indicators—such as decision quality under time pressure, procedural compliance, coordination performance, situational awareness, or persistence of competence over time—thereby limiting the evidence base required to justify investment, certification pathways, and recurring training cycles. More broadly, metrics that quantify resilience-oriented learning outcomes (e.g., adaptive collaboration and robust decision-making under uncertainty) remain embryonic, and reporting practices often omit contextual mediators (e.g., prior expertise, instructor role, organizational constraints) that strongly shape effectiveness.

From learning proxies to operational endpoints: a broken evidence chain. Across the corpus, the core limitation is not the absence of reported learning benefits, but the absence of a defensible evidence chain from training exposure to operational competence. Many studies demonstrate effects on experience-oriented or short-term outcomes (e.g., usability, presence, satisfaction, immediate knowledge gains), yet fewer articulate validity evidence that links simulator performance to job-relevant behaviors, decision quality, or risk-sensitive outcomes in CI workflows. Without this chain—objectives → observable behaviors → validated metrics → operational endpoints—immersive training remains difficult to compare across studies, justify for procurement, and institutionalize within certification and refresher cycles.

Technological and lifecycle constraints also represent persistent boundary conditions. Interoperability between XR platforms and CI data infrastructures (e.g., BIM/GIS datasets, operational databases, and real-time sensor streams) remains inconsistent, and rapid hardware/software obsolescence undermines the sustainability and reproducibility of training assets. Scalability is primarily constrained by lifecycle operability rather than by immersion level. Beyond interoperability, the literature rarely reports the practical determinants of scale: instructor workload, scenario authoring and update cycles, hardware logistics, cybersecurity constraints, and total cost of ownership. These factors matter because CI organizations adopt training systems as maintained assets—requiring change control, versioning, audit trails, and predictable operational overhead—rather than as one-off demonstrators. As a result, promising prototypes risk remaining confined to pilot-stage deployments even when technical feasibility is demonstrated.

These challenges intensify as systems incorporate operational datasets, monitoring streams, and digital-twin representations, turning governance of data, models, and scenarios into a central design and institutional requirement. Questions of data quality, cybersecurity, privacy, and responsibility for model updates cannot be treated as secondary, because without clear stewardship, version control, and documentation—

together with transparency about modeling assumptions—scenario logic may drift from current procedures and regulatory requirements. Governance is under-specified as a design variable. In multi-actor CI settings, effective training depends on explicit agreements about (i) scenario ownership and responsibility for modeling assumptions; (ii) data stewardship and access rules when operational datasets or digital twins are used; and (iii) auditable performance thresholds that define competence and enable accountability. When these elements remain implicit, training evidence cannot be compared across sites or agencies, and "success" becomes locally defined—undermining cross-sector coordination and mutual recognition of training outcomes.

The result can be either false reassurance or training misaligned with regulated practice. Sustainability considerations therefore extend beyond technology selection to lifecycle management: maintaining scenario relevance, ensuring traceability of updates, and safeguarding the integrity of training data and analytics.

Finally, a neglected yet crucial limitation concerns preservation. Many immersive applications are designed as stand-alone prototypes with limited documentation and no archival strategy, leading to the loss of valuable pedagogical and design knowledge as platforms, operating systems, and devices evolve. In this sense, the fragility of digital learning products can mirror the fragility of the infrastructures they aim to protect, underscoring the need for robust conservation strategies, metadata standardization, and—where feasible—open and portable simulation datasets that enable reuse and cumulative learning across projects and organizations.

5.3. Implications for Practice and Research

What stakeholders should take away from this review is that effective CI resilience training depends less on "XR adoption" per se and more on aligning the training objectives, the interaction modality (desktop/web vs. VR vs. AR/MR), and the learning loop (scenario design, feedback, debriefing, and assessment) with organizational constraints such as scalability, safety requirements, and governance capacity.

- Educators and training designers: Select and deploy immersive and simulation tools as facilitated learning sequences (scenario + structured debriefing + competence-oriented assessment), not as stand-alone experiences. Prioritize platforms that enable reflection and traceability (event logs, replay, prompts, performance dashboards) and design role-based scenarios (e.g., coordinator/analyst/responder) that connect disciplinary content to authentic CI decision contexts. Educators and trainers should be supported as learning-system operators, with authoring tools, analytics, and institutional backing to orchestrate scenarios and translate performance into procedural knowledge and risk communication.
- Infrastructure operators and CI organizations (including asset managers and training units): Implement training as a tiered ecosystem: scalable desktop/web simulations for broad coverage and procedural baselines, complemented by higher-immersion XR for high-risk tasks, teamwork coordination, and stress-exposure training. Procurement should require audit-ready evaluation hooks (standardized logs, exportable analytics, configurable dashboards) that link training evidence to competence management, certification, and refresher cycles. Treat scenarios as living assets—with version control, documented assumptions, and update routines—to keep rule sets aligned with evolving regulations, assets, and hazard profiles (including where digital-twin pipelines are used).
- Emergency services and multi-agency actors (civil protection, first responders, inter-organizational teams): Prioritize multi-user training with explicit coordination objectives (information sharing, handovers, command decisions) to strengthen shared situational awareness and inter-organizational interoperability. Pair scenarios

with structured after-action review workflows (timeline reconstruction, replay, decision-point analysis) to convert simulation experience into transferable procedures. This is particularly important in multi-hazard events, where responsibilities and information are distributed across agencies.

- Policymakers and regulators (standard-setting bodies, public funders, oversight agencies): Enable uptake by clarifying expectations for competence frameworks, validation, and interoperability requirements, which the literature still treats unevenly. Accelerate adoption through funding and mandates for shared assessment frameworks that connect learning analytics to safety- and competence-relevant outcomes, and through support for repositories and preservation standards to avoid loss of public-value training knowledge as technologies evolve. Incentivize cross-sector consortia (academia–operators–civil protection) to align scenarios with governance needs and support mutual recognition of training evidence across CI sectors.

These practice implications point to a corresponding research priority: moving beyond isolated demonstration studies toward cumulative, comparable evidence and sustainable governance models that enable immersive training to scale beyond pilots and function as institutional learning infrastructure in critical infrastructure contexts. Future research should explicitly articulate learning objectives, document simulation logic, feedback, and facilitation mechanisms in a reproducible manner, and adopt shared outcome categories encompassing knowledge and procedural understanding, decision-making and coordination performance, as well as longer-term retention and transfer to drills and operational practice.

6. Conclusions

This review clarifies how immersive and simulation-based technologies contribute to hazard-oriented training in critical infrastructure contexts. Rather than advancing specific tools, it identifies design principles and priorities that shape learning effectiveness, transferability, and sustainability.

6.1. Key Technological Takeaways

- Hazard modeling is the core determinant of training value. Learning effectiveness depends on how hazards are abstracted, coupled with infrastructure behavior, and made responsive to human decisions, rather than on immersion level alone.
- Realism must be functionally negotiated. Physical, geometric, and data fidelity enhance plausibility but must be balanced against real-time interaction, scalability, and pedagogical control to preserve behavioral validity.
- Spatial and semantic models enable hazard-aware interaction only when selectively curated. GIS-, BIM-, and digital-twin-based representations support exposure analysis and procedural rehearsal, but require abstraction and governance to avoid conflating visual accuracy with learning outcomes.
- Interactivity and coordination outweigh sensory immersion. Learning transfer is most consistently associated with active control, feedback, and multi-user coordination, especially in multi-hazard and multi-agency scenarios.
- Sustainability is a technological constraint, not a secondary concern. Interoperability, maintenance effort, scenario transferability, and infrastructure costs determine whether hazard-training technologies remain prototypes or evolve into institutional capabilities.

6.2. Agenda for Research and Development

- Shift evaluation from experiential proxies to operationally meaningful outcomes. Future studies should link training performance to decision quality, coordination effectiveness, and behavior under time pressure, rather than relying primarily on presence or usability metrics.
- Advance hybrid hazard modeling approaches. Research should explore combinations of physics-based, rule-based, and data-driven models that balance fidelity with real-time interaction and scalability.
- Strengthen learning-loop instrumentation. Logging, replay, analytics, and after-action review mechanisms should be treated as core system components to enable assessment, comparison, and longitudinal learning.
- Address lifecycle governance and interoperability explicitly. More work is needed on standards, versioning, and governance models that support reuse, maintenance, and cross-organizational adoption of hazard-training systems.
- Design for transfer and coordination across roles and organizations. Future training technologies should prioritize competencies and coordination patterns that generalize across assets, hazards, and institutional contexts.

Immersive and simulation-based technologies add value to hazard training when hazard modeling, interaction design, and learning loops are deliberately aligned to support transferable, assessable, and sustainable competence development. Progress in this field depends less on increasing immersion and more on designing technologies that make risk dynamics actionable over time.

Looking ahead, the consolidation of immersive and simulation-based training as an evidence-based practice will depend on the ability to align technological sophistication with human-centered design and evaluative rigor. Future progress requires shared assessment frameworks that connect learning analytics to operational competence, the responsible use of AI and data-driven methods to support adaptive and longitudinal learning trajectories, and a sustainability-oriented approach in which immersive environments are conceived as living repositories of institutional knowledge. Bridging innovation and governance is therefore essential to ensure that digital training experiences contribute to the cumulative intelligence of resilient operators and organizations over time.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18063067/s1, PRISMA 2020 Main Checklist [147].

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
AM	Asset Management
AR	Augmented Reality
CAVE	Cave Automatic Virtual Environment
DT	Digital Twin
GPPs	Gas Power Plants
HMDs	Head-Mounted Displays
HSE	Health, Safety and Environment
IFC	Industry Foundation Class
IoT	Internet of Things
IVR	Immersive Virtual Reality
ML	Machine Learning
MR	Mixed Reality
NaTech	Natural Hazard Triggering Technological Disasters
NPCs	Non-Player Characters
O&G	Oil and Gas
PMT	Protection Motivation Theory
PPE	Personal Protective Equipment
RETURN	Multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate
SGs	Serious Games
SLODs	Slow-Onset Disasters
SUODs	Sudden-Onset Disasters
USAR	Urban Search and Rescue
VR	Virtual Reality
XR	Extended Reality

Appendix A

((TITLE ((“scenario based” OR training OR preparedness OR exercise OR Education OR Learning OR awareness OR teaching) AND (immersive OR Experien* OR interactive OR “virtual-reality-based” OR VR OR virtual OR cyber OR “web-based” OR “serious game” OR “Serious Games” OR “Serious Game” OR “augmented reality” OR “Mixed reality” OR “extended reality” OR “Virtual Reality” OR “situational awareness” OR metaverse OR hologram OR platform OR simulation OR simulations OR simulator) AND (Crisis OR drought OR risk OR safety OR emergency OR flood* OR earthquake OR tsunami OR landslide OR hydro* OR fire OR evacuation OR hazard OR disaster OR volcan* OR tornado OR hurricane OR Cyclones) AND NOT (“training data”)) AND (ABS (earthquake OR worldwide OR flood* OR hydro* OR landslide OR tsunami OR cyclones OR Hurricane OR volcano* OR Tornado OR sea OR school OR cit* OR factory OR industr* OR plant* OR airport OR station OR railway OR seaport OR bridge* OR tunnel OR buil* OR stadium* OR road OR subway OR metro* OR construction OR transport OR grid OR hydro* OR aqueduct OR dam OR canal OR gas OR pipeline OR off-shore OR infrastructure OR corridor OR highway OR urban OR oil OR nuclear OR power OR underpass OR overpass OR viaduct)))) AND PUBYEAR > 2014 AND PUBYEAR < 2026 AND (EXCLUDE (SUBJAREA, “IMMU”) OR EXCLUDE (SUBJAREA, “VETE”) OR EXCLUDE (SUBJAREA, “DENT”) OR EXCLUDE (SUBJAREA, “PHAR”) OR EXCLUDE (SUBJAREA, “NEUR”)

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